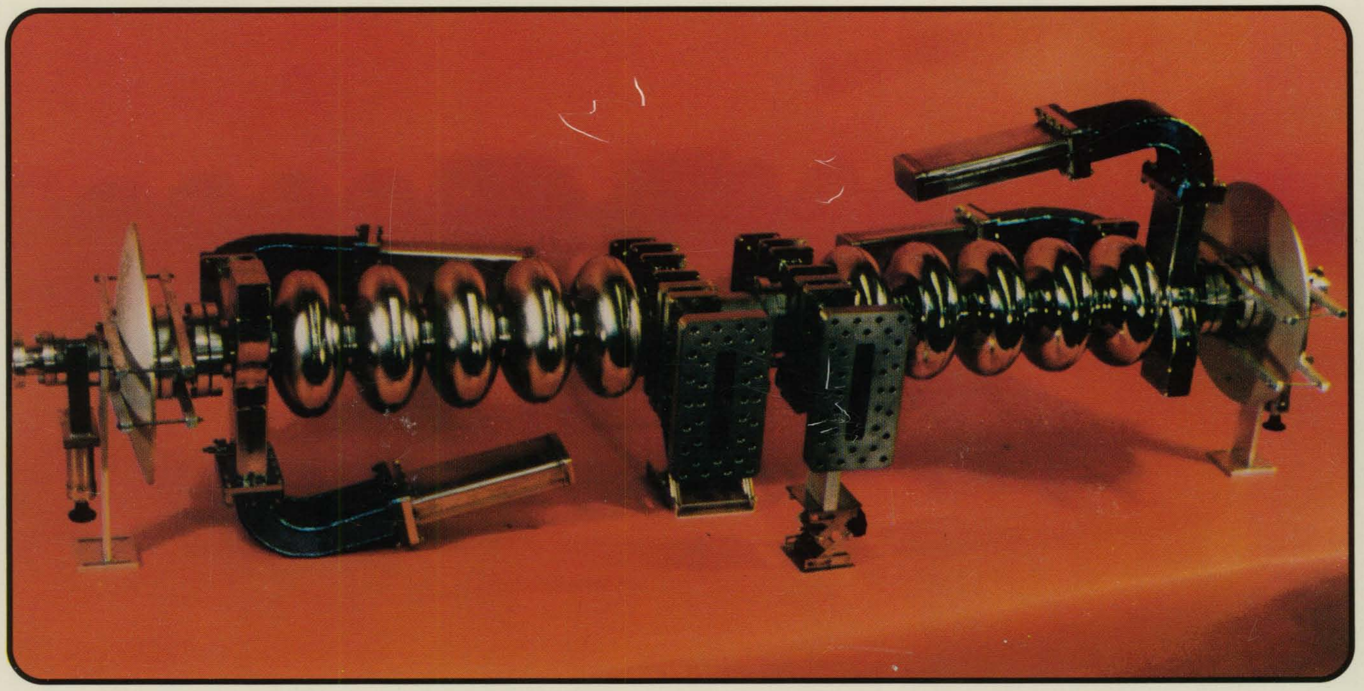
Nuclei, Nucleons, Quarks

Nuclear Science in the 1990's

A Long Range Plan by the
DOE/NSF Nuclear Science Advisory Committee

December 1989



U.S. Department of Energy • Office of Energy Research
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Cover Photo

A two-cell, 1m superconducting niobium resonator, originally developed at Cornell University and now the crucial element for CEBAF, the 4-GeV continuous-wave electron accelerator under construction at Newport News, Virginia. These resonators have demonstrated accelerating fields as high as 7MV/m at an operating temperature of 2K.

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SUMMARY and RECOMMENDATIONS

The central thrust of nuclear science is the study of strongly interacting matter and of the forces that govern its structure and dynamics.

As we enter the last decade of the 20th century, this agenda ranges from large-scale collective nuclear behavior through the motions of individual nucleons and mesons (collectively called hadrons) in atomic nuclei, to the underlying distribution of quarks and gluons. It extends to conditions at the extremes of temperature and density which are of significance to astrophysics and cosmology and are conducive to the creation of new forms of strongly-interacting matter.

Another important focus is on the study of the electroweak force, which plays an important role in nuclear stability, and on precision tests of fundamental interactions.

Over the last 20 years our understanding of both the strong and electroweak interactions has undergone profound development, resulting in a theoretical framework referred to as the Standard Model. A major goal of nuclear physics today is the further exploration of this theory and its application to nuclear systems. A particular challenge is to show how the accepted theory of the strong interaction, quantum chromodynamics (QCD), which is cast in terms of unobservable quarks and gluons, can be developed to yield a low-energy description consistent with the baryons and mesons observed in the physical world. This development would provide a theory of hadronic matter of sufficient power and generality that it could be applied to almost all phenomena in the universe. New phenomena that give a glimpse of matter as it existed at the very beginning of time have already been predicted to occur in the collisions of heavy nuclei. The search for this "quark-gluon plasma", like the search for rare decays of strange mesons and of muons, may lead to improvements to the Standard Model.

At the same time, the nucleus, as a fundamental many-body system governed by the rules of quantum mechanics, continues to be a source of new phenomena, most interestingly at the limits of nuclear stability. The description of cooperative effects in terms of the interactions of the nuclear constituents, in a strongly correlated system such as the atomic nucleus, is a challenge to many-body theory.

The tools needed to pursue this broad and fundamental research program with efficiency are diverse. They both drive and depend upon significant advances in technology: (1) first and foremost, accelerators that produce high-quality beams of electrons, hadrons, and heavy ions, over a very large energy range; (2) detectors and targets that are novel in concept and complexity; and (3) large-scale computational facilities for theoretical work and data analysis.

The nation's ability to maintain nuclear science at the intellectual cutting edge, to provide research tools in a timely fashion and to support the necessary educational activities depends upon responsible long-range planning. This 1989 Long Range Plan (LRP) for Nuclear Science has been prepared in response to a joint request from the U. S. Department of Energy (DOE) and the National Science Foundation (NSF) to the Nuclear Science Advisory Committee (NSAC), to provide the agencies with advice for the next decade. While building upon the LRPs prepared in 1979 and 1983, NSAC undertook a thorough assessment of the new scientific opportunities in nuclear physics, and of the facilities and funding required to pursue these. Input was obtained from all segments of the nuclear science community through : "Town Meetings" sponsored by the Division of Nuclear Physics of the American Physical Society; presentations to NSAC by laboratory directors; and, finally, deliberations by a broadly representative Long-Range Plan Working Group (LRPWG) of 54 nuclear scientists, at a week-long meeting. The work and the recommendations of the LRPWG form the basis of this report.

Based on the major scientific opportunities described in the body of this text, the LRPWG began laying out the LRP by first addressing the issues of major new facilities. Specifically, the merits of the Relativistic Heavy Ion Collider which had been proposed in 1983, were re-evaluated extensively. The scientific merits of an advanced hadron facility, KAON, were also discussed in detail. Accordingly, the recommendations with respect to major facilities are as follows:

1. The highest priority in U.S. nuclear science at this time is the timely completion of the Continuous Electron Beam Accelerator Facility (CEBAF) and the beginning of its important research program.

2. We strongly reaffirm the very high scientific importance of the Relativistic Heavy Ion Collider (RHIC). Since the last LRP, theoretical progress has strengthened the case for the existence of a quark-gluon plasma, and recent experiments demonstrate the likelihood that conditions favorable to its formation will be attained. RHIC will provide unprecedented opportunities to produce and study ultradense matter. Therefore, we strongly endorse the recommendation of the 1983 LRP and subsequent NSAC deliberations that RHIC has the highest priority for new construction in the nuclear physics program. We urge a swift beginning for this important project.

3. NSAC recently endorsed the fundamental and exciting scientific opportunities that will become available with a high-intensity, multi-GeV hadron facility. These opportunities will extend our knowledge both of the strong force, which determines nuclear dynamics based on quarks and gluons, and of the electroweak force, which provides stringent tests of the basic laws governing subatomic phenomena. The Canadian invitation for U.S. participation in the construction of an international research facility, KAON, with Canada providing full support for the operation of the facility, provides an exceptionally cost-effective way for the U.S. nuclear science community to address this important physics in a timely fashion. We recommend with very high priority that the U.S. enter into negotiations with Canada to participate in the construction and use of KAON.

The above facilities are essential to carry nuclear physics into the next century. They emphasize the high-energy frontier of nuclear physics. In addition, it is important to recognize the challenges and opportunities across the broad frontiers of nuclear science. Many of these can be addressed by existing facilities, in particular since several of them are new and most have acquired significant new capabilities in the recent past. A good number of these are located at universities and provide an important focus for research and educational activity close to the source of the next generation of scientists. This report outlines the wide scope of today's and tomorrow's nuclear physics, and the need for a variety of facilities, large and small. This leads to the following recommendation:

4. Crucial elements of nuclear physics are not addressed by the major new facilities of recommendations 1–3. Opportunities range across almost all subject areas discussed in this report. Indeed, the wide range of nuclear phenomena and the unity of the underlying understanding, from the phenomenology of nuclei through collective, nucleon, and meson degrees of freedom, and finally to quarks and gluons, is an essential feature of modern nuclear science. Exploration of these frontiers requires a vigorous program using existing facilities that provide electron, hadron, and heavy-ion beams across a wide energy range. The distribution of funds between ongoing programs and new initiatives should provide for a broadly based and balanced advance.

A number of additional smaller facilities are now being considered by various groups: an accelerator for radioactive beams; intense higher energy pion beams; a 0.5 to 1-GeV/nucleon high-resolution heavy ion accelerator; a proton cooler ring in the range of 10-20 GeV, for the exploitation of spin degrees of freedom; a facility for high fluxes of cold and ultracold neutrons for fundamental measurements. The conceptual development of some of these projects, or others of comparable scale, is important for the field's continuing vitality. We anticipate that at least one such project will achieve high scientific viability over the period of this LRP.

Nuclear physics has always pushed against the boundaries of the field. The emergence of the fundamental theories of the strong and electroweak interactions and their combination in the Standard Model, and the recently increased interest in nuclear astrophysics arising from the spectacular observation of supernova neutrinos as well as the continuing solar neutrino puzzle, provide many new opportunities for nuclear physicists to contribute to the solution of some of the most fundamental questions of physics. Experiments in such areas often require tools not normally provided by nuclear laboratories. The needs for these activities are the subject of the following recommendation:

5. Precision tests of fundamental interactions probe physics at mass scales beyond the reach of any planned accelerator and beyond the Standard Model. Nuclear astrophysics provides both tests of nuclear physics in new regimes and perspectives on the evolution of the universe. Experiments at very high energies allow us to probe the quark structure of nuclei at very small distance scales. These activities are important to our field. Experiments in these areas employ a range of facilities from non-accelerator instruments through reactors and small accelerators, to the largest machines. We recommend effective pursuit of these topics by strong and timely support for the specialized instrumentation needs of this field, and the cost-effective use of the world's high-energy facilities.

An exciting example of such new instrumentation is the Sudbury Neutrino Observatory (SNO), a joint Canada-U.S.-U.K. project, for which NSAC recently enthusiastically endorsed U.S. participation.

As nuclear physicists open these new areas of investigation and deepen their explorations in traditional areas, a commensurate increase in theoretical activity is needed. New ideas must be developed and the predictive power within the framework of QCD must be improved. Each of the previous LRPs noted a need to strengthen the U.S. nuclear theory effort. Progress has been made recently in the funding for nuclear theory and through the founding of a National Institute for Nuclear Theory, but there is still an imbalance between the experimental and theoretical efforts in nuclear physics:

6. As nuclear science explores new frontiers, a strong theory program becomes increasingly essential. We therefore reaffirm the recommendations of the 1988 NSAC Report on Nuclear Theory, and the statements of previous LRPs calling for an expansion of the nuclear theory effort. We recommend that the agencies continue the recent trend of increased support for theory.

The broad range of scientific questions addressed by nuclear physics requires continuous technological developments. It is often through the invention and development of the required technology that nuclear physics makes its most important contributions to our technological society. This report describes many of these significant advances. We cite here only the Gammasphere project, which will greatly expand the horizons of nuclear spectroscopy. There is a broad consensus in the nuclear community that the present level of capital funds available for novel instrumentation is inadequate. In addition, as university groups are changing more and more to a user's role, an improved level of technical infrastructure at universities is required if the development of novel and complex detectors is to be effectively pursued by faculty and students. Thus we recommend as follows:

7. Nuclear physics is moving into many new experimental domains that require novel concepts and/or increasing complexity in detectors, targets, and other instrumentation. To realize the most promising new ideas and projects in this area requires an increase in capital equipment funds over the present level, and increasing attention to the technological support structure at university laboratories.

The quality and vitality of any scientific endeavor are determined by the intellectual strength and the creativity of its scientists. Are there enough nuclear physicists to take up all the expanding challenges offered in this report? The number of active scientists in nuclear physics has been historically limited to about 1400, plus about 800 Ph.D. students, by a constant funding situation. Nevertheless, it is estimated that sufficient scientific manpower exists in the field to exploit the new facilities *and* maintain the important programs at the existing ones. Of course, as the major new accelerators which are the subject of recommendations 1–3 are realized, some redistribution of scientific effort must be expected.

The continuing and vigorous involvement of the universities, as the well-spring and training ground of future scientific manpower, in nuclear research programs is vital. Nuclear physics is fortunate to have many research facilities, some quite large, located at universities. We note with satisfaction the present strong interest of graduate students in our science. As an important part of our nation's basic research effort, nuclear physics will continue to play a significant role in the scientific education and training of young Americans.

8. We urge the agencies to maintain support for the educational and specifically the university-based programs that produce the skilled young scientists so vital to the well-being of nuclear science, and that provide high-level training of manpower for the many related sciences and the technology base of the country.

At this time, nuclear physics, like high energy physics, is moved by the intellectual development of its science to invest heavily in new facilities. Major scientific opportunities that had already been identified in 1983 will be lost to U.S. science unless construction of the appropriate facilities, most importantly RHIC, is started very soon. With this background in mind the LRPWG has carefully considered the minimum requirements for an effective and efficient nuclear physics program in the U.S. over the next decade.

We have constructed a budgetary profile that can accomplish the highest priority goals in nuclear science in a timely, cost-effective way. These goals include the effective utilization of key capabilities now in place or under construction, the realization of the major new facilities recommended in this plan, and the proper attention to the human and technical infrastructure that ensures continued success in research and education.

Our extrapolation starts with the assessment that the present needs for nuclear science come to (all in FY91 Dollars) about $340 Million in the DOE program and $50 Million in the NSF program. When these needs are extrapolated to 1997, beyond the completion of both CEBAF and RHIC, the programs in the field will require a base budget of at least $340 Million in the DOE program and $62 Million in the NSF program. These levels would provide for an austere, but scientifically viable, program, and recognize the need to increase funding for operation at some facilities, for increases in equipment funds and support for university users groups, as well as for nuclear theory.

They do not include funds for KAON, and we urge that new money be sought for this cooperative venture once it is approved by Canada. The above estimate also does not include funds for construction of a new smaller facility or upgrade. It is highly desirable to allow for construction or upgrade of at least one small facility in the time frame of this LRP, and we propose addition of about $20 Million per year in new construction funds later in the decade.

Nuclear physics is an important component of the intellectual, scientific and technological foundation of a prosperous, technologically developed society. Because of its connections to other fields adjoining its wide perimeter, nuclear physics plays a very significant role in supplying scientific manpower for industry and national laboratories. Nuclear physics continues to make essential contributions to our society – its industry, technology, and national defense –through advances in basic knowledge, through technical developments, and through the demonstration of new technical concepts. The size of the U.S. nuclear program has clearly recognized this important role in the past. It is our hope that this Long Range Plan will contribute to maintaining this role through the 1990s.

PREAMBLE

Basic nuclear physics research in the United States is a large effort. It involves about 2200 scientists and graduate students, many laboratories and universities, and about $330 Million in funds in 1989. Thus long-range planning is essential.

In the late 1970s the Nuclear Science Advisory Committee (NSAC) was established as the main scientific advisory body to the federal agencies which traditionally fund nuclear science, the Department of Energy (DOE) and the National Science Foundation (NSF). Since then, NSAC has played a major and, one dares say, successful role in the long range planning process for nuclear physics. Long range planning documents were prepared in 1979 and in 1983. This year, in 1989, NSAC was again asked by the agencies to prepare such a plan for the next decade.

The charge issued by Dr. Marcel Bardon from NSF and Dr. Wilmot Hess from DOE (which is appended to this report) on June 13, 1989, requests that

> *NSAC conduct a new study of scientific opportunities and priorities in U.S. basic nuclear physics research and recommend a long range plan which will provide a framework for coordinated advancement of the Nation's basic nuclear research programs over the next decade.*

The charge lists the high priority recommendations from the earlier plans, i.e., the high-energy high-duty-factor electron accelerator, CEBAF, now under construction, and the relativistic heavy ion accelerator, RHIC, now in an advanced stage of planning, as starting points for the new plan.

In response to this charge, NSAC has held a number of preparatory meetings and collaborated with the Division of Nuclear Physics of the American Physical Society in arranging a number of open Town Meetings (the list of meetings is given in the appendix) at which input from the entire nuclear science community was obtained. The planning process culminated in a meeting of a Long Range Plan Working Group (LRPWG), consisting of 54 members (including the NSAC membership) broadly representative of the entire scope of nuclear physics. At that meeting, held from August 6 to 11, 1989, on the campus of the University of Colorado in Boulder, the priorities and recommendations for the 1989 Long Range Plan were worked out in long and open discussions. In parallel, the LRPWG wrote nine scientific position papers covering the various subfields of nuclear physics that provide the background and motivation for the priorities and recommendations. These nine scientific sections make up the main body of this report, the 1989 Long Range Plan. The scope and layout of the report follow quite closely the successful model of the 1983 LRP. Accordingly, the scientific section is supplemented by material which describes the facilities and instruments of nuclear physics, the impact on science, industry and society, and by an overview of the scientific manpower and funding pattern of the field.

As was the case for its predecessor, this report is not addressed to the experts in the field, although they might find it useful to obtain an overview over the broad landscape which nuclear physics represents today. It is the aim of the authors to convey to a broader audience the excitement and the vitality which pervades nuclear physics today, and to make the priorities and recommendations understandable to an educated general public.

Finally, although this report looks at a horizon of ten years, it is likely that it will be outdated before 1999. Scientific research is a rapidly evolving and sometimes not very predictable enterprise. It speaks for the foresight of the 1983 LRP that the LRPWG in 1989 reaffirms the direction which was initiated by the earlier plan, providing additional scientific motivation and momentum to extend it through the 1990s. It is our modest hope that the next LRPWG will find, in turn, that the priorities and recommendations presented here were sound, and led to a solid advancement of nuclear science.

I. NUCLEAR PHYSICS: AN EVOLVING SCIENCE

• The Science

The next decade of nuclear physics will build on over 60 years of discovery and progress. As nuclear physics evolved over this period, it spawned the sister discipline of elementary particle physics (high energy physics) and developed many experimental and theoretical methods that are now routinely used in atomic, molecular and condensed-matter physics. This fertility arises in part from the pivotal position of nuclear physics at the border between the physics of our daily experience and that of the subatomic world.

Today, the horizons of nuclear science are expanding in substantial ways. Our understanding of basic issues, such as nuclear collective motion and its relation to the underlying nucleon-nucleon force, has deepened as we have discovered more powerful experimental and theoretical techniques. Simultaneously, new frontiers are emerging: the properties of nuclear (or hadronic) matter at extremes of density and temperature; the connections between the meson-nucleon and the quark-gluon descriptions of strongly interacting systems; the application of the fundamental theory of the strong interaction, quantum chromodynamics, to nuclear systems; the nuclear physics of supernova explosions; the processes by which the elements were synthesized; and the exploitation of the nucleus as a medium for precise tests of the electroweak interaction and its connection to the strong interaction by the so-called Standard Model. The realm of nuclear physics now includes the study of all forms of natural and induced radioactivity, with emphasis on the production of new, exotic nuclei that have no counterparts among the stable elements that we encounter in our daily lives, as well as the study of neutrinos from the sun and other astrophysical phenomena. Nuclear phenomena of interest today thus involve natural scales that range from the shortest distances we can test with existing accelerators to those of the grandest events in astrophysics.

The recognition that quarks and gluons are the fundamental building blocks of strongly interacting particles, and thus of nuclear matter, and the advent of QCD as the fundamental theory of the strong interaction have had a great impact on nuclear physics over the last decade. They have expanded the horizons of nuclear physics into an energy domain that was, until very recently, considered the exclusive realm of elementary particle physics. This was already recognized in 1983 when the previous Long Range Plan was written. The trend has since become clearer and is now taking up more and more of the resources of the field, in terms of people as well as of accelerators and research funds. This change in balance is apparent in the ordering of the scientific topics that constitute the main body of this report. It is as natural today to begin the discussion of nuclei in terms of quarks and gluons as it was a decade ago to begin with nucleons and mesons. However, it is important to keep in mind the full panoply of nuclear phenomena. The nucleus, as the quintessential quantum-mechanical many-body system, is so rich in phenomena that many important new frontiers are opening up far from the level of detail where a description in terms of quarks becomes essential.

The historic evolution of nuclear physics, and with it the nuclear phenomena studied, are depicted schematically in Fig. 1. Nuclear history evolves from the top to the bottom of the figure. Not accidentally, this sequence also describes the nucleus on an increasingly finer length scale, i.e., as seen through increasingly powerful "microscopes." As the name implies, nuclei are at the center of atoms, with a dimension only about one hundred-thousandth that of an atom. This dimension is of the order of a few femtometers (1 fm = 10^{-15}m) which is commonly called a fermi after the great Italian-American physicist who first studied the interaction between neutrons and nuclei and who led the construction of the first nuclear reactor in 1942. Looking at the nucleus as a whole we can envision it as a droplet of liquid that can be deformed, that has oscillations and rotations, and that can change its shape or fission into two droplets. These phenomena are called "collective" because they involve many neutrons and protons in the nucleus moving in a concerted manner. So far, the nuclear liquid has been explored mostly at very low nuclear tem-

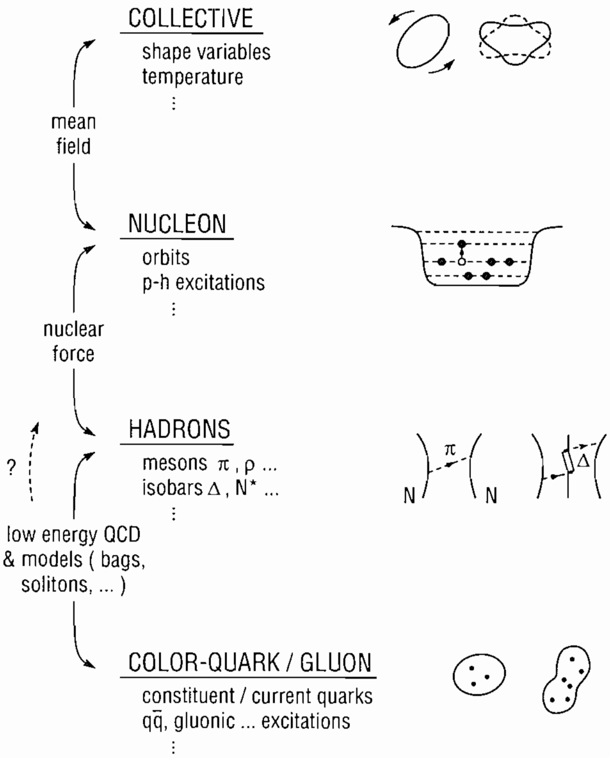

Figure 1: Diagram of nuclear properties and the models used to describe them, with increasingly fine spatial resolution ranging from the top to the bottom. At the finest detail the nucleus consists of quarks and gluons.

peratures, much like water near the freezing point. Only recently have physicists begun systematically to heat nuclei and to look at the nucleus as a thermodynamic system. Nuclear temperatures are expressed in million electron Volts (MeV). A temperature of 1 MeV is about one million times hotter than the surface of the sun. It has already been learned that whole nuclei can be heated up to a temperature of about 6 MeV, and that much hotter spots within nuclear matter can be created. It takes large amounts of energy on the very small scale of nuclei to heat the nucleus in order to study it as a thermodynamic system.

The nucleus is, of course, composed mostly of neutrons and protons (nucleons) which have dimensions of about 1 fermi. The nucleons move around in the nuclear "mean field" produced by *all* the nucleons, in an orderly way prescribed by quantum mechanics. Thus they can occupy only certain orbitals of specified energy and character. Much has been learned about these orbitals since their discovery in the 1940s. What remains to be learned is what happens when the mean field is stretched and strongly deformed, and when it is augmented by strong centrifugal forces created by very fast rotation of the nucleus.

Quantum mechanics dictates that only a limited, predetermined number of neutrons and protons can be fitted into each orbital. Thus the question arises of what happens if we grossly change the relative numbers of neutrons and protons from those that exist in stable nuclei. On earth, such exotic nuclei must be created by nuclear reactions. However, in astrophysical objects, such as neutron stars, they probably occur naturally. Fig. 2 shows the remarkable multitude of nuclei that are either stable (263 in number) or quasistable (potentially about 6000, of which so far only 2200 have been synthesized). Nuclei that contain certain "magic" numbers of neutrons and protons (indicated by either N or Z in Fig. 2) are especially stable, and an island of superheavy "stable" nuclei far beyond the actinide elements has been predicted since the 1960s.

Nucleons interact with each other by the so-called strong force. It is about a thousand times stronger than the electromagnetic force, which holds atoms together, and is effective only over a very short distance, about 1 fm, the size of a nucleon. Particles interact with each other by exchanging characteristic bits of energy, often in the form of other particles. In nuclei, the strong interaction between nucleons, for separations greater than the nucleon radius, can be quite successfully described in terms of the exchange of medium-weight particles called mesons, such as the π and ρ mesons. The strong interaction can also produce excitations of the nucleon itself, so-called isobars. Although much is known about the motions of nucleons in nuclei, much less is known about the motions of these isobars and the mesons in the nuclear medium. Some of the new accelerator capabilities in nuclear physics are aimed at elucidating these aspects.

It is now well known that nucleons are made up of quarks which interact by exchanging gluons. Three constituent quarks make up a nucleon, whereas a quark and an antiquark together produce a meson. It is then the ultimate aim of nuclear physics to relate the known phenomena of the nu-

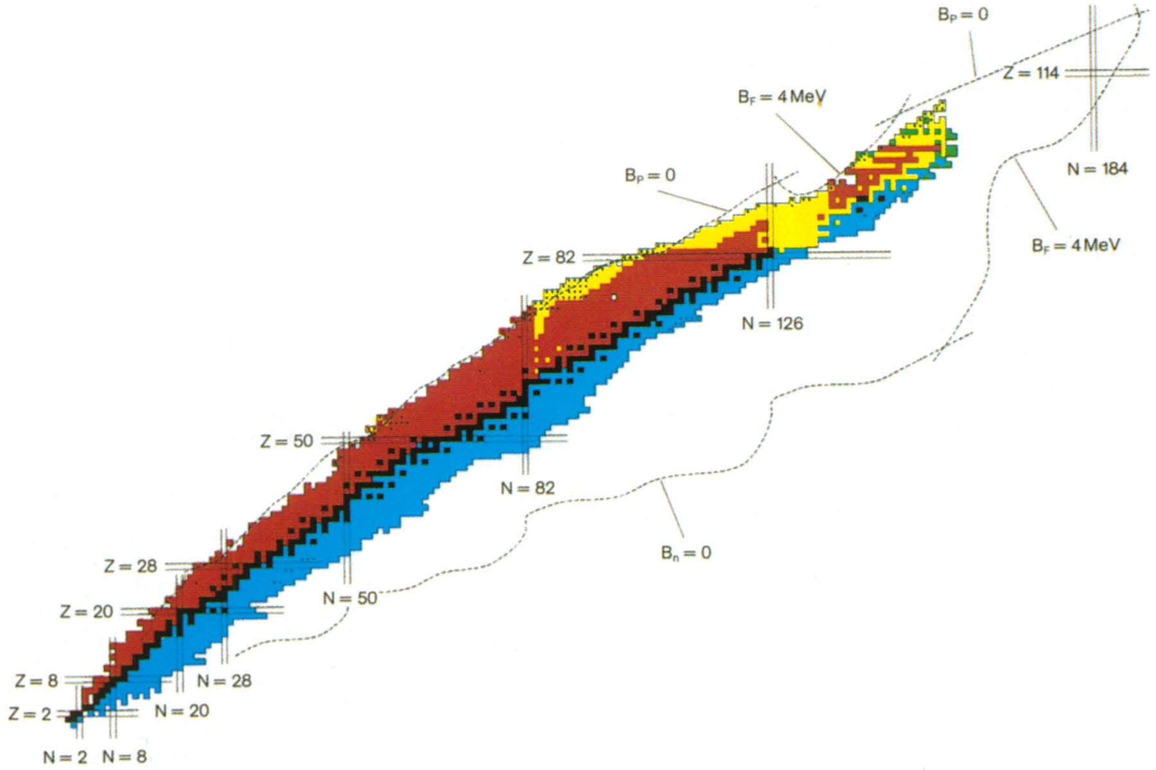

Figure 2: Island of stable or quasi-stable nuclei, defined by the dashed border contour. The black squares indicate the stable nuclei. The colored areas contain the quasi-stable nuclei that have been produced. Indicated N and Z numbers refer to magic numbers, and doubly-magic regions are especially stable. The actinide nuclei complete the known mass table at the upper right end. The long-sought superheavy nuclei would lie around Z=114, N=184.

clear medium to the quarks and gluons and the corresponding theory, QCD. This theory has already predicted completely new phenomena, such as the existence of a new form of matter, the quark-gluon plasma, at very high energy density. A major recommendation of this report is aimed at observing and studying this phenomenon. However, such predictions are as difficult to make as they are fundamental. The application of QCD is relatively straightforward at very high energies and high momentum transfer —the so-called perturbative region— but very complex at the energies normally associated with nuclear phenomena. This has led to simplifying models, such as holding the quarks together in "bags" that stand for the nucleons. Only at very high nuclear temperatures, about 150 MeV, may it be possible to "melt" these bags and allow quarks to range freely over the distance of a few nucleons. The energies required to induce this process are so high as to blur the boundary between nuclear and high-energy physics.

The step from nucleons and mesons to quarks and gluons has had still wider implications for nuclear science. This is because quarks come in six different "flavors". Two of these, the "up" and "down" quarks, are present as the major constituent quarks in normal nucleons. Another flavor, called "strange" quarks, can be created in laboratory experiments, thereby producing "strange" nucleons, called hyperons. These can be inserted into nuclei to form hypernuclei. The behavior of the strange quarks in nuclear matter is an important part of understanding the strong interaction in the nuclear medium. Again, a promising beginning has been made towards cataloguing the states of excitation of hypernuclei, but much more remains to be done. The creation of new forms of strange matter is one of these goals.

Nature also provides us with astrophysical "laboratories", such as stars, neutron stars, and supernovae, in which we can study the properties and behavior of nuclear matter under unusual conditions. The energy density characterizing the transition from nucleons to quarks, or the reverse, was presumably produced at the birth of our universe, the Big Bang. This transition should have left its mark on the relative abundances of the light elements that we observe today. Similarly, a stellar collapse, such as indicated by the recent supernova observation, provides an opportunity to study nuclear matter at extremes of density and temperature, and with neutron-to-proton ratios that have not yet been reached in the laboratory. The skills of the nuclear physicist have become essential to any quantitative modeling of the physical and chemical processes that govern the long-term evolution of our universe.

Nuclear radioactivity has produced some of the most fundamental insights into nature and some of the most important practical applications of nuclear physics. This stems from the fact that beta radioactivity involves another fundamental force of nature, the weak interaction. The latter brings a new set of very light elementary particles, leptons, into play and is today understood within a framework that also includes the electromagnetic force. A key verification of this aspect of the Standard Model occurred recently, with the discovery of the W and Z particles, the predicted carriers of the weak force. The Standard Model also predicts the interaction between leptons and quarks, as depicted schematically in Fig. 3. While all known phenomena seem to fit within the Standard Model, including all the recently studied detailed properties of the Z particle, there are reasons to believe that the model is incomplete and must ultimately fail. Nuclei offer unique opportunities for isolating certain "low-energy" aspects of the Standard Model and testing it with high precision. Thus, probing the electro-weak interaction has become an area of common interest between nuclear and particle physicists.

- **The Tools**

This modern agenda stretches nuclear physics over a wider range of energies and phenomena than ever before in its history. A set of basic tools are needed, which is described in more detail in later sections of this report. It includes:

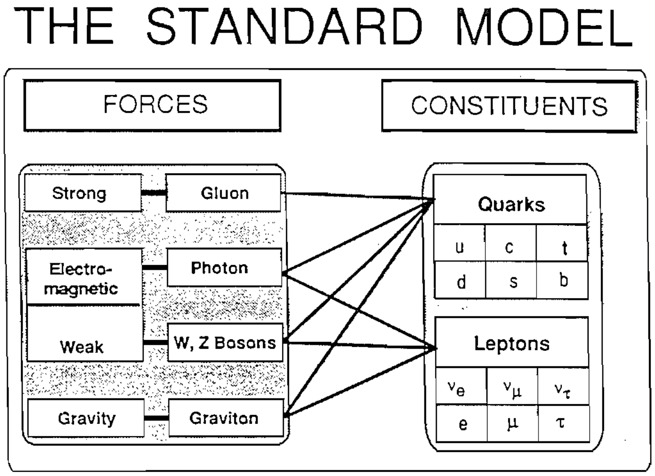

Figure 3: A list of the forces and their participants – quarks and leptons— that are interconnected by the Standard Model. The connections between the different sectors – strong, electromagnetic and weak– are indicated by the lines.

- *Electron beams* interact with nuclei or their charged constituents, the quarks, via the well-known electromagnetic interaction. Thus they provide a tool that can test unknown properties inside the nucleus in a precise way. Very energetic muon beams play a similar role in elucidating the quark structure of nucleons and nuclei.

- *Proton beams* are needed for several tasks: to test particular aspects of the interaction between nucleons; to produce other particles, such as mesons, neutrons, neutrinos, or even strange particles, and to study their interactions or decays; and to act as "vessels" of quarks to be brought into the target nucleus. An accelerator capable of producing these beams is broadly defined as a hadron facility.

- *Heavy-ion beams* of energetic nuclei, of almost any species available in the table of the stable and even unstable elements, can deposit large amounts of energy over a large part of the nuclear medium. They are needed to produce exotic nuclei; to compress and heat nuclear matter; or to induce rapid rotation of nuclei upon impact. Finally, they also serve as carriers of quarks and gluons.

- *Neutron beams* from reactors and accelerators are used for nuclear reactions or to produce nuclei far from stability as products from nuclear fission; highly polarized cold and ultracold neutrons serve as tools for precise tests of fundamental interactions.

The arsenal of nuclear physics accelerators has undergone a significant modernization and expansion since the 1983 LRP. However, as we explain more fully below, key facilities remain either to be completed (for electron beams), to be started (a relativistic heavy ion collider), or to be fully defined (an advanced hadron facility) at the time of the present report.

From the very beginning of nuclear science, nuclear physicists have been inventive builders of accelerators. Many different kinds of accelerators, initially conceived for nuclear physics, have since found applications in other sciences,including medicine. In many cases, nuclear physics accelerator development has pushed new technologies to their first large-scale applications. For example, superconducting high-precision magnets for cyclotrons and superconducting resonators for linear accelerators have been developed into mature technologies. These devices make it possible to produce energetic particle beams at great savings in electric power, and, because they lead to a reduction in accelerator size, at reduced construction costs. The concept of cooling a beam of protons or heavy ions, contained in a storage ring, by interaction with a cold electron beam has been successfully implemented, and, for heavy ions, recently demonstrated for the first time.

It was already recognized in 1983 that a new agenda for nuclear physics was emerging. This agenda would require new facilities for each of the three species of beams – electrons, protons, and heavy ions– to investigate the consequences of QCD in nuclei. Of necessity, these facilities would have to have much higher energy capability than any of the existing nuclear physics facilities and rival the scale of some high-energy physics projects. Typically they are designed to provide beams of high quality, high intensity and, recently, high duty factor. Responding to the new agenda, an initial step for electrons is the Continuous Electron Beam Accelerator Facility (CEBAF), now under construction at Newport News, Virginia. It will use superconducting resonators to produce three simultaneous intense electron beams at a peak energy of 4 GeV (4 billion electron volts).

The proposed project to increase our capability with heavy-ion beams is a very bold one. The Relativistic Heavy Ion Collider (RHIC) is a very cost-effective facility owing to previous development and construction that had been invested in an earlier proposed proton collider at Brookhaven National Laboratory. It will consist of two intersecting rings of superconducting magnets, 2.5 miles in circumference, in which energetic beams of nuclei from protons to gold will be accelerated, stored, and brought into collision at six interaction regions. Its energy capability of 100 GeV per nucleon for each beam will be uniquely suited for producing and studying the predicted quark-gluon plasma.

For the third machine, the modern hadron facility, a group in Canada is presently proposing a proton accelerator, KAON, with a combination of beam energy and intensity unprecedented in nuclear physics. This accelerator would in turn provide the intense secondary beams needed for a thorough investigation of the nuclear physics of "strange" particles and for testing the limits of the Standard Model at nuclear energies.

- **The Agenda**

As we extend the nuclear physics agenda into the 1990s, we can summarize the central goals, based on the scientific discussions in Chapter II (and in that sequence), as follows:

(1) Study of the nucleus as a strongly interacting many-body system, consisting of nucleons and mesons. This traditional focus can now take advantage of the theoretical and experimental advances of the past decade, and will use the new experimental facilities being readied, to decisively introduce excited states of the nucleons, and strange particles, into the nuclear medium.

(2) Exploration of the fundamental theory of the strong interaction, QCD, in the nuclear medium. This is a task for theoretical nuclear physics, which must find reliable and practical ways to apply QCD

to the nuclear energy range. Clearly this effort involves significant connections to elementary-particle theorists. It is also a task for experimental nuclear physics, one that relies crucially on new energetic electron and hadron facilities. Because quarks are primarily confined in the nucleons, it is important to study the nucleus on a dimensional scale that is small compared to 1 fm. This requires beams in the billion electron volt (GeV) range. On the other hand, some manifestations of quarks can be studied at somewhat lower energies by the use of ingenious methods such as polarized (i.e., spin-oriented) beams and targets. If strange quarks or mesons need to be produced then this again requires primary beams of high energy and high intensity.

(3) Study of the thermodynamic properties of nuclear matter, expressed in the equation of state, and its phase transitions. The most spectacular phase transition is that from normal nuclear matter to the quark-gluon plasma, a completely new form of matter. It is predicted to occur at a temperature of about 150 MeV. To produce the required conditions of energy- and mass density in nuclei demands the capabilities of the Relativistic Heavy Ion Collider. However, there is a large regime of lower temperatures and moderately increased densities that remain to be explored with lower-energy heavy-ion beams. The exploration of hot nuclear matter is still in its infancy.

(4) Searches for new phenomena at the very limits of nuclear stability. In this context a nucleus is considered stable even if it is created in a nuclear reaction in the laboratory and lives only for a brief moment. Even these broad stability limits are tested when the nucleus is formed under the stress of ever larger centrifugal forces or increasing temperatures, and with a very unusual composition of neutrons and protons. Some of these conditions prevail in astrophysical objects; so understanding their properties in the laboratory contributes to our understanding of the universe. The decades-old goal of reaching the predicted island of stability for superheavy, transuranic nuclei, and the recent possibility of producing regions of pure neutron matter in nuclei, are intriguing possibilities in this area.

(5) Exploration of the electroweak force and its connection to the quarks, as prescribed by the Standard Model, in the nuclear medium. In the laboratory, this often requires some of the most powerful accelerators available. But, if the object of study is astrophysical, such as the sun, a neutron star, or a supernova, some very sophisticated and large stand-alone detectors are needed.

As one considers this broad agenda, it is instructive to note a certain analogy with recent developments in another major field of science, molecular biology. A huge body of information on biological systems and effects has been accumulated, and is well understood and widely applied, without taking reference to the underlying "theory", namely, that all these properties are ultimately expressions of an alphabet of only four letters, the four nucleotides A,C,G,T, of the genetic code. Now, molecular biology is embarking on a huge project to determine the sequences of these letters in the human genome, in order to relate the "macroscopic" biological properties to the fundamental building blocks of biological systems. Substituting six quarks for the four nucleotides makes the analogy clear. Just as biology and molecular biology will need to maintain a broad effort *in addition* to the genome project, for the many aspects that do not require invoking the ultimate building blocks, so nuclear physics must make advances on a broad front, in addition to the quark-related programs.

The major scientific goals outlined above require new instrumentation and new technologies, as well as new ways of accumulating, processing and analyzing data. It is these aspects that have made nuclear physics, throughout its history, a major source of technical innovation for our industry and society. Nuclear techniques of a wide variety are used today in solid-state research and even in the production process of the most advanced semiconductor chips. The applications of radioactive three-dimensional imaging for medical diagnostics, and the use of beams of radiation for cancer treatments are widely known and continue to be further developed. The use of neutron beams to detect explosives and to produce the first practically useful wires of high-temperature superconducting materials, are very recent developments.

II. THE SCIENTIFIC FRONTIERS

This chapter represents the core of the Long Range Plan. It describes the present status of the various important fields of nuclear physics and gives examples of significant achievements made since the last LRP, in 1983. The sections also list the opportunities which are ripe to be exploited in these subareas. It is from these discussions that our plan for the next decade emerges.

The ordering of sections in this chapter deviates from the essentially historical order of the 1983 LRP. The reason is the great expansion in the scope of nuclear physics in the intervening years. Nuclear physics now spans the realm stretching from the macroscopic structure of the nucleus as a whole, through the behavior of individual nucleons inside the nucleus, through the meson cloud that pervades the nuclear medium, and ultimately to the underlying quark structure of the nucleons and mesons themselves. Reflecting the increased importance of these most fundamental topics, it is this logical, rather than the historical, sequence of ever more microscopic views that is emphasized in the progression from Sections 1 to 4.

At the same time, great strides have been made in recent years in studying the nucleus as a whole, including its excitations and interactions. The limits of angular momentum, excitation energy, and neutron-proton composition to which nuclei are being pushed today offer a vastly increased range for exploring nuclear matter and nuclear structure.

Similarly, the interactions of colliding nuclei can now be studied in energy regions and with a sensitivity heretofore impossible. At extremely high collision energies, it appears likely that sufficient energy can be focused to break apart individual nucleons, forming a quark-gluon plasma. Sections 5 to 7 describe these facets of nuclear science, and Section 7 forges clear links with Sections 3 and 4. Section 8 emphasizes the role of the nucleus as a unique laboratory for testing fundamental symmetries and interactions, which play a deep role in physics as a whole, using both terrestrial tools and the stellar environment. Finally, Section 9 builds on all previous sections in addressing the key role played by nuclei and their interactions in the formation and evolution of the universe and the nucleosynthesis of the elements.

II.1 Nucleons in Nuclei

Introduction

The nucleus can be described most directly in terms of neutrons and protons. These nucleons interact by exchanging mesons, and the nucleons and mesons themselves have a complicated internal structure of quarks and gluons. There is a rich variety of phenomena that can be explained in terms of nucleons alone, moving in regular orbits in a mean field that they themselves create. This is the simple picture at the heart of the nuclear shell model, a model that has had enormous success in describing, with few parameters, the detailed properties of low-lying states in many nuclei. Interactions between these nucleons give rise to correlated motions of pairs of particles and to interesting collective phenomena involving many nucleons. Nuclear experimentalists have cleverly exploited a wide range of probes to reveal these and many other facets of the nuclear response. High-energy and low-energy particles, heavy ions and light ions, neutrons and electrons, particles with spin and without spin- all see specific aspects of the richness of nuclei. Here we describe some highlights from recent work illustrating progress and current issues in nucleonic descriptions of nuclear structure and reactions. We will find that a complete discussion of some of these topics requires the introduction of explicit meson and perhaps quark interactions, described in later sections.

The Nuclear Many-Body Problem

Nonrelativistic nuclear many-body theory has the task of generating, from the Schrödinger equation, the static and dynamic properties of a quantum many-body system–the nucleus–starting with only the masses of the nucleons and their basic interactions. The nucleon-nucleon interaction contains a strong attraction outside a strong, short-range repulsive core. The quantitative description of a many-body system with this type of interaction (liquid helium and neutron stars are other examples) has proved very difficult. Recently there have been significant breakthroughs in the many-body theory of such systems, with many of these advances depending on the rapid increase in the power of modern computers. Despite this progress, many important questions can be answered only by continuing to improve the quantitative accuracy of nuclear many-body calculations: Can nuclear densities, shell-model potentials, momentum distributions, and collective and single-particle excitations be computed directly from an underlying Schrödinger equation? Can nucleon-nucleon correlations be understood microscopically? At what levels of momentum transfer, energy transfer, and nuclear density does a nonrelativistic approach based on static interactions fail demonstrably? Continued development can generate a firm basis for extensions into the domain of relativistic dynamics, hadronic degrees of freedom, and quantum chromodynamics (QCD).

Relativity

In parallel with improving the quantitative treatment of the nuclear many-body problem via the Schrödinger equation, it is important to build on recent progress in understanding the implications of a fully relativistic treatment of nucleon-nucleon interactions in a nucleus. There is evidence that the relativistic Dirac equation provides a natural description of spin effects in the nuclear medium, just as it did much earlier for atomic systems. For example, the spin-orbit force underlying the success of the shell model arises naturally in relativistic descriptions of nuclear structure. One also seems to obtain a more economical account of polarization effects in medium-energy nucleon-nucleus collisions, as illustrated in Fig. 4 by a comparison of data and theory for the elastic scattering of 500-MeV protons by ^{40}Ca.

The relativistic calculations in Fig. 4 explain the spin effects considerably better than do the nonrelativistic ones, at the same level of approximation. Similar results have been obtained for other energies and targets. As extensive polarization measurements for a variety of nucleon-nucleus reactions are needed for further tests, it is important to develop more intense polarized beams, polarized targets, and detection systems able to measure the polarization of scattered particles. It is equally important to find ways to test other charac-

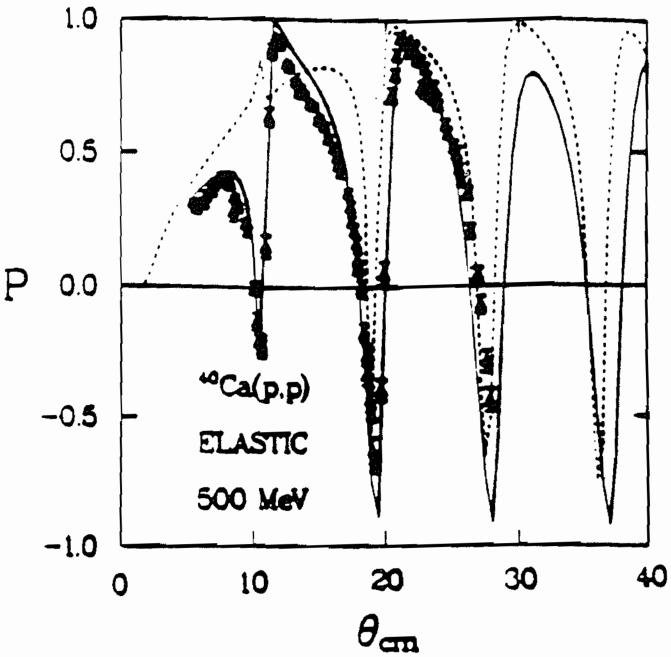

Figure 4: Polarization data for the elastic scattering of 500-MeV protons by ^{40}Ca. The solid and dashed curves are the results of relativistic and nonrelativistic calculations, respectively.

teristic features of relativistic dynamics, such as the expected large role of scattering processes in which virtual nucleon-antinucleon pairs are created. The relativistic mean field produces a significant change in the effective mass of a nucleon when it is inside nuclear matter. Initial relativistic structure calculations suggest that relativity may be an important ingredient in understanding the Coulomb sum-rule anomaly (discussed below), the saturation of nuclear matter, and the behavior of nuclear matter under extreme conditions of excitation or compression, such as are attained in high-energy heavy-ion collisions.

Even if the Dirac-based techniques continue to have phenomenological success, this does not guarantee the soundness of the method. Significant theoretical effort is also needed to understand the foundations of relativistic nuclear dynamics. The relevance of relativistic quantum fields (and the Dirac equation) for describing composite nucleons remains controversial, as is the dynamics of some of the mesons responsible for the interactions. The formulation of systematic, reliable, practical techniques for strongly coupled, relativistic many-body systems is a challenging problem that will require both experimental and theoretical input and ingenuity. These techniques are crucial for understanding experiments at CEBAF and RHIC and for connecting the traditional nuclear theory of nonrelativistic nucleons with a fundamental description based on quark and gluon degrees of freedom.

Correlations and Collectivity

Particles moving in single-particle orbits in the nuclear mean field, relativistic or not, are correlated. At low excitation energies, the nucleus is certainly not a gas of particles in random motion. If the motion of many particles is sufficiently correlated, it is often simply described by collective, mostly macroscopic, models. A long-range objective of nuclear physics is the development of a self-consistent theory of collective and single-particle motions. Progress toward this goal has been impressive, but we are far from being able to describe the rich spectrum of nuclear excitations on this basis.

The pion double-charge-exchange (π^+, π^-) reaction is particularly sensitive to the correlated motion of two particles because the pion must trade its charge with two different nucleons. If the nucleons inside the nucleus were completely uncorrelated, one would naively expect the double-charge-exchange cross section to be proportional to the number of excess neutron pairs available. Measurements with 50-MeV pions showed that the cross section for ^{44}Ca is only half that for ^{42}Ca; this differs by an order of magnitude from the simple rule. This result can be explained in part by the long-range correlations arising from standard shell-model calculations. However, there are hints that short-range correlations associated with the hard core of the nucleon-nucleon interaction may also play a role.

The correlated motion of a proton and a neutron (*p*-*n*) in a state of total isospin zero has recently been found to be critical to the development of configuration mixing and collectivity in nuclei. Originally known to be an important factor in light nuclei, the *p*-*n* correlation is now realized to be equally central to the rapid shape transitions in heavy nuclei. The complementary roles of its monopole and quadrupole components are being unraveled empirically and exploited in new shell-model and Hartree-Fock calculations. The key role of the valence p-n interaction motivates the recently proposed scheme in which nuclear observables are plotted against the product of the number of valence protons and neutrons. This scheme greatly simplifies the very complex systematics presented by standard plots against N, Z, or A, and also reveals the unexpectedly similar behavior of diverse mass regions. What is critically needed is to graduate from this phenomenology to a real microscopic theory of low-energy nuclear structure and its evolution. Recent Hartree-Fock calculations provide a first step in this direction.

Dynamical symmetries, reflecting simplicities in the interactions of the constituents of many-body systems, offer an alternative approach to nuclear structure that has been widely exploited in recent years. The interacting boson model (IBM), which interprets low-lying collective modes by treating the valence nucleons as correlated pairs, leads to three such symmetries, each of which has now been found empirically: SU(3), a type of deformed axially symmetric rotor, O(6), an axially asymmetric rotor, and the vibrator symmetry U(5). The number of correlated pairs included in the IBM is restricted. This key aspect of the model leads to parameter-independent variations of nuclear properties with N and Z, and these predictions have been widely confirmed. The IBM also provides a simple one-parameter treatment of the complex regions between the nuclei where the exact symmetries provide good descriptions. Extensions of the IBM to odd-A nuclei and to light nuclei are current frontier areas in this field. The successes of the IBM have fostered intense interest in other algebraic approaches that promise to be both more microscopic and more general. Some of these focus on the symmetries among the fermions (the neutrons and protons) in the valence shell, while others incorporate excitations across all shells and give hope of explaining collectivity up to high excitation energies.

Experiments with electron and proton beams are now able to produce detailed maps of the overlap in the proton and neutron valence-particle wave functions of the ground state and low-lying excited states. These test our understanding of nuclear collective and single-particle motion. Figure 5(A) shows such transition charge-density distributions for the three lowest 2^+ states of the deformed nucleus ^{154}Gd measured in high-resolution electron scattering. These states are generally characterized as the lowest rotational state, the "beta" vibration along the long axis, and the "gamma" vibration along the short axis. The densities peak at different radii and qualitatively confirm the geometrical pictures of these collective states. Proton beams provide complementary information about the overlap in the neutron wave functions once the information on the protons has been determined; this is a classic example of the need for complementary probes. Some results for the two lowest 2^+ states in ^{34}S are shown in Fig. 5(B). The newly developed precision in these densities poses a clear challenge to theory.

Giant Resonances

Giant resonances dominate the spectrum of nuclear excitations below about 25 MeV. A good example is shown in Fig. 6, where the wide giant resonance at about 18 MeV overwhelms other features of this spectrum observed in the ^{40}Ca(p,p') reaction at 319-MeV incident energy. These resonances can be thought of in macroscopic terms as nuclear vibrations involving the motion of many nucleons in phase. Excitation of giant resonances by inelastic scattering of medium-energy heavy-ion beams provides very large cross sections and low backgrounds. The use of coincidence reactions such as $(e, e'n)$ at electron accelerators with 100% duty factor provides the opportunity to study electromagnetic excitation of giant resonances, also without much background. Both techniques will lead to improved microscopic descriptions of these states, which are so important for the response of the nucleus to the impact of various probes.

The nucleus responds in different ways to the spin and isospin of a bombarding particle. Resonances that do not require spin or isospin transfer are generally strongly excited by hadronic probes (see Fig. 6), and tend to mask spin or isospin resonances that may also be present in the same spectrum. New facilities for the measurement of the transfer of spin from the projectile to the target

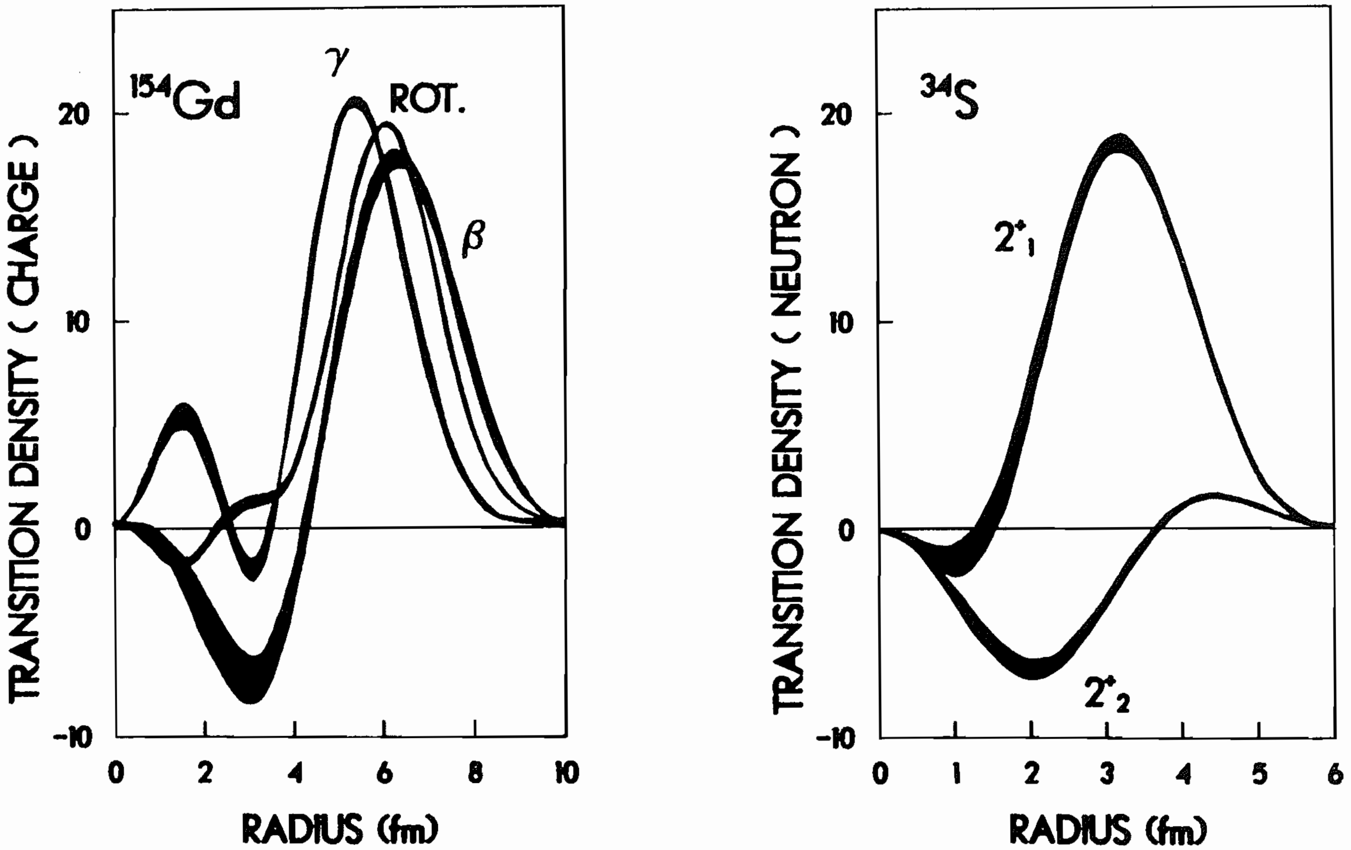

Figure 5: (A) Transition charge densities determined from scattering on ^{154}Gd for three types of states. The transition density is the overlap in the valence charge distributions of the ground and the excited state. The shaded area shows the precision of the measurement.

(B) Neutron transition densities derived from proton scattering on two states of very different character in ^{34}S.

are becoming available at both IUCF and LAMPF. Such measurements are vital in separating spin-transfer resonances from other overlapping excitations. With a polarized beam and a focal-plane polarimeter, it has been possible to measure the probability that the incoming projectile flips its spin in the reaction. The spin-flip data show what part of the cross section is due to spin transfer, and this is shown as the hatched area in Fig. 6. A spin resonance is now clearly seen, just under the spinless resonance, and the spin strength at high excitation seems surprisingly large —a result not yet understood.

Resonances are also classified according to the transfer of orbital angular momentum as monopole, dipole, quadrupole, etc. The giant dipole resonance was the first resonance discovered. Very recently, evidence for the double dipole resonance has been observed in the pion double-charge-exchange reaction; this is a high-lying dipole resonance built upon the familiar giant dipole. Excitation of the giant dipole requires the transfer of isospin to the nucleus; seeing higher-multipolarity isospin resonances has proved very difficult. However, it has been shown that these states are excited in reactions with heavy-ion beams at about 100 MeV/A, and that the cross sections increase markedly at higher energies.

The Gamow-Teller resonance is a spin-isospin resonance of particular importance. It is cleanly separated in charge-exchange reactions, and important progress in understanding its strength has been made since the last Long Range Plan, particularly because of new data on the (n,p) reaction from TRIUMF. Theorists have shown that both conventional correlations and those involving the high-lying delta resonance are important ingredients for understanding the cross sections for excitation of this resonance, which are smaller than sum-rule expectations.

portant for understanding the nucleon-nucleon interaction in the nuclear medium, for using charge-exchange reactions to calibrate solar neutrino detectors, and for fixing important parameters of models of stellar evolution. Polarization measurements are essential here. It appears that heavy ions can also play an important role, provided the reaction mechanism is sufficiently well understood. For example, the (^{6}Li,^{6}Li*) reaction leaving the ^{6}Li nucleus in its second excited state is an inelastic probe of spin-isospin transfer without the background of competing processes found with nucleon projectiles.

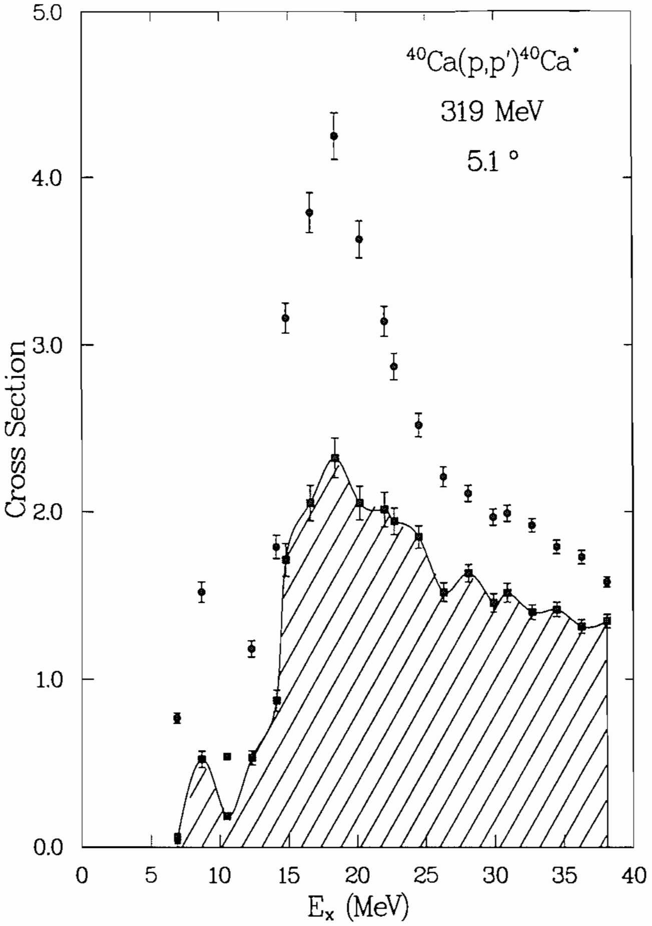

Figure 6: The experimental points are the cross sections for inelastic scattering of 319-MeV protons from ^{40}Ca plotted against excitation energy. A giant resonance is seen at about 18 MeV. The shaded area represents the spin-transfer part of this cross section, determined from polarization measurements.

Nuclear Quasielastic Response and The Coulomb Sum Rule

A prominent feature of the nuclear response is the quasielastic peak; it corresponds to the knockout of individual nucleons from the nucleus. This peak is evidence that nucleons, to a large degree, maintain their identity in the nuclear medium, and it provides graphic support for the basic premise of the mean-field approximation. In the past decade, measurements with electron beams have been made of the quasielastic response of many nuclei over a kinematic range sufficient to permit the separation of the charge response from the magnetic response. Within the standard framework of nuclear physics, the integral of the charge response over the excitation energy at fixed momentum transfer should approach the charge Z of the target. This is the so-called Coulomb sum rule. Departures from Z should reflect dynamical correlations in the ground state. These expectations are realized in the hydrogen and helium isotopes (see Fig. 7), where the sum reaches Z by about 500 MeV/c; the proton correlations are evident in ^{3}He and absent in ^{3}H (as they should be for $Z = 1$). In heavier nuclei,

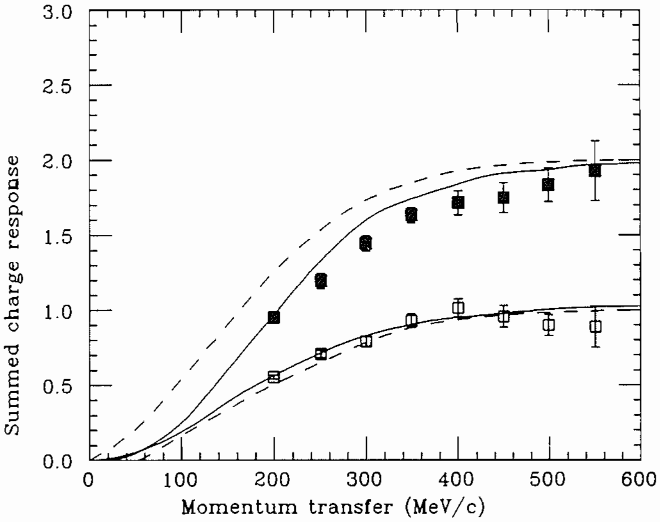

Figure 7: The summed charge response of ^{3}He (solid) and ^{3}H (open) is plotted against momentum transfer. At high momentum transfer, the data are close to the charge Z of the target. The effect of correlations is seen by comparing the theoretical curves plotted without (dashed) and with (solid) correlations.

however, the sums seem too low by about 40%. These deficiencies have provoked considerable theoretical activity, discussed in Section 2. Understanding the strength of these inclusive structure functions is essential not only because they represent the nuclear response to our best-understood probe, but also because the exclusive channels, such as $(e,e'p)$, $(e,e'd)$, $(e,e'\pi)$, etc., contain indispensable information on the occupation of shell-model orbits, possible multinucleon currents and correlations, and the pion content of nuclei, respectively. Continuous electron beams (100% duty factor), together with high-resolution spectrometers and polarization apparatus, will make possible extensive studies of these exclusive channels. These data may indeed indicate the limits of a description of nuclei in terms of nucleons moving in a mean field. It is important that this interpretation be subjected to rigorous examination.

II.2 Hadrons in the Nuclear Medium

Introduction

For many nuclear phenomena, a more general description in terms of hadrons, i.e., of nucleons *and* mesons, appears to provide the clearest insight into the underlying physics. We look beyond the nucleon as the only fundamental constituent of nuclei to discuss phenomena in which mesonic degrees of freedom play an essential role, and address a number of questions central to characterizing their importance. How close together can two nucleons be before it becomes inappropriate to use a description in terms of baryons alone? Is the structure of the nucleon altered by the nuclear medium? What is the pionic content of the nucleus? How are mesons produced and how do they propagate within the nucleus? How important are the baryon excitations in understanding the nucleon-nucleon force and medium-energy scattering reactions?

It is the interplay of such features of hadronic excitations with the properties of multinucleon systems that provides the basis for a powerful phenomenological model of nuclear forces and nuclear structure. Ultimately, this phenomenology will place rigorous constraints on the application of QCD in the strongly coupled nuclear domain.

The Nucleon-Nucleon Force

For many decades we have viewed the nucleon-nucleon (N-N) force as arising from the exchange of mesons and the excitation of nucleons. In the past few years, great strides have been made toward developing realistic and consistent force models within this picture. These models have two important advantages over previous "realistic" potentials: (1) One can now examine electromagnetic, weak, and mesonic processes in a single consistent framework. (2) One can begin to build models of the N-N interaction above the pion threshold. Over the next few years, these theoretical developments should be tested with experimental studies of pion production from two- and three-nucleon systems. A subject that has just begun to develop is the implications of quark-based models for the N-N force. Consistent hadronic models will provide us with benchmarks against which we can test the success of QCD-motivated results.

The two-body scattering amplitudes are the basic quantities that relate these theoretical concepts to experiment, and vice versa. The lightest meson that can be exchanged between nucleons is the π meson, and it leads directly to the existence of an interaction between the spins of the nucleons: the tensor force. At low and intermediate energies, the effects of the tensor force have not been well determined, owing to the difficulty of carrying out double spin-flip experiments. The recent development of polarized-beam polarized-target technology has made such experiments more feasible. The next few years should see high-precision measurements that will lead to a much better determination of the tensor force.

At higher energies, the scattering amplitudes have not yet been as thoroughly investigated. One important accomplishment over the past five years has been the determination of a complete set of proton-proton scattering amplitudes at selected energies up to 800 MeV at LAMPF. An important task for the next few years is the significant improvement of the neutron-proton scattering amplitudes in this energy range. These are essential to our understanding of the scattering of nucleons from nuclei at a few hundred MeV, a process we will have to understand very well in order to extract information from many of the experiments planned at CEBAF.

A property of the strong force that has been known almost as long as we have known about neutrons is charge independence: neutrons and protons look the same to the strong force. The only difference is that protons also have electric charge and thus feel the Coulomb force, while neutrons do not. This leads to one of the fundamental organizing principles of nuclear physics: isotopic spin. However, we know that even after we remove the effect of the Coulomb force, neutrons and protons are not precisely identical. Their masses are slightly different. This and other effects lead to breaking of the charge independence of the strong force.

One of the interesting facts about the breaking of charge independence is that it may give us a way to observe two nucleons when they are close together. One charge-symmetry-breaking force arises from the mixing of exchanged mesons having different isospin states. For example, if there is a charge-asymmetric part to the nuclear Hamiltonian, it can convert a ρ to an ω meson in flight and mix the isospins. This occurs primarily when the nucleons are about 1 fm apart.

If charge symmetry holds, it implies certain symmetries in neutron-proton scattering. For example, the analyzing power for scattering a polarized proton from an unpolarized neutron should equal that for scattering a polarized neutron from an unpolarized proton. In the past few years, two extremely difficult neutron-proton scattering experiments have been carried out at TRIUMF and IUCF at 477 MeV and 183 MeV, respectively. Early theoretical analyses of these results show that ρ-ω mixing provides an important and necessary contribution at the lower energy. Similar analyses have provided a possible explanation of long-standing puzzles about the mass differences in mirror nuclei.

Mesonic models therefore appear to describe the two-nucleon system very well, even when the nucleons are separated by distances on the order of 1 fm. In the next few years it will be very important to confirm these results and see if they can be similarly described as arising from the up-down quark-mass difference in QCD-inspired models built to describe the quark structure of nucleons.

Three-Nucleon Systems

The few-body problem is one of the few places in nuclear physics where one can do both detailed experiments and complete or nearly complete calculations. In the past few years, models of the nuclear few-body system based on hadronic degrees of freedom—consisting of nucleons, mesons, and excited nucleons—have been developed to a high level of sophistication. At the same time, a number of tour-de-force experiments have provided severe tests of these models. In most cases, these three-body models have been very successful, though much remains to be done. Again, these results will surely produce strong constraints on how QCD must be organized in the low-energy regime.

A major advance has been the complete solution of the Schrödinger equation for realistic potentials for both bound and scattering states using the Faddeev method. Bound-state calculations using a large variety of realistic two- and three-body potentials show that there appears to be only a single undetermined parameter in the bound three-nucleon system. All of the low-energy observables scale together: if one chooses a set of potentials that give the right triton binding energy, almost all other low-energy observables are correctly reproduced. For the scattering states, recent accurate measurements of spin observables are in excellent agreement with new complete solutions of the Schrödinger equation, with no adjustable parameters. This marks the beginning of a detailed study of three-body forces over the next few years.

In the past five years, electron scattering experiments at Bates and Saclay have studied light nuclei in detail. Elastic and quasielastic cross sections are now available for deuterium, tritium, and ^{3}He for momentum transfers beyond 5 fm^{-1}. These experiments probe the nuclear currents at distance scales below 1 fm.

For the triton and ^{3}He, which are mirror nuclei under the exchange of neutrons and protons, nucleons-only models that fit most low-energy properties fail to fit the form factors beyond inverse length scales of about 2 fm^{-1}. Great improvements are achieved when the contributions of meson exchange currents and Δ's are included; this permits a consistent treatment of the three-body bound-state wave function, the two-nucleon interaction, and the meson-exchange currents. The results are shown in Fig. 8. Although some discrepancies remain and a more consistent treatment of relativistic effects is needed, a longstanding problem has thus been solved. We now have a theoretical model that describes the data down to distance scales smaller than a nucleon.

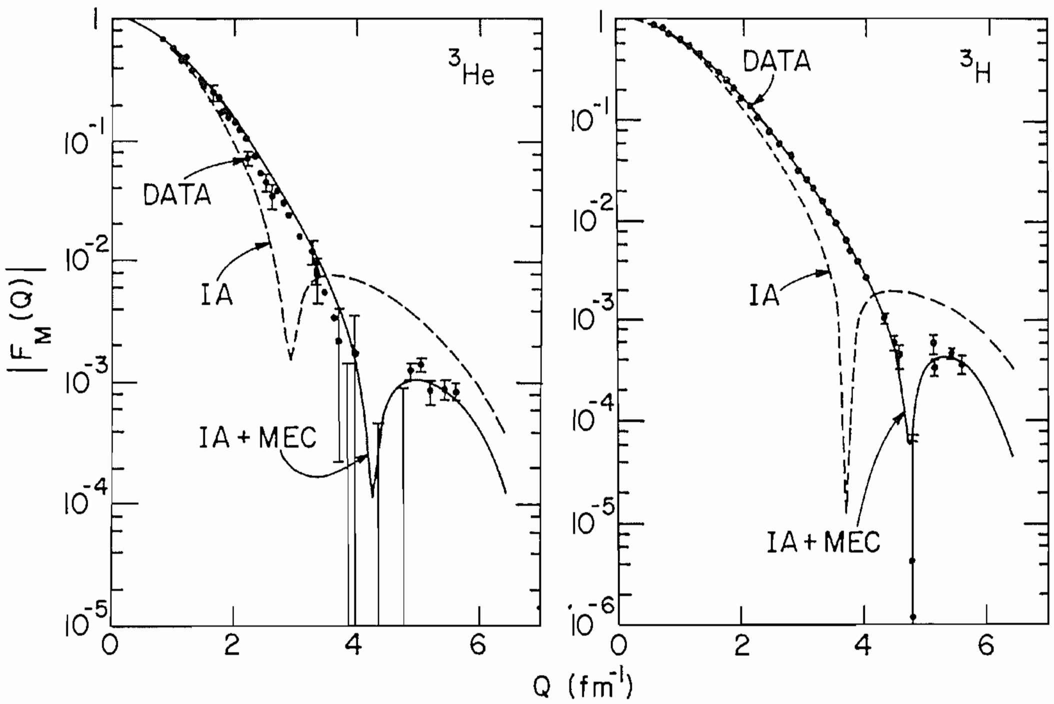

Figure 8: Magnetic form factors of tritium and ^{3}He compared with the impulse approximation (IA) and with the impulse approximation plus meson exchange currents (IA+MEC), demonstrating the needs for such currents.

Structure of Nucleons Inside the Nucleus

Changes in the internal structure of the constituent nucleons in nuclear matter have been a topic of much study and intense debate. If such modifications are present, as suggested by deep-inelastic lepton scattering, they should have significant implications for a hadronic description of nuclei. A variety of experiments has been carried out to search for these effects in medium-energy scattering reactions, with conflicting results!

Properties of the bound nucleons can be studied in quasifree electron scattering by examining the scaling properties of the cross section, i.e., the degree to which a single kinematic variable describes the reaction over a large range of energy and momentum transfer. Such experiments have set severe limits on the modification of the free nucleon properties by the nuclear medium. However, at lower momentum transfer, the failure of longitudinal quasifree electron scattering by heavy nuclei to approach the Coulomb sum-rule limit (see Section 1) has been attributed to modifications in the nucleon form factor. The possibility that this suppression of charge scattering has its origin in the nuclear medium's modifications of the nucleon structure was tested recently by studying the momentum-transfer dependence of the transverse response for the $(e, e'p)$ reaction on carbon and calcium. While the data are consistent with free-space nucleon form factors, the limited kinematic range of the measurements restricts the experimental sensitivity. There are intriguing suggestions from other experiments that meson masses change in the nuclear medium. Such modification results in a swelling of the meson cloud of the nucleon, with an attendant change in the nucleon form factor. K^+ total cross sections for carbon reveal anomalies that imply a K^+-nucleon interaction in nuclear matter differing from its interaction with free nucleons because of such mass rescaling. However, as alternative explanations exist, further investigation of these effects is clearly warranted. High-resolution $(e, e'p)$ studies at high momentum transfer and the exploitation of spin observables in electron scattering experiments will provide additional information.

A prime requisite for study of the structure of the nucleon in the nucleus is a knowledge of its structure in free space. The contribution to the mass of the nucleon arising from chiral symmetry breaking has recently been shown to be directly related to the content of the $q\bar{q}$ sea in the nucleon. One interpretation of deep-inelastic scattering suggests that about 25% of the quark pairs in the sea are of the strange variety. In order to be sure that we are indeed seeing a strange-quark component, and to measure it with some precision, better low-energy π-N experimental data and theoretical analyses are needed.

Pions in the Nucleus

The pion plays a central role in nuclear physics. Its coupling to the nucleon and its light mass makes it responsible for the long-range part ($r > 1.5$ fm) of the hadronic interaction. Pions can be produced or absorbed in the nuclear medium, and this process is fundamentally linked with the processes of meson exchange which generate the nuclear force. Its isovector character, i.e., the fact that it exists in three charge states, makes the pion a unique probe of nuclear dynamics.

Pion Content of the Nucleus

One very important feature of the nuclear medium, its pion content, remains a puzzle. If current conceptions are correct, single and multiple exchanges of virtual pions are responsible for much of the long- and medium-range forces between nucleons. The pion excess from such exchanges, over and above the pion clouds associated with the individual nucleons, has been predicted to be about seven extra pions in ^{56}Fe. How then do we observe them? Such effects are expected to modify the response of the nucleus to spin and isospin probes. Studies of the nuclear response in the quasifree region have begun to address this crucial issue, with some surprising results. For such studies it is often useful to align the spin of the proton projectile along the beam axis (spin longitudinal) or perpendicular to it (spin transverse) before it interacts with the target. A 500-MeV proton scattering experiment performed at LAMPF extracted the ratio of spin-longitudinal to spin-transverse responses for quasifree scattering from lead and calcium from complete sets of polarization observables. As seen in Fig. 9, the theoretically predicted enhancement of the ratio of spin-longitudinal to spin-transverse response at small energy loss due to the attractive particle-hole force provided by pion exchange is not observed in the data. This has been interpreted as evidence against a pionic enhancement in nuclei; however, this deduction is controversial in part because both the isoscalar and isovector channels are involved in proton inelastic scattering, and the effect should be seen only in the isovector channel. It has been observed, however, that the position of the quasifree peak in the (^{3}He,t) reaction at 2 GeV is shifted toward lower apparent excitation energies as compared to (e, e') results. One speculation is that the shift observed in this more complex reaction may be due to spin-longitudinal correlations in the nucleus, that is, due to the pionic enhancement. Nucleon charge-exchange reactions offer a possible resolution to this apparent discrepancy because of their pure isovector nature and thus simpler interpretation. Future (p, n) polarization measurements thus appear very important for addressing this issue, which is at the heart of our understanding of nuclear forces. In addition, pion electroproduction experiments will be extremely valuable in attacking this problem, since under specific kinematic conditions they probe the distribution of the pion charge in nuclei directly.

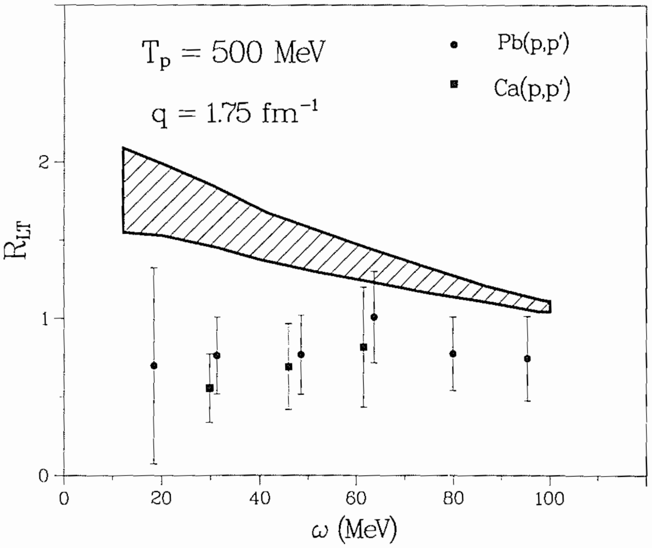

Figure 9: The ratio of the spin-longitudinal to spin-transverse response functions as measured in 500-MeV inelastic proton scattering on lead and calcium at a momentum transfer of $q = 1.75$ fm^{-1}. The curve indicates the effects of pionic enhancement expected for this reaction.

Pion Production, Propagation and Absorption

One of the most intriguing problems in medium-energy physics is the nature of pion absorption in nuclei. This process has a large cross section and has been thought for some time to be dominated by absorption on a pair of nucleons. While two-nucleon absorption is indeed important, recent experiments have shown evidence that processes involving more than two nucleons may account for about half of the absorption cross section. Recent Bates $(e, e'p)$ studies at large energy loss indicate that the energy and momentum of the virtual photon are often shared among several nucleons. This is almost certainly closely related to the processes seen in pion absorption. Interestingly, this excess $(e, e'p)$ strength at large energy loss appears to be primarily transverse in nature. Further studies of the absorption of pions and photons to resolve these very interesting questions are clearly indicated. Several next-generation experiments involving large-solid-angle detection of multiparticle final states are being planned and implemented in order to provide insights into this question.

At low beam energies, the pion is able to penetrate deeper into the nuclear interior. The deep minimum observed in the forward-angle single-charge exchange cross section on ^{14}C (see Fig. 10) demonstrate the dramatic increase in the nuclear transparency near a pion kinetic energy of 50 MeV. Pions of this energy thus sample the interior of the nucleus and probe the influence of the nuclear medium on the elementary pion-nucleon interaction. This is in contrast to energies near the delta resonance (~180 MeV) where the pion interacts mostly in the nuclear periphery. At energies near the deep minimum shown in Fig. 10 one is more sensitive to nucleon-nucleon correlations and possibly more exotic mechanisms, because sequential processes are inhibited. This transparency allows the pion to propagate into the interior of the nucleus, where modifications to the strong interaction are expected to be largest. This also offers greater sensitivity to nucleon correlations probed in pion double charge exchange. The addition of a superconducting momentum compressor and a high-resolution neutral meson spectrometer, soon to be operating on the low-energy pion channel at LAMPF, will provide the tools needed to pursue studies with high resolution and high intensity in this interesting low-energy regime.

With higher-energy pion beams, heavier mesons, such as η's, K's and ρ's, are produced. By studying their production and propagation, new selectivity in exclusive reactions can be achieved. For example, in the (π, η) reaction, only isovector, $\Delta T = 1$ transitions are excited, while in the (π, K) reaction a Λ particle is produced in the nucleus, leading to a hypernucleus. The latter is discussed extensively in Section 4.

Baryon Excitations

Pion degrees of freedom also become explicit with hadronic and electromagnetic probes in the excitation of the delta resonance. Studying this excitation with real or virtual photons as a function of mass number and comparing it to delta production on a free nucleon, one finds that the resonance energy is essentially the same, although the width is

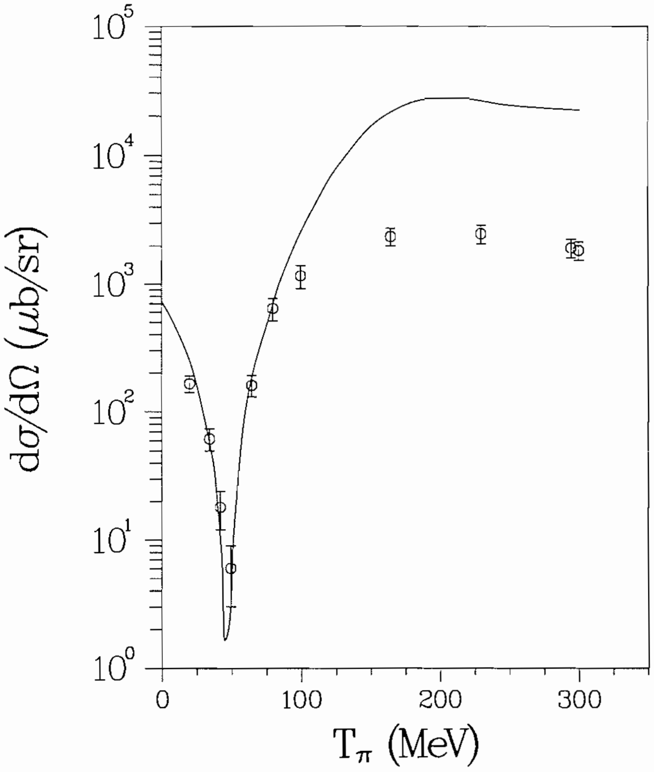

Figure 10: Pion single charge exchange on ^{14}C at 0°, showing the apparent transparency of the nucleus to low-energy pions, as evidenced by the deep minimum in the cross section.

broader in the nuclear medium. In inclusive hadron charge-exchange reactions, however, the position of the peak is shifted down by roughly 60 MeV in all nuclei above mass 12. While a number of explanations have been proposed, the purely kinematic explanations seem not to work unless a large shift due to the delta dynamics inside the nucleus is also included. Measurements in various exclusive channels will be required to delineate the various contributions to the inclusive cross section, as well as detailed polarization measurements to separate the spin-longitudinal and spin-transverse components in the excitation of the delta in nuclei.

The principal underlying motivation for studying Δ-nuclear interactions is the attempt to understand the role of baryon internal structure in the strong interaction. That is, by studying the interaction of different baryons with each other, we hope to gain insight into the importance of various degrees of freedom in determining the nuclear force and thus to guide the construction of models for the study of strong-interaction dynamics. As the lowest-energy excitation of the nucleon, the Δ is accessible to medium-energy mesonic and electromagnetic probes and consequently has provided a major focus for study over the last decade. The richness of the Δ-nuclear system for this purpose is suggested by quark-model calculations, which typically predict qualitatively different interactions in various N-N, N-Δ, and Δ-Δ systems (e.g., very strong attraction or very strong repulsion in certain Δ-Δ and N-Δ channels, respectively). The very short lifetime of the Δ requires that it be formed inside nuclei so that its subsequent interaction can be studied.

For the average Δ-nucleus interaction, a wealth of data obtained with pionic and electromagnetic probes has led to a simple phenomenology that systematically describes a variety of processes. The density dependence of the interaction indicates the need for a significant spin-orbit contribution. The most striking aspect in comparison with the nucleon optical potential is the very large central absorption part associated with the underlying pion-annihilation mechanism. Inelastic processes, involving nucleon knockout or particle-hole excitation are beginning to provide more microscopic information on the Δ-N interaction. The large Δ-nucleus interaction discussed above suggests that the Δ can itself induce the inelastic process in colliding with a nucleon. This process interferes with the usual process to produce qualitative modifications of well-chosen observables. Specifically, excitation of isospin partners (i.e., the use of discrete transitions to "filter" the interaction) and coincidence measurement of nucleon knockout in pion scattering and photoproduction suggest the strong repulsion in certain Δ-N channels which is predicted by quark models.

An interesting future direction will be the extension of such studies to the higher nucleon excitations. There are many open questions about the quark structures of these resonances, and a study of their strong interactions can resolve some of the key issues. These programs are difficult because of the overlapping nature of the spectrum at high excitation energy, so special signals, such as η production, will be important.

II.3 Quarks in Nuclei and Hadrons

Introduction

The internal structure of the proton has been convincingly revealed in many experiments studying proton structure at short length scales. In the past decade, the theory of colored, point-like, spin-$\frac{1}{2}$ quarks interacting via spin-1 gluons—quantum chromodynamics (QCD)—has developed from an attractive picture to a successful, established theory with a number of critical experimental confirmations. All of these confirmations are at large energy and momentum transfer scales, where the interactions between quarks and gluons become weak ("asymptotic freedom") and perturbative techniques can be applied.

This development changes our traditional view of nuclear physics. Quarks and gluons are the fundamental building blocks of the nucleus. The "color" carried by the quarks and gluons is analogous to electric charge; in the laboratory we can only detect combinations of quarks with a net color charge of zero. The traditional picture of the nucleus as built from neutrons, protons, and mesons (collectively referred to as hadrons) is a low-energy approximation of QCD. There are therefore more degrees of freedom to consider. This may alter our view of the effect of the Pauli exclusion principle in nuclear systems or on the value of sum-rule limits on excitations, to give only two examples. The connection of the traditional meson-nucleon description with the high-energy, short-distance limit of quarks and gluons is a fundamental, open problem. Even at low energies, the nucleon structure may have important consequences, just as the electronic structure of atoms is necessary to explain the electrical conductivity of a metal.

We believe that a description of the nucleus in terms of quarks and gluons is fundamentally correct. At high energies, theorists know how to derive predictions from QCD using the perturbative approach. At low energies, quarks and gluons are confined in the hadrons and nuclei that we observe. Understanding QCD in the low-energy (nonperturbative) regime of confinement is one of our most important challenges, as most aspects of the behavior of nuclei are manifestations of QCD in this limit characterized by strong coupling. Nuclei have a special role in the study of confinement, since the nucleus provides a "laboratory" where the nucleons are naturally in relatively close contact. At this level, the structure of individual hadrons and the structure of nuclei may be inextricably intertwined.

There are three obvious paths to studying the role of QCD in hadrons and nuclei. The first is to use high-energy probes that interact with individual quarks and gluons to determine the internal structure in terms of the elementary constituents. The second is to study carefully the structure of free hadrons at lower energies and learn if the structure of these hadrons changes within a nucleus. The third is to study the interactions between hadrons, particularly as one changes the flavor (up, down, strange, etc.) of the quarks; again it is important to learn how these interactions change inside the nucleus. We must be alert for new phenomena, such as quark percolation among hadrons or new groupings of large numbers of quarks, for which our traditional hadronic description will provide little guidance.

Deep-Inelastic Scattering and Quark Distributions

Deep-inelastic lepton scattering (electron, muon, and neutrino) has been especially powerful in elucidating the quark structure of a target. By using a simple, structureless probe interacting at high energies via the electroweak interaction, it is possible to extract the distribution functions of quark momenta (ultimately, a consequence of confinement) from the experimental cross sections. The observation that the distribution of quark momenta in iron is not the same as it is in deuterium (the EMC effect) provided the first clear evidence of the importance of the nuclear medium at the quark level. In the last few years, a series of new measurements using high-energy electrons and muons has yielded the remarkable results on the ratio of structure functions shown in Fig. 11. These results may reflect a change in the scale of confinement inside a nucleus, suggesting that the structure of a proton may be different in free space and inside a nucleus.

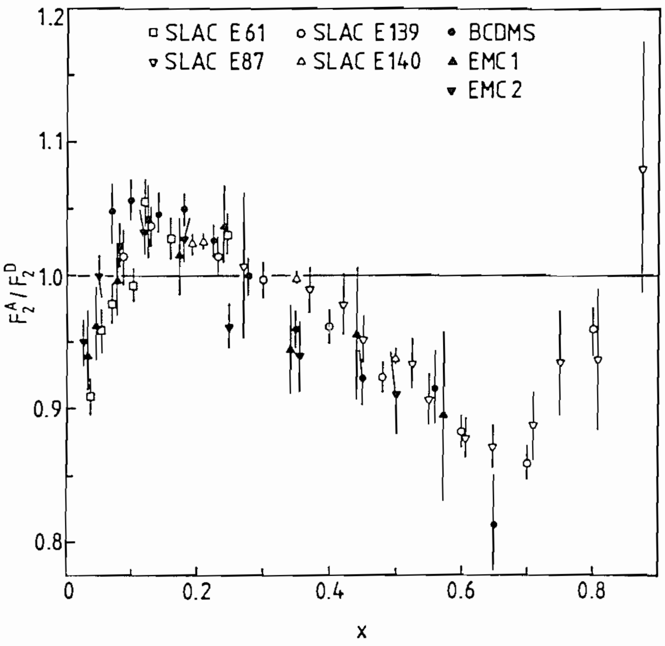

Figure 11: The measured ratio of the deep-inelastic structure function $F_2(x)$ of iron to that of deuterium is plotted vs the fraction of the nucleon's momentum carried by the struck quark, x. The data are from electron and muon scattering experiments from the U.S. and Europe. The observation that the ratio is not unity demonstrates that the quark structure of iron is not the same as that of deuterium.

But in other interpretations, the EMC effect may be more directly related to the forces that bind the nucleus. As we continue to examine the quark momentum distribution, we see additional evidence of nuclear effects. In the region where a quark has a very small fraction, x, of the momentum of the nucleon ($x < 0.1$), the recent experiments have shown that nuclear effects are also significant (see Fig. 11). This has changed our picture of photon-hadron interactions. At high energies the photon is believed to interact very much like a hadron and so to be "shadowed" from fully interacting with all the nucleons in a nucleus. However, the new data with virtual photons at larger momentum transfer, Q^2, show that this shadowing (seen as the decrease of the ratio of cross sections below one at small x in Fig. 11) can also be related to the quark distributions in nuclei. Another interesting region is where a quark has more momentum than it could possess in a single free nucleon ($x > 1$); here one might expect to find evidence of clusters of more than three quarks.

New experiments are looking at nuclear effects in the quark distribution functions for individual flavors of quarks, either by detecting and identifying the jets of hadrons that are the remnants of the struck quark, or by selectively annihilating quarks and antiquarks in the target with those in an incident hadron and detecting the emitted virtual photon (the Drell-Yan process). In this way we can more cleanly identify the underlying nuclear mechanism and perhaps cast some light on the issue of the number of pions in nuclei. Nuclei also provide powerful "rulers" to measure the length scales of QCD processes, e.g., how a fast-moving quark undergoes the transition to a jet of hadrons. Nuclei can be used to measure the time it takes for hadrons to form and the effect of nuclear matter in modifying this process. These techniques illustrate how the nucleus has a unique role to play in the study of QCD.

At high energies, the quarks are known to carry roughly half the momentum of the proton, with the rest being carried by the gluons. An exciting new experimental result naively implies that only a small fraction of the spin of the proton is carried by the quarks, contrary to expectations from simple quark models. This has caused a critical re-examination of the link between low-energy effective quark models and the quark distributions observed in deep-inelastic scattering. It is now essential to measure the spin structure function of the neutron, which requires the use of polarized nuclear targets such as deuterium and ^{3}He. With these data, we will be able to test a fundamental result of QCD, the Bjorken sum rule, which provides a clear prediction for the difference between the integrated proton and neutron spin distributions.

The possibly small contribution of the quarks to the proton spin may indicate that an important role is played by pairs of strange quarks and antiquarks. Analyses of low-energy pion-nucleon scattering also suggest that the strange-quark content of the proton might be surprisingly large. New experiments in (neutral-current) neutrino scattering and (parity-violating) electron scattering show promise for improving our knowledge on this important question in the near future. Thus we will have many opportunities to explore further the spin and flavor composition of the nucleon.

Hadron Form Factors and Hadron Structure

Much of our knowledge of the structure of nucleons and nuclei comes from measurements of the currents by which they interact with electroweak probes. These currents are characterized by form factors that parametrize the underlying flavor structure. They reveal, for example, the distribution of charge within a proton or a nucleus. Figure 12 illustrates the magnetic form factor of the proton. At present, little is known about the corresponding electromagnetic structure of the neutron,which stands as a significant challenge for experimentalists. Since the neutron is electrically neutral, its charge distribution is quite sensitive to models of the charged constituents. The lack of knowledge of the neutron form factors also limits our ability to interpret some experiments on the deuteron and heavier nuclei. Other transition form factors, such as the quark spin-flip excitation of the Δ resonance, allow us to concentrate on individual features of the quark wave functions. Higher resonances, such as the $P_{11}(1440)$ and the $D_{13}(1520)$, provide additional specific tests. The new CW electron accelerators at CEBAF and MIT-Bates with polarized electron beams and polarized targets are ideal for these form-factor studies.

At short distances, perturbative QCD makes specific predictions for the momentum dependence of these hadron form factors; these predictions are simply related to counting the number of quarks that must interact to keep the hadron intact. In addition, perturbative QCD places important constraints on the spin structure of the form factors. We must learn when these perturbative techniques can be applied. The elastic form factors of the pion and proton (see Fig. 12) appear to follow the counting rules of QCD at high Q^2, but attempts to calculate the absolute magnitude of the proton form factor by nonperturbative techniques seem to require quite complicated quark distributions. Remarkably, studies of the deuteron show some evidence of this type of behavior at relatively low energies, 1–2 GeV in the $d(\gamma,p)n$ reaction. Figure 13 shows a different property of the deuteron, the magnetic form factor, $B(Q^2)$, measured by elastic electron scattering in the nuclear physics program at SLAC, NPAS; the minimum in these data at $Q^2 \approx 2\ (\mathrm{GeV}/c)^2$ is not easily explained in a perturbative quark model. Indeed, the average momentum transferred to a single proton in deuterium is larger in the $d(\gamma,p)n$ reaction data than in the magnetic form-factor data. We need to extend all these types of measurements to higher momentum transfer. The distinct predictions of spin observables are expected to be key signatures of the applicability of perturbative QCD.

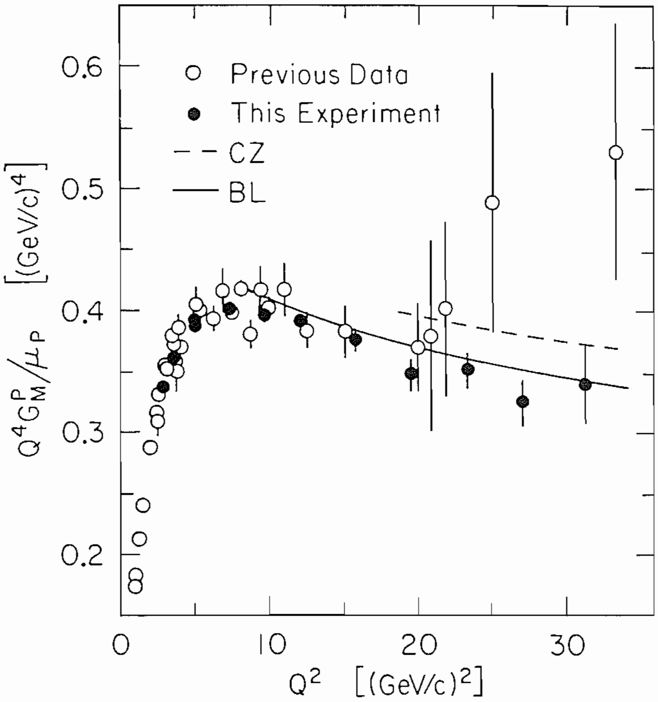

Figure 12: The proton magnetic form factor $G_M^p(Q^2)$ times Q^4 is plotted vs. four-momentum transfer Q^2. The approximate constancy of these data is evidence of scattering from three quarks in the proton. Perturbative QCD techniques do correctly predict the shape of the deviations from a constant, but it is not yet clear if they give the correct absolute magnitude. Two typical calculations are shown, but others give much smaller values.

A central idea in perturbative QCD is that the only way a hadron can recoil intact from a very hard collision is to be caught momentarily in a very small state with all its quarks packed close together. A hadron in such a small, colorless state is

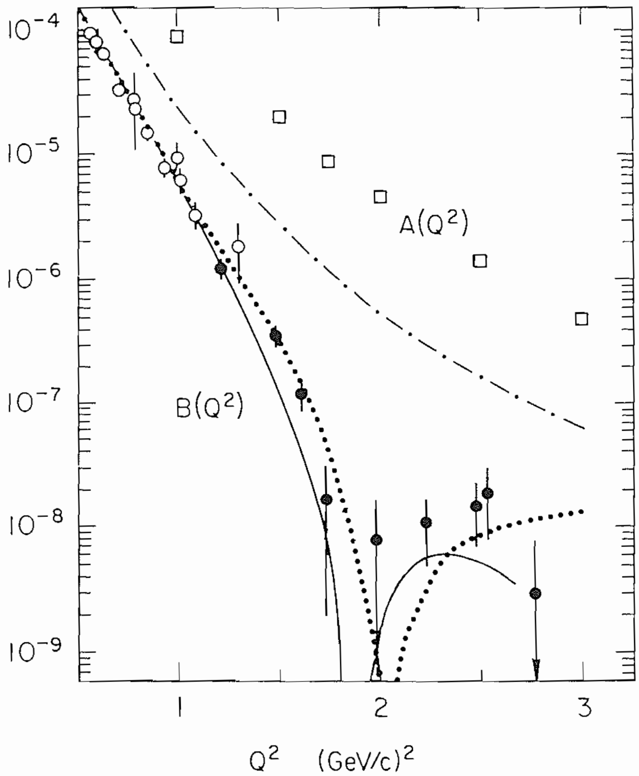

Figure 13: The deuteron magnetic form factor $B(Q^2)$ is plotted versus four-momentum transfer Q^2. The new data (solid points) are from a recent NPAS experiment at the Stanford Linear Accelerator Center. The smoothly decreasing dot-dashed curve is the shape predicted by the quark scaling models assuming hard scattering on six quarks. Such models were able to describe the smooth Q^2 dependence of another deuteron form factor, A(Q^2), shown by the open squares. The solid curve is from one meson-nucleon model but is quite sensitive to assumptions for nucleon and meson currents in the deuteron. Another low-energy, QCD-inspired model of the electromagnetic current (dotted curve) is similar in shape to the meson-nucleon curve.

expected to travel through matter with little interaction. By studying hard collisions in nuclei, this idea can be verified, and the space-time evolution of the hadron from this compact state can be determined. Recent data on p-nucleus scattering offer an intriguing glimpse but are complicated by the presence of significant nonperturbative amplitudes. Electroweak probes, used for initiating the hard scattering process, do not suffer from these nonperturbative amplitudes and exhibit behavior consistent with the perturbative predictions in scattering from free nucleons, as discussed above. New experiments using these probes are clearly required to explore this issue.

Can we see evidence that the structure of the proton has changed inside the nucleus? The data from searches using electron scattering, such as measurements of the Coulomb sum rule, have been discussed in Sections 1 and 2; many-body physics is seen to be essential in interpreting these results. In the suggested explanations of the EMC effect, we also see an interplay between a single-particle explanation, the possible change in confinement scale, and many-body effects. We will probably need a consistent explanation of data, with both a hadronic description and a quark description, to provide a convincing case for a change of the structure of the nucleon inside the nucleus. Such a change would have tremendous repercussions in our understanding of nuclear structure and interactions.

Hadron-Hadron Interactions

It is natural to look to QCD to give us new insight into novel hadronic structures and the interactions between hadrons. The most distinct predictions of the various models are manifest in new particles such as glueballs (composed of gluons rather than quarks) or other exotic hybrid states. One collection of six quarks, the H particle, may be stable; it is a symmetric combination of two up, two down, and two strange quarks (see Section 4). Some models suggest that, in bulk nuclear matter, the effects of the Coulomb and color interactions make states with large numbers of strange quarks preferred. Often quark models provide simple explanations for observations that require a complicated explanation in the meson picture; the small spin-orbit interaction in Λ hypernuclei discussed in Section 4 is one such case. Perturbative techniques are important here also, where they can be used to make powerful predictions for hadron-hadron scattering at high energies, just as for the electroweak form factors.

We expect that QCD will not only predict new phenomena in nuclear physics but will help us resolve some of the long-standing problems in the field. Here the nucleon-nucleon interaction remains a central issue. That the N-N interaction must be strongly repulsive at short distances was already evident in 1951. A meson description at very short distances is very complicated and involves many arbitrary parameters. In QCD inspired models, this repulsion is generated by the Pauli restrictions, the color-magnetic interaction generated by one-gluon exchange, and other manifestations of the confining forces. More information on other baryon-baryon systems, such as the Λ-N, Σ-N, $\bar{p}$-p (and possibly Δ-N, Δ-Δ) will provide significant tests; this variety of short-range interactions should reveal further evidence for QCD effects, such as quark-exchange forces.

Theoretical Progress

The theory of QCD in the strong interaction regime has been pursued vigorously on many fronts. Lattice gauge calculations appear to offer the possibility of obtaining numerical static solutions to the QCD Lagrangian. These calculations have already had some success in illuminating the nature of confinement and of the phase transition between the low-energy confined system and the high-energy quark-gluon plasma described in Section 7. There are many attempts to incorporate approximate models of confinement (e.g., bags, strings, flux tubes), which have been quite successful at a phenomenological level. The constituent quark model predates QCD; its successes (magnetic moments, approximate flavor symmetry) are only partially understood in terms of the more modern approaches. Bag models attempt to incorporate the correct quark degrees of freedom. In another approximation, i.e., in the limit that the number of colors is large, QCD can be reduced to an effective theory with the remarkable property that the quark degrees of freedom can be eliminated and only meson degrees of freedom remain. Such a picture has much in common with our traditional view of the nucleus. Chiral bag models incorporate both quark and mesonic elements to deal with the transition between the deconfined and confined regions.

QCD provides a direct explanation for a powerful symmetry principle, chiral symmetry. It expresses the fact that the energy of the system is unchanged under suitable rotation of its fields. This symmetry is automatically built into a theory of massless quarks, while in a meson-nucleon picture it implies that the mass of the pion is negligible. A powerful phenomenology, chiral perturbation theory, is built on this symmetry principle and offers much hope for providing a basis for low-energy theory with fundamental connections to QCD. A considerable amount of precise low-energy experimental work on meson interactions (strong and electroweak) is required to test this theory.

An important question is the relationship between two phenomena: the confinement transition from weakly interacting quarks to mesons, and the chiral phase transition from massless quarks to mesons. This issue must be addressed both in the structure of the hadrons and in the phase transition to the quark-gluon plasma.

Progress on these theoretical avenues has been rapid since the last Long Range Plan and this area has developed into one of the most exciting areas of nuclear theory research. This progress must continue, in conjunction with the new experimental efforts, to provide an understanding of how we use QCD in the nucleus and how we connect our quark and hadron pictures of nuclei.

Summary

Incorporating quark and gluon degrees of freedom in nuclei has significantly expanded the scope of our field. It is important to understand these issues of confinement in QCD to address a host of long-standing issues in nuclear physics. Since QCD is solvable at high energies, the transition between the simple perturbative regime and the confinement regime must be explored. This requires a well-stocked arsenal of probes of the nucleus, many of which are not available at nuclear physics facilities. High-energy leptons have been and will continue to be central to these studies. High-energy hadron probes provide unique sensitivities to flavor and gluon distributions. Nuclear physics has or is developing some of the facilities for the study of hadron structure and interactions at CEBAF, LAMPF, MIT-Bates, NPAS, and a future high-intensity, higher-energy hadron accelerator. However, as is evident from the figures in this section, it is vital to carry out a number of the critical experiments at truly high-energy accelerators. Nuclear physics efforts at traditionally "high-energy" facilities must be vigorously pursued in addition to work at dedicated nuclear physics facilities.

The development of QCD has provided nuclear physics a great challenge and an enormously stimulating scientific opportunity. We must now attack questions that we could not even state in a meaningful way in the recent past. In the past five years, we have moved from the first confrontation with experimental data on explicit quark effects to a field-wide appreciation of the impact of QCD on nuclear science and on clear directions for the future.

II.4 Flavor Physics in Nuclei

Overview

As stated earlier, the neutrons and protons that make up ordinary nuclei are in turn built up of quarks of "up" or "down" (u or d) flavors. Heavier baryons, which are called hyperons, contain one or more "strange" (s) quarks. For example, an s quark, together with a ud combination, forms the lightest hyperon, called the lambda particle (Λ). The strong and electromagnetic interactions do not allow decays that change flavors. Thus the Λ decays via the weak interaction and hence can form rather long-lived (lifetime $\tau \approx 10^{-10}$ sec) nuclear systems, called hypernuclei. Examples of these were discovered some 35 years ago in experiments with nuclear emulsions. There is also some information on nuclear composites containing the heavier sigma (Σ) or cascade (Ξ) hyperons, the latter containing two strange quarks. These systems decay via strong interactions, with a typical time scale of 10^{-22} sec, so their properties are more elusive. Heavier quark flavors, namely "charm" (c), "bottom" (b) and "top" (t), can be produced in high-energy collisions. In general, the study of nuclear many-body systems that incorporate one or more heavy quarks (s,c,b,t) is called "flavor physics in nuclei." It forms the subject of this chapter.

Hypernuclei have been produced with beams of mesons using both pions (π) and their strange counterparts, the kaons (K), antiprotons, or even heavy ions, incident on nuclear targets. The pioneering hypernuclear work with meson beams has been carried out at proton synchrotrons at Brookhaven, CERN, and at KEK (the Japanese High Energy Physics Laboratory), using beams of limited intensity and spectrometers of modest resolution. At CERN and Fermilab, production of hyperon-antihyperon and charm-anticharm pairs has been achieved with antiproton beams.

There are a number of outstanding issues in flavor physics to be addressed in the next decade. These include the clarification of the strangeness ($s\bar{s}$) content of the nucleon, the interaction with nucleons and nuclei of mesons containing $s\bar{s}$ pairs, such as the η and ϕ mesons, the search for strange two-baryon bound states (dibaryons), investigations of the structure of hypernuclei with high energy resolution, further exploration of the isospin dependence of the hyperon-nucleon weak force, and the study of nuclear medium effects with strange probes, for instance the K^+. There are many examples of the significant role that heavier quarks play in understanding the physics of strongly interacting multiquark systems. We focus later in this section on a selection of problems that highlight the broad scope of physics questions that can be addressed by measurements involving strangeness and heavier flavors.

For the future development of this field, the proposed Canadian KAON project will provide a forefront facility capable of attacking a variety of fundamental problems with a wide range of reactions. This 30-GeV, 100-μA CW proton accelerator will have kaon, antiproton, pion, muon, and neutrino beams that would make possible extensive studies of flavor physics in nuclei. As a complement, CEBAF provides the capability of probing the spin-flip strength in hypernuclei via the $(e, e'K)$ electroproduction with high resolution. Until the more intense beams of kaons and pions at KAON become available, the Brookhaven AGS must play the primary role in these investigations, and continued support for this facility is essential in providing a bridge to the future.

The Baryons and Their Interactions

Strangeness in the Nucleon

The presence of strange quark-antiquark ($s\bar{s}$) pairs in the nucleon and their role in nucleon structure is a question of intense interest at this time. There are indications of a relatively large number of $s\bar{s}$ pairs in the quark sea of the nucleon, as revealed, for instance, by deep-inelastic ν_μ scattering. Recent measurements of the spin-dependent structure function of the proton and the neutral weak-elastic scattering of neutrinos by the proton may indicate that the strange-quark sea carries a fair fraction of the proton spin, although there is controversy regarding the contribution of gluons to the spin. This is an issue of basic importance, which was treated in more detail in Section 3.

Hyperon-Nucleon Interactions and Strangeness Production

In investigations of baryon-baryon interactions the hyperon-nucleon interaction plays a special role as a test of the SU(3) flavor structure of the strong interactions. There are interesting charge-symmetry breaking effects and significant three-body forces which involve hyperons. Direct investigation of Λ-N scattering using tagged hyperon production will become feasible as high-flux beams of protons, antiprotons, pions, and kaons become available to produce tagged Λ, Σ, and Ξ particles. These particles decay in free space via the weak interaction, and the spatial asymmetries of the decay products give information about the polarization of these hyperons. In addition, the study of antiproton annihilation processes on nucleons and nuclei, leading to the production of strangeness- and charm-carrying particles, deserves a high priority. The relative production rates of strange mesons and baryons in $\bar{p}$-nucleus collisions are an excellent probe of energy dissipation and equilibration in heated nuclear matter.

An example of the high-quality data of this nature, obtained at the Low Energy Antiproton Ring (LEAR) facility at CERN, is shown in Figure 14. This represents the first precise study of lambda-antilambda ($\Lambda\bar{\Lambda}$) production very close to threshold. A large p-wave component is present, posing an interesting and unsolved problem for the reaction mechanism.

Strange Dibaryons

The spin-spin interaction between pairs of quarks plays an important role for the differences between the masses of the various baryons and mesons. The existence of multiquark hadron states beyond quark-antiquark and three-quark systems has been predicted for many years. Strange six-quark states are of particular interest, since some of these may be stable or quasistable with respect to strong decay. Of particular interest is the lowest-lying doubly strange state, the H dibaryon. The experimental verification of the existence of the H particle is a high priority. If the H exists, an investigation of its decay modes will test the special quark character of its wave function and the effective weak interactions for nonleptonic decays. What is needed is a high-sensitivity measurement in the region of the $\Lambda\Lambda$ mass and below. The first such experiments are now under development at the Brookhaven AGS facility. This direction of research will retain a high priority at a future kaon facility.

The Structure of Hypernuclei

The conversion of a nucleon to a hyperon, such as the Λ, provides a "tagged" baryon probe for nu-

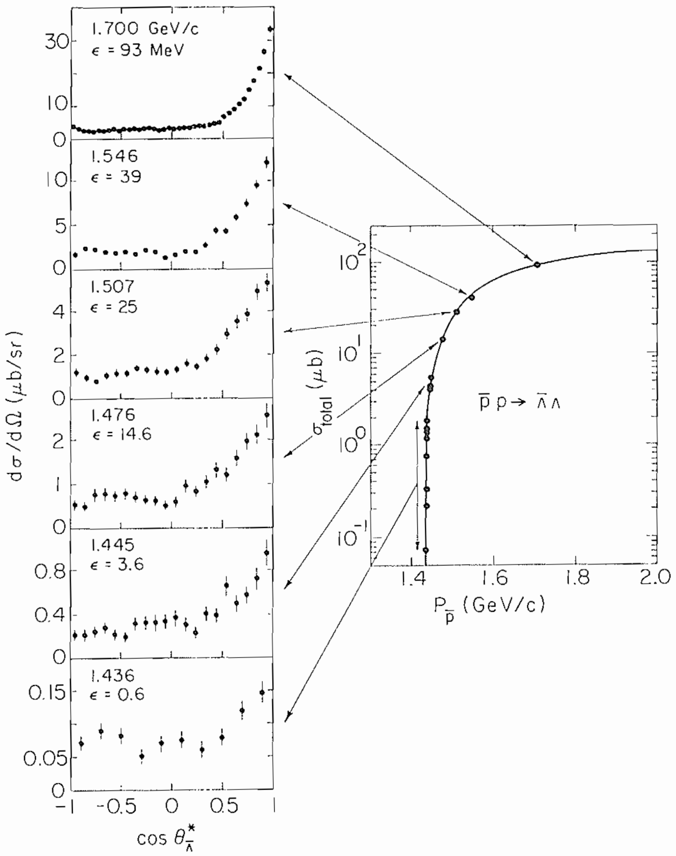

Figure 14: Total and differential cross sections for the production of $\bar{\Lambda}\Lambda$ pairs in the reaction $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$ near threshold. Investigation of this reaction permits a study of the mechanism for strangeness production. The polarization of the Λ's, obtained from the weak-decay asymmetry of the hyperons, was found to be large at backward angles.

clear structure studies. Such "flavor tagging" is analogous to the technique of radioisotope tracers in studying the structure of biological molecules. Hypernuclei exhibit new features absent in the structure of nonstrange systems. The issue arises as to whether hyperons behave as distinguishable fermions in the nucleus or whether the quark substructure is revealed when the hyperon is immersed in the nuclear medium. The nonmesonic weak decay of hypernuclei enables one to explore the $\Lambda N \rightarrow NN$ strangeness-changing weak interaction, which is inaccessible in free space.

The exploration of hypernuclei tests our understanding of their structure, constrains our models of nuclear forces, and may even exhibit new phenomena. The ΛN spin-orbit force has been shown to be at least an order of magnitude smaller than that for NN, but has yet to be precisely determined. Three-body ΛNN forces play a relatively important role in hypernuclei. They are signaled by a significant density dependence of the Λ-nucleus mean field. Detailed shell-model calculations have revealed significant deviations from the weak coupling picture, which reflect the properties of the ΛN effective interaction. Unique features of hypernuclear structure have also been seen: for instance, supersymmetric configurations, which are forbidden by the Pauli principle for ordinary nuclei. Exploiting hypernuclei to increase our understanding of nuclear structure requires significant improvement in excitation-energy resolution, to the level of 100 keV, in order to resolve individual levels and to determine their quantum numbers.

At the hadron level, the Λ is certainly distinguishable from the proton and neutron, so the Pauli principle does not apply. However, at the quark level one might anticipate that the Λ would experience a Pauli pressure due to the antisymmetrization of its u and d quarks with the quarks of the same flavor in the nucleus. Still, present experimental results on the atomic-number (A) dependence of ground- and excited-state hypernuclear binding energies are consistent with a simple one-body (mean-field) potential for the Λ. Recent results from the Brookhaven AGS on the associated production of hypernuclei with pion (π^+) beams are displayed in Fig. 15. The effects of quark structure would contribute to the observed nonlinear density dependence of the Λ-nucleus potential, but conventional nuclear medium corrections and three-body forces produce similar effects.

The multiplet structure in hypernuclear spectra reveals the spin dependence of the ΛN interaction. The spin splittings are usually small, and high energy resolution is required for their direct observation. The principal hadronic mechanisms for producing hypernuclei are (K^-, π) strangeness exchange and (π^+, K^+) associated production. The (π^+, K^+) reaction populates high-spin, natural parity states. The photo- and electro-production reactions (γ, K^+) and $(e, e'K^+)$, which will be studied at CEBAF, display similar kinematics but favor spin-flip transitions to unnatural parity configurations. The spin splittings are generally small throughout the p-shell, so their direct measurement in any of these reactions requires a high-resolution spectrometer. Decay γ rays from hypernuclei have been of particular importance; transitions in several p-shell hypernuclei have been observed. The transitions between the members of the ground-state doublet are particularly interesting, but, except for the $A = 4$ hypernuclei, these have not been detected. At Brookhaven, upper limits of order 80 keV have been obtained for several transitions, indicating that the Λ-nucleon spin coupling is small indeed. In the study of hypernuclear spectra, there is a need for intense kaon or pion beams coupled with high-resolution spectrometers and large-acceptance detectors.

Weak Decay of Hypernuclei

The ultimate fate of a Λ hypernucleus is to undergo weak decay via a mesonic ($\Lambda \rightarrow N\pi$) or a nucleon-catalyzed non-mesonic transition ($\Lambda N \rightarrow NN$). The nonmesonic mode dominates for all but the lightest systems. The decay can take place from the ground state or from an excited state whose electromagnetic lifetime is long compared with that for weak decay (typically 200 psec). Hypernuclear weak-decay lifetimes for light systems have recently been measured at the AGS, and for heavy hypernuclei at LEAR. Of even more interest are measurements of the various partial decay rates, especially the ratio of proton-stimulated to neutron-stimulated nonmesonic decay. This ratio is very sensitive to the relative contribution of dif-

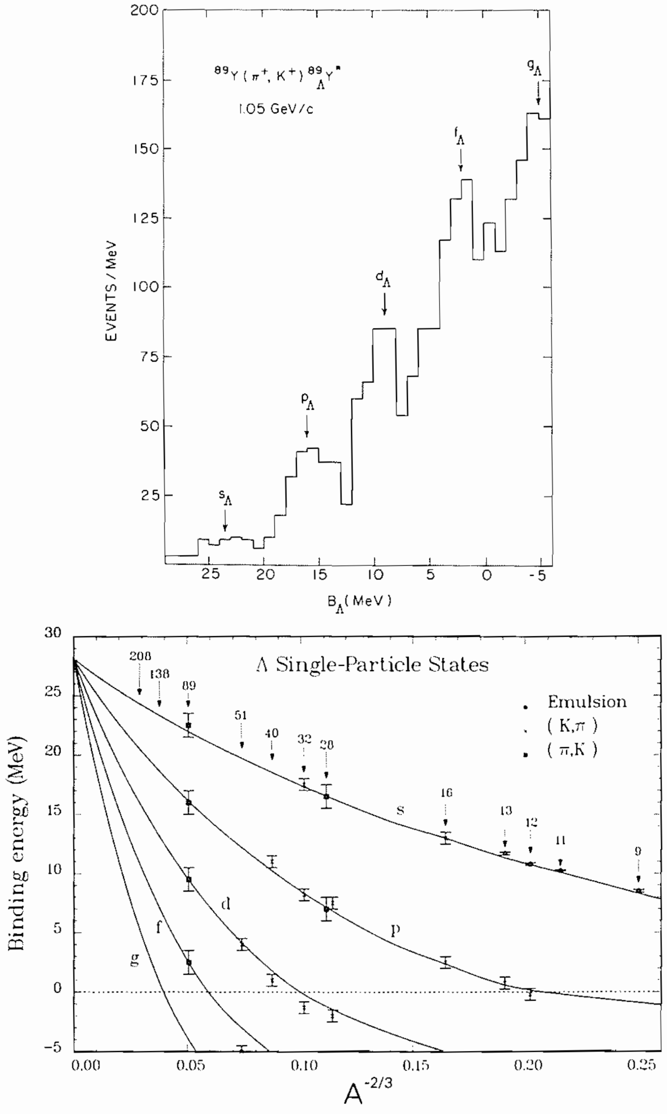

Figure 15: Identification of single-particle states in Λ hypernuclei.

(A) Observation of the Λ single particle orbits in the reaction $\pi^+ + {}^{89}\mathrm{Y} \rightarrow {}^{89}_{\Lambda}\mathrm{Y}^* + K^+$.

(B) Measured dependence of the binding energy of Λ-single particle states on mass number A. Solid curves correspond to a Hartree-Fock description of the Λ-nucleus mean field.

ferent mesons exchanged in the $\Lambda N \rightarrow NN$ weak decay process. Current data seem to be at odds with theoretical predictions based on one-pion exchange.

The π^0 and π^- mesonic decay rates, the decay excitation functions, and the pion angular distributions from polarized hypernuclei have been predicted. The π^0/π^- ratio can, in many cases, be used to distinguish the spin of the decaying member of a ground-state doublet. The pionic decays offer a sensitive test of nucleon occupation probabilities and of the low-energy pion-nucleus interaction.

Large polarizations can be obtained for certain hypernuclear states that are populated with appreciable cross section in the (π^+, K^+) reaction. This polarization is especially useful when combined with coincidence measurements of secondary decay particles, as in the weak decay process. One could test models of the weak decay mechanism by studying the angular correlation between the weak decay products and the hypernuclear spin.

Doubly Strange Hypernuclei

The existing data on doubly strange hypernuclei are very sparse. There are two ΛΛ hypernuclear events known, and several others that have been interpreted as Ξ hypernuclei. The (K^-, K^+) or (K^-, K^0) reactions can be used to produce Ξ hypernuclei in a single-step process. The momentum transfer q is sizable, and hence high-spin states are populated. The central question is whether the width from $\Xi N \rightarrow \Lambda\Lambda$ conversion becomes too large for the Ξ single-particle states to be observed. Model calculations suggest that widths of order 5 MeV might be expected for Ξ ground states. The 2-GeV/c kaon/pion beam line under construction at the AGS will provide access to this uncharted domain.

For ΛΛ hypernuclei, production cross sections of order 1 to 10 nb/sr have been estimated with kaon beams, for certain high-spin states. In order to measure such small cross sections in a reasonable running time, the full capability of the proposed KAON facility will be needed. Multiply strange hypernuclei could also be produced with relativistic heavy-ion beams. Beyond this, "strangelet" production from the quark-gluon plasma is a more exotic possibility.

K^+-Nucleus Scattering

The K^+ meson is an excellent probe of nuclear matter because of its relatively feeble interaction with nuclear constituents. It has a relatively long mean free path (5-7 fm) in the nucleus. Analyses of K^+-nucleus scattering point up a serious discrepancy between theoretical expectations and measurements of the elastic differential cross sections, and of total cross sections relative to that of ^{2}H. In order to reconcile these discrepancies, it has been suggested that the effect of the nuclear medium is to modify the effective size of nucleons, as suggested by the EMC effect. This can be interpreted as a partial deconfinement effect or as a lowering of the effective mass of mesons in nuclear matter, leading to a density-dependent K^+N amplitude. Whatever the ultimate explanation, the K^+-nucleus interaction provides an important test of our basic understanding of hadron interactions in strongly interacting many-body systems.

Conclusions

The properties of baryons and nuclei are significantly altered when strange quarks or heavier flavors are introduced. This provides an excellent opportunity to test our understanding of these systems in terms of the interactions of quarks and gluons. Discovery of a stable strange dibaryon would be a major confirmation of our understanding of quark confinement. The comparison of hyperon-nucleon scattering with nucleon-nucleon scattering provides an important test of strong interactions. The investigation of hypernuclear properties is important, both for exploring the origin of specifically nuclear effects such as the spin-orbit and tensor forces, and as a means of investigating interactions not otherwise accessible in the laboratory. Examples would be the weak $\Lambda - N$ force and the strong $\Lambda - \Lambda$ force.

There is a wide range of provocative questions in this sector of nuclear physics that should be explored in the next five to ten years. Obtaining answers to these questions will ultimately require the intense beams of kaons, antiprotons, and pions of a high-intensity, multi-GeV proton facility, such as KAON. In the interim, continued support for the Brookhaven AGS will be essential.

II.5 The Nucleus Under Extreme Conditions

Introduction

The structure of nuclei has been a central subject of nuclear physics since its beginning. As a result, the main aspects of the modes of excitation of nuclei near their ground-state configurations, and in the valley of stability, are now quite well understood. The major models, principally the spherical or deformed shell model, or the interacting boson model, are well in hand. The new emphasis is on stressing the nucleus in order to learn about the limits of our nuclear models. New phenomena appear when nuclei are driven to the limits of stability by adding angular momentum (i.e., centrifugal stress), by increasing their excitation energy to values near 100 MeV, by raising the nuclear temperature beyond 1 MeV, or by drastically changing the balance between the number of neutrons and protons from that prevailing in stable nuclei. Advances in our knowledge of these areas have come about by the recent development of powerful new experimental techniques.

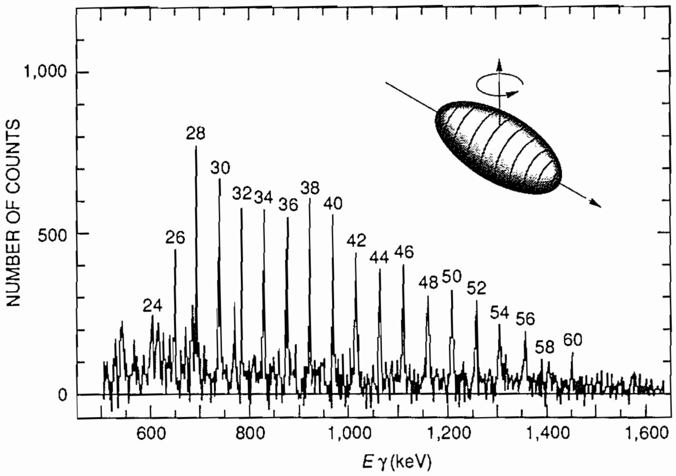

Figure 16: Spectrum of γ rays emitted as the rapidly rotating superdeformed ^{152}Dy nucleus slows down. In such a system the γ-ray energies are proportional to the spin of the rotating nucleus, generating the regular pattern as the spin decreases in steps of two units. The spacing between the peaks yields an ellipsoidal shape having an axis ratio of 2:1. This highly deformed shape is shown in the inset.

Rapidly Rotating Nuclei

Rapidly rotating nuclei are produced by beams of heavy ions when a massive projectile makes a near-grazing collision with a target nucleus and the two fuse. It was long predicted that such rapidly rotating nuclei could be driven to unusually large deformations, but it was only with the development of large arrays of high-resolution γ-ray detectors that such superdeformed nuclei were observed. Since their discovery in 1986, examples of superdeformation have been found in a variety of medium-heavy and very heavy nuclei. The energies of the electromagnetic transitions between the states of excitation in a superdeformed rotational band provide a direct measure of the nuclear shape. The shape of the observed superdeformed nuclei is that of a prolate spheroid with a ratio of major to minor axes of 2:1, in contrast to the ratio of only 1.3:1 that is characteristic of more typical deformed nuclei. A single rotational band is typically observed connecting states from an angular momentum of about 30 up to 60 units. Such a beautifully simple sequence of γ lines, observed in the nucleus ^{152}Dy, is shown in Fig. 16. Many questions concerning these states remain. Why is the superdeformed band so strongly populated relative to the states of normal deformation? How do the superdeformed states de-excite to the states of normal shape? Are new collective modes, such as the bending of the elongated nucleus into a banana shape, associated with the superdeformed shape? Experiments with the next generation of large γ-ray detectors, such as the Gammasphere, will help to clarify these issues. The enhanced sensitivity of these future detector systems may also allow even more extreme deformations to be observed, if they exist. For example, a stable shape with a 3:1 axis ratio is predicted in some nuclei. The search for these extreme shapes is aided by impressive advances in our capability to compute the nuclear structure from microscopic models for large deformations, very high angular momenta, and non-zero temperature. Fig. 17 shows such a description for ^{152}Dy, together

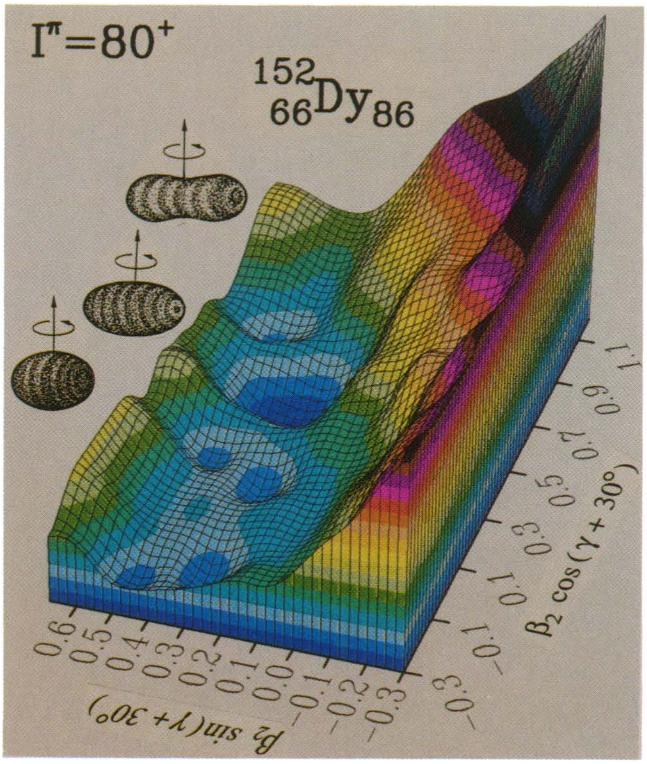

Figure 17: Contour plot of the potential energy of the nucleus ^{152}Dy with 80 units of angular momentum, as a function of the nuclear deformation parameters beta and gamma. Deep minima are associated with normally deformed (axis ratio 1.3:1), superdeformed (2:1) and the as yet unobserved hyperdeformed (3:1) shapes which are depicted at the left.

with the nearly spherical, normally-deformed and superdeformed shapes, which have been established for this nucleus.

When a nucleus rotates rapidly, the normal pairing between nucleons is quenched, a result of the Coriolis force acting on the nucleons moving in the rotating system. This effect is analogous to the quenching of superconductivity in a magnetic field. The crossing of different rotational bands in the spectrum, a signature of pair correlations, is found to be absent at the highest spins. The transition from paired to unpaired states as the rotational motion increases is of considerable interest. For example, the nucleus does not exhibit the sharp, first-order phase transition that characterizes a bulk superconductor. The limited number of nucleons in the system smears out the phase transition. The two-nucleon transfer reaction between high-spin states is a sensitive probe of the pairing properties of rotating nuclei. Such measurements will be relatively easy with high-efficiency detection systems such as Gammasphere.

Although it is sometimes useful to think of nuclei as rigid macroscopic rotors, the finite number of nucleons in the nucleus implies that the rotational bands must eventually end. The angular momentum, which must be constructed from the constituent nucleons, is limited. Nuclear shell structure is important in determining exactly when this limit is reached. At the angular momentum limit, the collective rotational motion of the nucleus ceases, and the complete angular momentum is carried noncollectively by the individual nucleons moving about a common axis of rotation. An example of this has recently been observed in ^{158}Er at very high spin. This nucleus shows a normal collective rotational band up to a spin of about 30 units. At this point the collectivity of the band begins to decrease, and it has vanished by spin 40. This happens because there are only about a dozen nucleons available (beyond the closed shells) to support the rotation, and they cannot contribute more than about 30 units of collective angular momentum. This effect, called band termination, has now been seen in a number of additional nuclei near ^{158}Er.

Exotic Shapes and Decay Modes

Until recently the known nuclear shapes consisted of spherical closed-shell nuclei, of ellipsoidal shapes of deformed nuclei, and of the highly elongated shapes assumed by a nucleus on its way to fission. In the last few years, new shapes have been established. Besides the extreme ellipsoidal shapes discussed in the previous section, there is new evidence for pear-shaped nuclei. Because such a nucleus does not have reflection symmetry, there is a doubling of the number of states into rotational bands containing states of both parities. A beautiful example of such a band structure, called "parity doublets", recently observed in actinide nuclei, is shown in Figure 18.

It has long been thought that the only naturally occurring radioactive decays that could change the mass of a nucleus were α radioactivity or spontaneous fission. However, new kinds of radioactive decay have been discovered recently, in which a heavy nucleus emits a particle intermediate in size between that of an alpha particle and a fission fragment. Examples of radioactive decay have been found in which the neutron-rich nuclei ^{14}C, ^{24}Ne, and ^{28}Mg are ejected. To explain the observed rates of such decays, the parent nucleus must fluctuate in shape, occasionally acquiring a shape with the heavy decay fragment formed at the surface. This heavy-particle radioactivity, which was actually predicted prior to observation, is understood on a phenomenological level in terms of the formation of clusters that tunnel through a potential barrier. A complete understanding of the dynamics of the shape change, consistent with other dynamical phenomena, remains a goal.

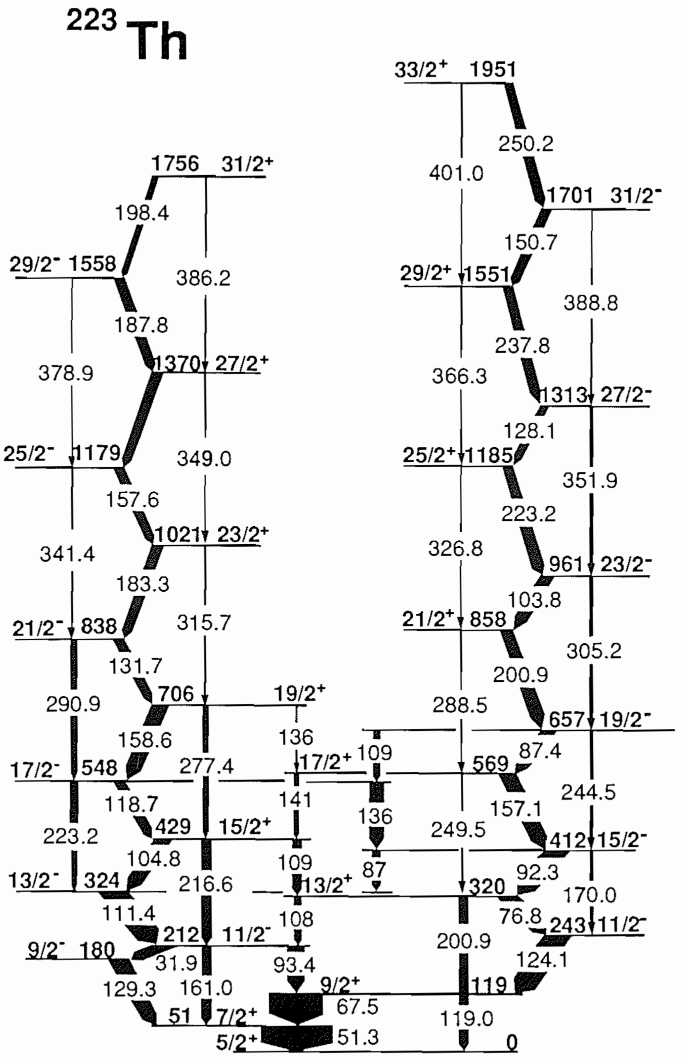

Figure 18: Level scheme of ^{223}Th, illustrating two sets of parity doublets associated with reflection-asymmetric shapes (pear-shaped nuclei). The widths of the arrows indicate the relative γ transition strength.

Nuclei Far from Stability

When the balance between neutrons and protons is far from equilibrium, new phenomena may be encountered. Some possibilities are illustrated in Figure 19. Large γ-ray detector arrays, sensitive particle-γ coincidence techniques (e.g., recoil mass analyzers), and the development of a new generation of ion sources that permit on-line isotope separation of reaction products produced at accelerators or reactors have greatly increased our knowledge of these nuclei.

In the simplest shell-model picture, the nucleus is viewed as a central core of nucleons surrounded by a shell of outer, or valence, protons and neutrons. The long chains of isotopes that are often accessible far from stability give extensive information on changing nuclear shapes and excitations and have reinforced the idea that the interactions of the valence protons with valence neutrons are crucial in determining the structure of nuclei. Nuclei far from stability have combinations of proton and neutron numbers, and hence of orbits and interactions, that are not otherwise accessible. This is critical, since these interactions depend on the configuration of these nucleons leading to either the reinforcement or the obliteration of energy gaps in the single-particle levels. Moreover, shell gaps for deformed shapes are now realized to be as important as gaps for spherical shapes. This is revising our view of the behavior of transition regions, such as those near nucleon numbers $A = 30$, 70, 100, 130, and 150, where the nuclear shapes change rapidly when the number of protons or neutrons is even slightly altered. In addition, data on nuclei far from stability have inspired simple counting schemes of proton-neutron interactions that offer predictions for unknown nuclei and that help guide the further development of microscopic theories.

The study of $N = Z$ nuclei is particularly important. Such nuclei should have maximal interaction between protons and neutrons, and questions of the behavior of proton-neutron pairing can be

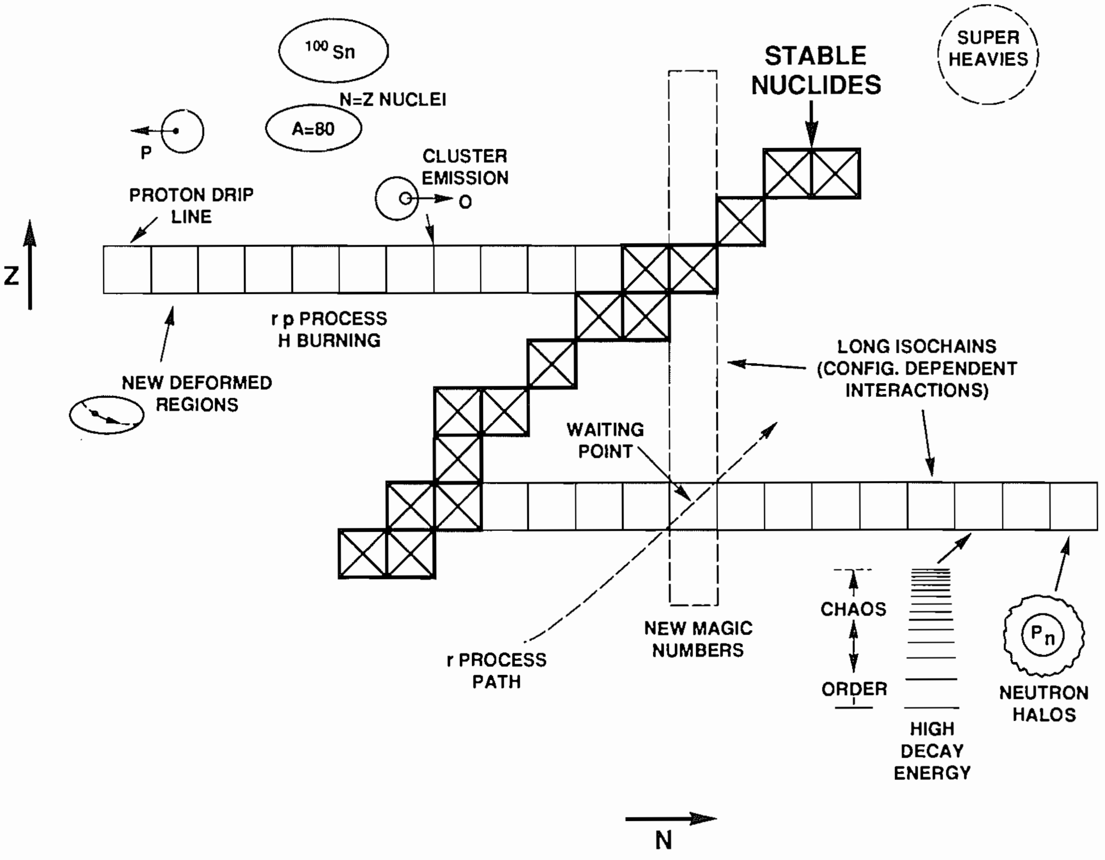

Figure 19: Schematic diagram illustrating some phenomena associated with nuclei far from stability.

answered by their systematic study. No stable nuclei with $N = Z$ exist beyond ^{40}Ca, but of course they can be produced in nuclear reactions. The recent measurement of the excitation spectrum of the heaviest known $N = \mathrm{Z}$ nucleus, ^{80}Zr, indicates that it is highly deformed. This result is in contradiction to the long-held belief that, for either N or Z, 40 is a magic number for spherical shapes, as indeed it is in ^{90}Zr and ^{68}Ni. However, it agrees with calculations suggesting that a new deformed shell gap stabilizes this island of deformation. The next generation of γ-detector arrays will allow heavier $N = Z$ nuclei to be studied, with an eventual goal of producing ^{100}Sn. It is not clear whether the even more definite magic number of 50, which is responsible for the element tin having the largest number of stable isotopes of any element in nature, will persist for this very neutron-deficient nucleus with 50 protons and 50 neutrons.

It is now possible to study neutron-rich nuclei at the very limit of stability against neutron emission. These nuclei have very weakly bound neutrons and may have an interesting structure associated with the low-density neutron skin. Recently, a secondary beam of ^{11}Li (made up of 3 protons and 8 neutrons) was produced at the Bevalac facility at LBL, and several of its properties were measured. The study of the interactions of this and other very neutron-rich nuclei suggests a very extended nucleus, with a normal core but a neutron-rich halo in the outer region. For example, its interaction radius is large, it breaks up by emitting neutrons without transferring much momentum to the core, and it seems to be very easily excited by Coulomb fields. Questions abound concerning the spectroscopy of such weakly bound neutrons. For example, could these nuclei have low-energy dipole vibrations corresponding to the oscillations of the core against the halo? Are the correlations between the neutrons in the skin strong enough to favor deuteron formation in beta decay when a neutron changes into a proton? The technology is in hand to produce intense beams of ^{11}Li and similar highly neutron-rich nuclei with a radioactive-beam accelerator. This would make the nearly pure neutron matter in the low-density outer region accessible to experiment – only one of many interesting possibilities of such an accelerator.

Other applications of radioactive beams include the measurement of nuclei important in the nucleosynthesis of the heavy elements. For example, all but the heaviest of the so-called waiting-point nuclei in the production chains can now be produced for study. Perhaps even the remaining example, ^{195}Tm, can be studied with radioactive beams. Also, the increased neutron excess achievable with such beams will allow the heaviest nuclei produced to approach within a few mass units of the $Z = 114$ island of stability. This predicted region of superheavy nuclei has been a long-sought goal, but it has proven inaccessible by the methods available so far.

Hot Nuclei

When the excitation energy of the nucleus is increased, the spacing between the individual nuclear levels decreases dramatically. The point is rather quickly reached where the energies of the individual γ rays emitted from these levels can no longer be resolved. It is then appropriate to treat the nucleus as a thermodynamic system with a nuclear temperature. Indeed, the study of the nucleus as a thermodynamic system should reasonably start with the study of temperature effects on nuclear structure.

Following heavy-ion fusion reactions, some γ rays are emitted from rotational states in this excitation-energy range. Although individual γ ray transitions cannot be resolved because of the high density of states, the correlations between the energies of γ rays in a specific rotational band remain (recall the nearly constant spacing of the γ ray energies shown in Fig. 16.). These correlations are indeed observed even at high excitation energy (i.e., at an elevated temperature), but turn out to be much weaker than is expected for normal rotational behavior. The explanation appears to be a strong mixing between states of the same spin and parity in different rotational bands in the high-energy region. This mixing does not destroy the collectivity; however, it does destroy the correlations between the γ-ray energies. The mixing appears to set in rather suddenly where the average separation between the levels is about equal to the average residual interaction between the levels. At this point, part of the shell structure is destroyed, and the system becomes chaotic. The rapid loss of correlation between γ-ray energies with increasing excitation energies can be thought of as a phase transition in the order of the system.

Recently it has been demonstrated that the giant dipole vibration of nuclei can serve as a probe of the nucleus at very high excitation energies (temperatures). The giant dipole vibration is an oscillation of the protons in the nucleus with respect to the neutrons. Such a vibration exists for all nuclear states, including those at high temperature. The γ-ray decays of this vibrational state to the state on which the vibration is constructed are sensitive to both the size and the shape of the nucleus. By measuring the shape of the γ-ray spectrum that is de-exciting states at temperatures of 1-2 MeV, it has been possible to show that excited nuclei remain deformed (though the detailed shape is not yet clear) in a temperature range where naive calculations would have predicted that nucleon-nucleon correlations are destroyed. At higher temperatures a variety of interesting predicted phenomena (for example, radical shape changes and a complete disappearance of shell effects) promise to become accessible. For example, at temperatures greater than 4-5 MeV (which is close to the maximal temperature of 5-6 MeV that can be given to a compound nucleus) the intensity of these giant-resonance γ rays decreases, suggesting that the structure of the nucleus does not remain stable long enough for such a vibration to take place. This measurement provides the first information on this limit of stability in nuclei.

Chaos

Nuclear many-body systems provide an excellent laboratory to study the evolution of a quantum mechanical system from ordered to chaotic behavior. It has been known for some time, from studies of proton and neutron resonances in nuclear reactions, that the distribution of the spacing of nuclear energy levels at high excitation energy can be accounted for by random-matrix theory. This theory is known to describe correctly the quantum mechanical analogs of classically chaotic systems.

The ability to identify all of the levels in a nucleus of a given spin and parity permits the comparison with random matrix theory to be extended to low-lying states. Such a comparison has recently been performed for the lowest 100 positive parity states in ^{26}Al; the results suggest that even near the ground state, the level spacings follow the chaotic distribution. This is particularly interesting in that the system has an approximate symmetry, isospin, which, if conserved, should affect the level distribution. Evidently, and as expected by theory, even small violations of a symmetry are sufficient to induce the apparently chaotic behavior of the level distributions. Such statistical analyses may also be applied to study the breaking of other symmetries, including time-reversal invariance.

Summary and Outlook

The nucleus is a superb system for the study of many-body quantum physics, and especially its collective manifestations; in this aspect, it has links to numerous other physical systems. Yet, its finite, even small, number of constituents lends a unique richness through which such phenomena as the evolution of structure with nucleon number, the fluctuation properties of finite-body phase transitions, and the interplay of collective and single particle motion can be probed. Much can be learned about nuclear structure, and the models which describe it, by stressing the nucleus to extreme limits, whether these be of angular momentum, excitation energy, or neutron-to-proton ratio. The collective and macroscopic facet of nuclei is highlighted by the recent observations of superdeformation at high spin, and of nuclei with pear-shaped ground states, as well as by the hyperdeformed shapes which are the subject of current searches. The interplay between collective and single-particle aspects is prominent in the concepts of pairing quenching and band termination. Studies of the phase transition from spherical to deformed shapes, of shape coexistence, and of $N = Z$ nuclei far from stability focus on the critical role of the orbit dependent valence p-n interaction, and are leading to a unified microscopic view of the origin of collectivity in nuclei. New studies of rotational damping and of giant resonances built on highly excited states probe the dissolution of shell structure, the transition from collective to non-collective deformation and from order to chaos at the limits of nuclear excitation energy.

Discoveries in all these areas have been made possible by recent major advances in experimental techniques. New instruments such as Gammasphere and recoil fragment separators, which represent the next stage of experimental sophistication, are crucial for the exploitation of the opportunities described in this section. Wholly new vistas would be opened by a radioactive nuclear beam (RNB) accelerator. Already, experiments with radioactive beams at the Bevalac facility have given evidence for neutron halos in neutron-rich nuclei, and provide tantalizing hints that nuclei with regions of nearly pure neutron matter can be produced. An RNB facility would also provide critical information for nuclear astrophysics, give access to entirely new nuclei even further from stability, and enable the investigation of novel phenomena such as massive isospin transfer, or of new forms of multiparticle radioactivity. Last but not least, it may lead us closer to the long-sought superheavy island of nuclear stability.

II.6 The Dynamics and Thermodynamics of Colliding Nuclei

Introduction

When nuclei collide, their kinetic energy of relative motion becomes available to excite the matter in both nuclei to high-energy quantum states. Likewise, the orbital angular momentum of the colliding nuclei may be transformed into intrinsic rotation of the final fragments. In this way it is possible, in a controlled fashion in the laboratory, to produce densities (up to 10^{15} gm·cm^{-3}, which is several times nuclear matter density of ~1/6 nucleon per fm^3) and temperatures (up to $T = 10^{12}$ K, or equivalently, ~80 MeV) otherwise found only in supernovae and in the first millisecond of the Big Bang, and to produce matter rotating with unprecedented speed (10^{22} rpm). Collisions of heavy ions thus provide a remarkable tool for the production of nuclei under extreme conditions, the study of which is outlined in Section 5. In addition, understanding the detailed mechanisms in such collisions is a fascinating and important problem in its own right, because it relates to fundamental properties of nuclear matter, such as the nuclear equation of state.

The study and understanding of nuclear collisions represents a far more complex problem than the study of the nuclei themselves. That is because the collision mechanisms depend not only on the properties of the colliding nuclei but also on the dynamical processes that occur during the short time of the collision. In general, this implies that the level of sophistication that can be brought to bear on the problem is less than in the static case and that approximations must be made in order to obtain a solution. It is, however, precisely this complexity that makes the problem so challenging and worthy of study.

Many approaches to the problem are possible. Time-dependent mean-field theory, successful in describing the static properties of nuclei (Hartree-Fock theory), has been applied to the case of collisions by including the time dependence of the motion of the mean field. It has thus been possible to simulate in a qualitative way many of the observed features of heavy-ion collisions. Alternatively, the almost classical behavior that occurs when the wavelength of the particle is small compared to the characteristic dimension of the system, and that leads to the scattering of low-energy heavy ions on well-defined trajectories, can be exploited. In this way, concepts familiar from the interactions of macroscopic systems (orbiting, frictional dissipation, temperature, entropy, *etc.*) have found a place. Approaches that combine aspects of both classical and quantum treatments have been very successful in the low-energy regime, as has been the application of transport theories and fluid dynamics to features of intermediate-energy collisions. The combination and reconciliation of these widely differing approaches is one of the major goals of this area of research.

Both the properties of the nuclear matter and the processes by which it is created change drastically as the available energy is increased. In this chapter we discuss four different regimes of reactions encountered as the velocity of the projectile nucleus is increased. These are illustrated schematically in Fig. 20. A fifth regime, characterized by ultrarelativistic velocities, is treated in Section 7. At very low velocities, the electrostatic repulsion between the positively charged nuclei keeps them so far apart that they merely scatter from each other without any change in their internal structure (elastic scattering). With slightly larger velocity, the nuclei may approach each other closely enough that their shapes are distorted by the strong electric field gradients that exist, leaving them to vibrate and rotate as they separate (Coulomb excitation).

A crucial boundary in the description of heavy-ion collisions is the Coulomb barrier – the energy required to bring the surfaces of the two nuclei into contact. Below the Coulomb barrier, reactions occur rarely, and then only because of quantum tunneling; it is in this region that semiclassical models of reactions have found greatest application. At energies above the Coulomb barrier, reactions take place in which large amounts of nuclear matter are transferred between the participating nuclei, resulting in a strong damping of the entrance-channel kinetic energy into excitation energy of the resulting

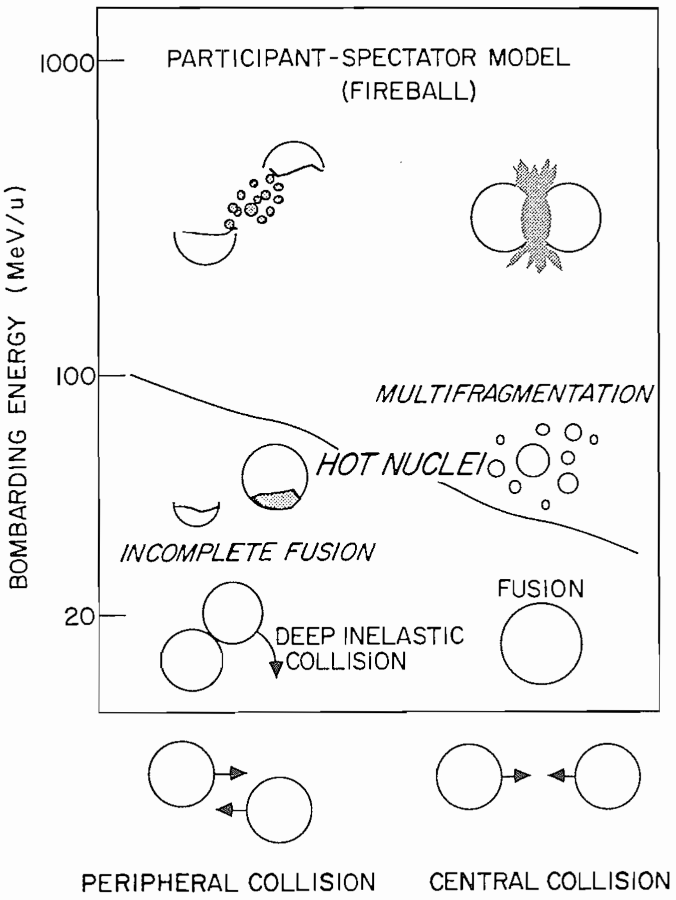

Figure 20: Schematic representation of the different classes of nuclear reactions that can occur at different incident energies.

fragments. This energy-loss process can be thought of as analogous to friction, which dissipates the organized kinetic energy of the relative motion into disorganized heat energy. The appearance of dissipative, irreversible behavior in these finite quantum systems has permitted remarkably successful applications of these typically macroscopic concepts.

A final consequence of the energy-loss process is the fusion of the colliding nuclei into a highly excited, rapidly rotating composite system that subsequently decays by the emission of nucleons, composite particles, and gamma rays. It is this process that forms the basic mechanism for the production of nuclei with large angular momenta and for the formation of nuclei far from stability. If the combined "compound" nucleus resulting from the fusion has a very large Z, a large angular momentum, or both, it may instead fission into two fragments, perhaps even before the fusion process is complete.

If the projectile has enough energy, the compound nucleus may fragment into many pieces. This third category of reactions is complicated by the fact that the large velocity of the projectile permits many of its nucleons to escape instead of being captured by the fused system. Theoretical studies raise many questions. Just how much energy can a nucleus hold before it breaks apart? Do the fragments break off sequentially, or does the matter dissociate into a mixture of liquid drops and hot gas, mimicking the liquid-gas phase transition familiar in macroscopic media? Experiments in this energy regime have been feasible only in the last few years. Since the data are fragmentary, controversies abound.

The fourth category of reactions occurs when the velocity of the projectile nucleus exceeds the average speed of the nucleons inside each nucleus. The response of the target nucleons is then such that they are unable to move aside to accommodate the projectile nucleons. This leads to the production of high-density nuclear matter. It also leads to a great deal of disorganization, or entropy, inevitably accompanied by heat. The pressure of the hot dense matter causes it to expand. During the expansion, the matter cools until it eventually becomes so rarefied that the nucleons no longer interact. Measurements of this low-density debris are used to reconstruct the conditions in the hot, dense matter from which it originates.

Important progress has been made in studying each of these categories of reactions. Below, we describe a few samples of research topics currently under investigation. These topics illustrate the unique and wide-ranging possibilities open to research with beams of nuclei at low and intermediate energies. They also show how the physics of these reactions connects to other areas of research.

Research Highlights

Dissipative Tunneling at Sub-Coulomb Energies

Even without enough energy to overcome the Coulomb barrier, quantum tunneling allows reactions to occur in which the colliding nuclei fuse or exchange nucleons. Recent measurements of these reactions show that their rates are strongly influ-

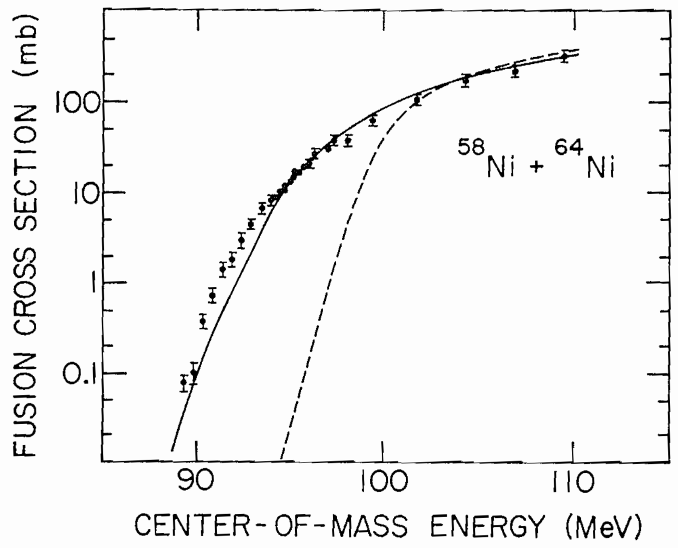

Figure 21: Cross sections for complete fusion of ^{58}Ni+^{64}Ni in the vicinity of the Coulomb barrier. The dashed lines show the results of calculations using a simple potential. The solid lines show the effects of allowing for the transfer of nucleons and for changes in the nuclear shape, resulting in the enhancement over the simple prediction. Despite this good agreement, there are still many features of the data that are not understood.

enced by the detailed structure of the participating nuclei. For example, the strong electric fields can cause the nuclei to change their shapes or orientations, which in turn may facilitate their fusion. Similarly, the transfer of nucleons by quantum tunneling can increase the likelihood of fusion by many orders of magnitude over what would have been expected in its absence. An example of such data is shown in Fig. 21. The results of these and similar studies indicate that fusion involves the coupling of several degrees of freedom — the relative separation of the nuclei, their shapes, and the motions of the individual nucleons in and between the nuclei. Dynamic oscillations of the shapes and the excitation of rotational degrees of freedom are suspected of playing important roles, although these effects are not yet fully understood. The enhancement of tunneling due to the coupling of many degrees of freedom is a general phenomenon that appears in many other areas, such as solid-state physics, surface physics, and the physics of superconducting junctions. Detailed investigations in the nuclear domain might therefore be expected to have wide significance. Recent experiments have resulted in a number of puzzling observations. Fusion products from sub-barrier tunneling have a broader distribution of angular momenta than expected. At even lower energies, the transfer of neutrons between the nuclei is found to occur much more frequently than predicted. These phenomena may parallel well-known cases in solid-state physics, such as electron tunneling in superconducting junctions. In the nuclear case, however, the dynamics of the nuclear shapes lends additional richness and complexity. It is important to note that, in addition to the fundamental interest in these phenomena, improved understanding of the mechanism is expected to provide guidance for future efforts to synthesize exotic nuclei and superheavy elements.

Time Scales for the Exchange of Mass, Charge and Energy

All these effects are thought to arise mainly from the same mechanism – diffusion of nucleons between the nuclei. Understanding this mechanism is therefore central to the explanation of the dissipative processes observed in these small quantum systems. Puzzles remain involving the sharing of energy between the target and projectile nuclei, and the role of quantum effects, such as the spectrum of energy levels of the transferred nucleons. In a number of examples, nucleons are observed to move preferentially from a light nucleus to a heavier one in cases where theory predicts that the forces acting on the nucleons should favor the opposite trend. An example of such an observation is shown in Fig. 22.

Hot Compound Nuclei from Fusion Reactions

The highly excited compound nuclei formed in heavy-ion fusion reactions lose their energy by the evaporation of nucleons or by fission. The competition between these processes has now been studied by distinguishing between neutrons emitted before and after fission. It turns out that highly excited nuclei fission more slowly than is predicted by the standard statistical theory. This slowing has been traced to the damping of the fission motion by dissipative processes. Related processes, intermediate between evaporation and fission, have also been ob-

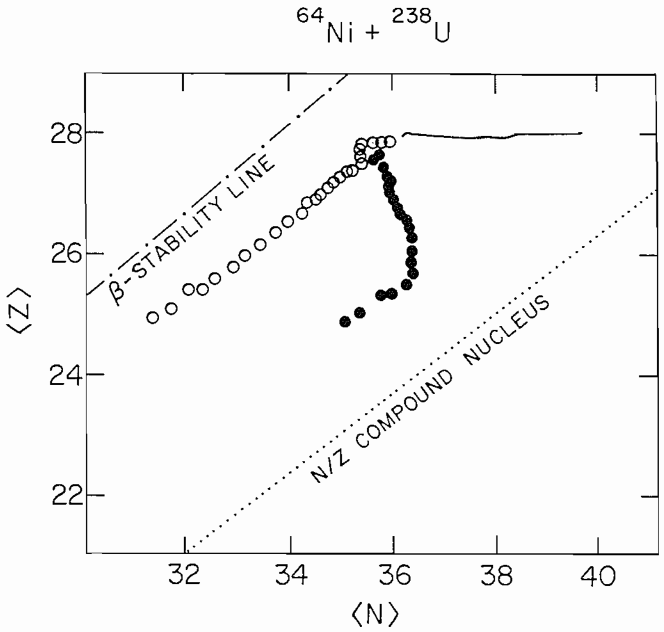

Figure 22: Evolution of the proton (Z) and neutron (N) distributions with energy loss for reactions of ^{64}Ni+^{238}U. The measured centroids of the N-Z distributions are designated by open circles. The resulting distributions following correction for neutron evaporation are shown as full circles. The solid line is the prediction of a transport model and is in clear disagreement with the data.

served in which the hot compound nucleus emits a fragment that is much heavier than the traditionally studied nucleons or α particles but that still represents only a small fraction of the total mass. Efforts to raise the temperature of compound nuclei by increasing the projectile velocity are seen to become ineffective when the heat energy is a little less than the energy by which the matter is bound together. Theory predicts that, if more energy were supplied, it would go into the formation of internal surfaces instead of heat, thus breaking the compound nucleus apart. These theoretical predictions seem to be partially verified by several still controversial experiments, but much more work is needed to prove or disprove conclusively these remarkable expectations. An important complication is the need to separate the inherent limitation of energy content from incidental limitations on the formation of the compound system. Do the rapidly moving projectile nucleons simply fail to deposit their energy because they are not stopped in the target? This question can be resolved by new high-efficiency detector systems capable of measuring simultaneously both fast projectile remnants and decay products of the compound system.

Properties of Hot Nuclear Matter

New observations show that large numbers of intermediate-sized fragments (clusters of more than four nucleons) are often produced in a single collision when the projectile velocity is a little larger than the speed of the nucleons inside the nuclei. These events suggest that the nuclear matter has broken up into a mixture of droplets with a low-density gas of nucleons between them, as would be expected if the matter expanded past the boundary of mechanical instability, known in macroscopic physics as the spinodal line in the phase diagram. However, the limited observations so far cannot rule out a scenario in which a single extended piece of nuclear matter divides and redivides sequentially. To completely understand the experimental observations of complex fragments will require a theoretical breakthrough. The best quantum theory available, based on the independent motion of nucleons, with only average effects of the forces between them considered, is unable to predict how the nucleons aggregate into clusters; other theories use classical or statistical mechanics, neither of which is likely to be accurate for these rapidly evolving quantum systems. The theoretical difficulties encountered here also appear in the ultrarelativistic nuclear collisions described in Section 7: quarks must eventually cluster into nucleons and mesons.

To help resolve the nature of these multifragmentation reactions, more complete measurements are needed with detector systems such as those mentioned under the previous heading, as well as with newly proven techniques. One new method determines the size of the hot nuclear system by measuring correlations of reaction products. An example of the application of this technique is shown in Fig. 23. Another technique determines the temperature at which fragments are emitted by measuring the relative populations of different final states of the fragments and assuming that they represent the equilibrium thermal distribution. The latter technique is necessary because the obvious temperature index, the fragment kinetic energy, can be altered by collective flow of the hot nuclear matter toward or away from the observing apparatus – the familiar Doppler effect. The flow of the matter also affects the correlations of the reaction products.

While these new techniques have to be applied more extensively before conclusions can be drawn about the flow of the matter in collisions at velocities below about half the speed of light, at higher velocities the flow becomes more pronounced and has therefore been thoroughly studied. The increased flow at higher energies is driven by the pressure arising from the compression and heating of the nuclear matter. The pattern of the flow can help determine this pressure, which is one of the most important properties of the matter (the rate at which the pressure increases with energy density determines how a neutron star can exist without collapsing into a black hole). However, this pattern also depends on how viscous the nuclear matter is, another interesting property in its own right. Thus, we see a feature typical of relativistic nuclear collisions: the outcome of a collision is sensitive to more than one unknown property of the matter (e.g., pressure and viscosity). The dual dependence of the correlations of reaction products on the flow as well as on the size of the system provides another illustration of this interdependence, which has made the interpretation of these collisions especially challenging.

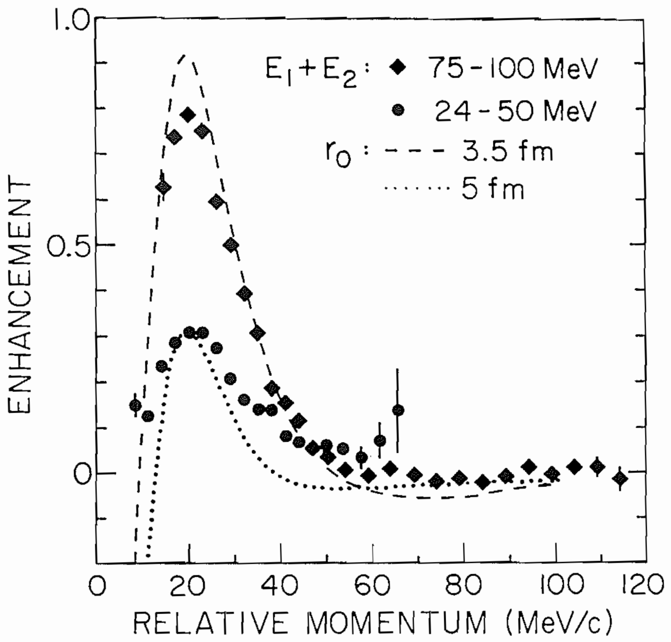

Figure 23: Measured two-proton correlation functions in intermediate-energy heavy-ion collisions provide information on the size of the reaction zone. Particles of different energies show different enhancements and thus appear to be emitted at different times from reaction zones of different sizes. This is consistent with the idea of an expanding reaction zone.

The Role of Pions in Hot, High-density Matter

Relativistic projectiles with nearly the speed of light seldom produce heavy fragments, which cannot survive the intense temperatures and are consequently broken up into their constituent nucleons. Additionally, these collisions produce large numbers of pions. The energy $m_\pi c^2$ needed to create these pions reduces the average kinetic energy of the nucleons. Because of this diversion of energy, the creation of pions cools the matter.

In a relativistic collision, as the hot nuclear matter expands and cools, some of the initially created pions are reabsorbed, releasing their energy as heat. These complex processes profoundly affect the observations of the collision products, from which many properties of the matter must be inferred. Since nuclear collisions are the only terrestrial source of information about hot, dense matter, they have to be used to deduce the matter's pressure, viscosity, heat capacity and conductivity, as well as how the nucleons and pions move in the matter and how pions are created and absorbed. Thus many observations have to be compared in order to sort out the unknown quantities.

Although great progress has been made in analyzing and interrelating the observations of the motion of hundreds of nucleons and pions at the end of the collision, firm conclusions have yet to be drawn. Hopes have been raised by the recent observation of certain electron-positron pairs thought to originate from the annihilation of pions. Because the pairs escape the hot matter undisturbed, they appear to carry key information on the properties of pions in hot, dense matter, where their strong interaction with nucleons makes pions move quite differently than they do in free space. Since the pions are central to the behavior of the hot nuclear matter, measurements of the pairs from their annihilation may help to interpret the puzzling traces of extreme temperature and density attained in relativistic nuclear collisions.

Future Goals

In the low-energy regime, the anticipated needs are covered by a range of accelerators that either exist or are currently under construction or being upgraded. A major impact is expected from new large-acceptance "4π" detectors able to register simultaneously γ rays and particles emerging in all directions from the target. The impact of these new detectors will be especially significant when they are combined with each other and with specialized equipment such as fragment separators or magnetic spectrometers. Such instruments, applied to reactions initiated by new high-intensity, high-resolution beams, will allow the outstanding questions in the low-energy regime to be addressed with the necessary efficiency and precision.

Systematic studies will further our understanding of sub-barrier reaction rates, dissipative collisions, and compound nuclei at the extremes of excitation energy and angular momentum. We still have only fragmentary understanding of the problems associated with quantum tunneling in systems with many degrees of freedom. There are major gaps in our knowledge of dissipative and diffusion reaction mechanisms, especially with regard to their sensitivity to nuclear shapes and to quantal effects. We also have only the first crude knowledge of the properties of hot nuclei, such as the rates at which they decay by evaporation and fission, their equilibrium shapes as a function of rotation, and the maximum temperatures they can sustain.

At intermediate energies, we have yet to establish the most rudimentary facts about how the colliding nuclear system evolves in time and space: how the kinetic energy of the projectile is turned into heat; how many nucleons escape and how many are stopped to generate heat; how the observed clusters form, and so on. These questions must be addressed by comprehensive experiments, often requiring large and specialized apparatus, before we will be able to deduce the properties of hot nuclear matter or to decide whether the mixed liquid-gas phase is actually formed. To separate effects of bulk nuclear matter from the influence of surfaces, experiments have to compare collisions of heavy and light nuclei. Similarly, the way observations change with the projectile's energy should provide clues to the presence of any phase transitions that may occur.

The general features of relativistic collisions are better established than those at intermediate energies, but promising new techniques such as measuring lepton-pair production will require further extensive experimentation before they can be fully exploited as a probe – the tell-tale pairs are produced in less than one percent of the collisions.

The above scientific questions are currently being addressed by a range of U.S. facilities. Since the most interesting questions still have to be answered, new discoveries are almost certain. International interest is demonstrated by the existence of major new facilities in France and Germany. The development of new techniques and experimental facilities by U.S. scientists will be essential for us to remain in the forefront of this field.

II.7 Confined and Deconfined Phases of Nuclear Matter

Introduction

The vitality of nuclear physics in the 1990s requires the simultaneous aggressive pursuit of (1) precise measurements aimed at refining our detailed understanding of hadronic structure and the many-body physics in nuclei, and (2) exploratory studies aimed at uncovering new dynamical phenomena of fundamental significance. The purpose of the first is to deepen and broaden the basic foundations of nuclear physics. The purpose of the second is to expand its frontiers into new and uncharted territory. The Standard Model, encompassing what is presently known about strong and electroweak interactions, provides a solid basis from which exciting and promising areas for future research can be identified.

The most outstanding prediction based on the theory of the strong interaction, QCD, is that the properties of matter should undergo a profound and fundamental change at an energy density only about one order of magnitude higher than that found in the center of ordinary nuclei. This change is expected to involve a transition from the confined phase of QCD, in which the degrees of freedom are the familiar nucleons and mesons and in which a quark is able to move around only inside its parent nucleon, to a new deconfined phase, called the quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume.

This prediction is of special interest because it provides the opportunity to study an entirely new form of matter. In the universe such matter may have existed only during the first millionth of a second after the Big Bang. It may also exist deep inside the cores of neutron stars. Verification of its existence and determination of its properties will provide a glimpse into that primordial form of matter.

The major force driving us toward this new frontier of research has come from the realization that extreme energy densities are generated experimentally during the collision of nuclei at very high energy. These extreme conditions are generated over regions of space and time much larger than the fundamental scale, $\Lambda_{QCD}^{-1} \approx 1$ fm, of QCD. Experiments with ultrarelativistic nuclear collisions thus provide a unique means for studying matter in the laboratory under unprecedented conditions of energy and baryon densities.

The extreme conditions of matter required to explore the physics associated with the deconfinement transition should be well within the range of conditions accessible with nuclear collisions at energies on the order of $100{\cdot}A$ GeV in the center of mass (CM). The Relativistic Heavy Ion Collider, RHIC, designed at Brookhaven National Laboratory in response to the 1983 Long Range Plan recommendations, is in an advanced stage of planning and readiness. This collider will accelerate and collide nuclei of masses spanning the entire periodic table and will extend the range of available center-of-mass energies by more than an order of magnitude. RHIC is fully capable of addressing the wide range of research opportunities in this area well into the next century.

Experiments at RHIC will also provide new information for understanding problems of astrophysics and cosmology. Studying ultrarelativistic heavy ion-collisions in which matter at very high density is formed could provide new insights into the behavior of the very dense matter forming neutron stars, which themselves are formed in the violent collapse of a star at the end of its life. Since all heavy elements in the universe are presumably formed in such collapses, the knowledge of the properties of nuclear matter at high densities is crucial to our understanding of the origin of the universe. Collisions of nuclei at the highest energies attainable at RHIC will produce matter at very high temperature and with approximately equal numbers of quarks and antiquarks. Such matter approximates that which presumably existed a few microseconds after the Big Bang, as the cooling and expanding cosmos condensed from a state consisting of quarks to one of hadrons. Experimental investigations of such collisions will therefore shed light on the very early stages of the evolution of our universe. Indeed, if the transition from quarks to hadrons is a first-order phase transition, as suggested by theory, a large latent heat is released as the transition is passed, and large density fluctuations may result. This would have strongly affected the primordial nucleosynthesis of light elements.

Advances in Theory

Since the 1983 LRP, there have been major advances in theory giving strong support for the above expectations. Significant progress has been made, notably in the areas of: (1) calculating the properties of very dense matter using QCD, (2) formulating dynamical models for the collisions of heavy nuclei, and (3) identifying likely observables that probe the properties of dense matter. These advances, together with the successful preliminary experiments at intermediate fixed-target energies (CM energies of the order of $10 \cdot A$ GeV) at the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS), as described in the next section, reaffirm and underscore the scientific validity and experimental feasibility of the proposed explorations at RHIC.

Calculations using QCD at the low energies appropriate to understanding the transition from confined to deconfined quarks necessarily involve applying the theory where the interactions it describes are strong and not amenable to treatment using the usual perturbation methods for studying field theories. This is usually dealt with for QCD by formulating the equations not in the usual terms of continuous space and time coordinates, but rather in terms of a discrete "lattice" of space-time coordinates. This makes it possible to obtain convergent results for calculations. At the time of the 1983 LRP, calculations using such lattice QCD approaches had only included gluons, the force carriers of QCD, and had been done for quite small lattices. Since then, quarks have been included, and lattices with a thousand times the volume have been used. Inclusion of quarks in the calculations leads to a *lowering* of the critical temperature, from $T_c \approx 200$ MeV to $T_c \approx 150$ MeV, at which the phase transition to a quark-gluon plasma is expected. New algorithms have been developed very recently that pave the way for eventual lattice calculations with a very large number of quarks.

The theoretical phase diagram of bulk nuclear matter is illustrated in Figure 24. It is the same as in the 1983 LRP; its experimental exploration remains a foremost challenge of nuclear physics. Investigations of nuclear systems at about twice normal density using the Bevalac accelerator at LBL uncovered, in 1984, evidence that the matter under these conditions could move in a coherent manner similar to a hydrodynamic flow. Ongoing and planned high-precision measurements of such collective flow phenomena are expected to provide the data necessary to constrain the description of nuclear matter at up to several times the density in the center of a heavy nucleus and up to temperatures of ~ 100 MeV. Studies at low energies of the disassembly of excited nuclei into many small fragments, at MSU and elsewhere, will shed light on the properties of nuclear matter at low density (see Section 6). At higher energies, the first explorations near the deconfinement boundaries have been initiated at the AGS and the SPS with light nuclear projectiles (see discussion below). Studies that reach well into the plasma domain await, however, the much higher energies of RHIC.

Calculations with several theoretical models have been performed to estimate how such nuclear collisions may evolve with time. Models that treat the nuclear matter in these collisions by using the equations of relativistic hydrodynamics have mapped out how collective flow behavior may influence the momentum distributions of the hadrons produced. The most important finding is that a characteristic signature of a first-order confinement transition is that it is slow and involves a large change in volume. Because the transition to a quark-gluon plasma is expected to be first-order, experimental measurements of the volume of the final state produced are important.

A second class of models treats the individual collisions of quarks by supposing that, as the result of such a collision between two quarks, a potential-energy "string" is formed between them. The energy stored in the color field described by this string derives from the initial kinetic energies of the quarks. Late in the collision, the energy stored in the string is converted into particles carrying kinetic energy. These models are applied to nuclei by superimposing the strings formed in many collisions of many quarks. They extend the known phenomenology of e^+e^- and pp collisions to nuclear

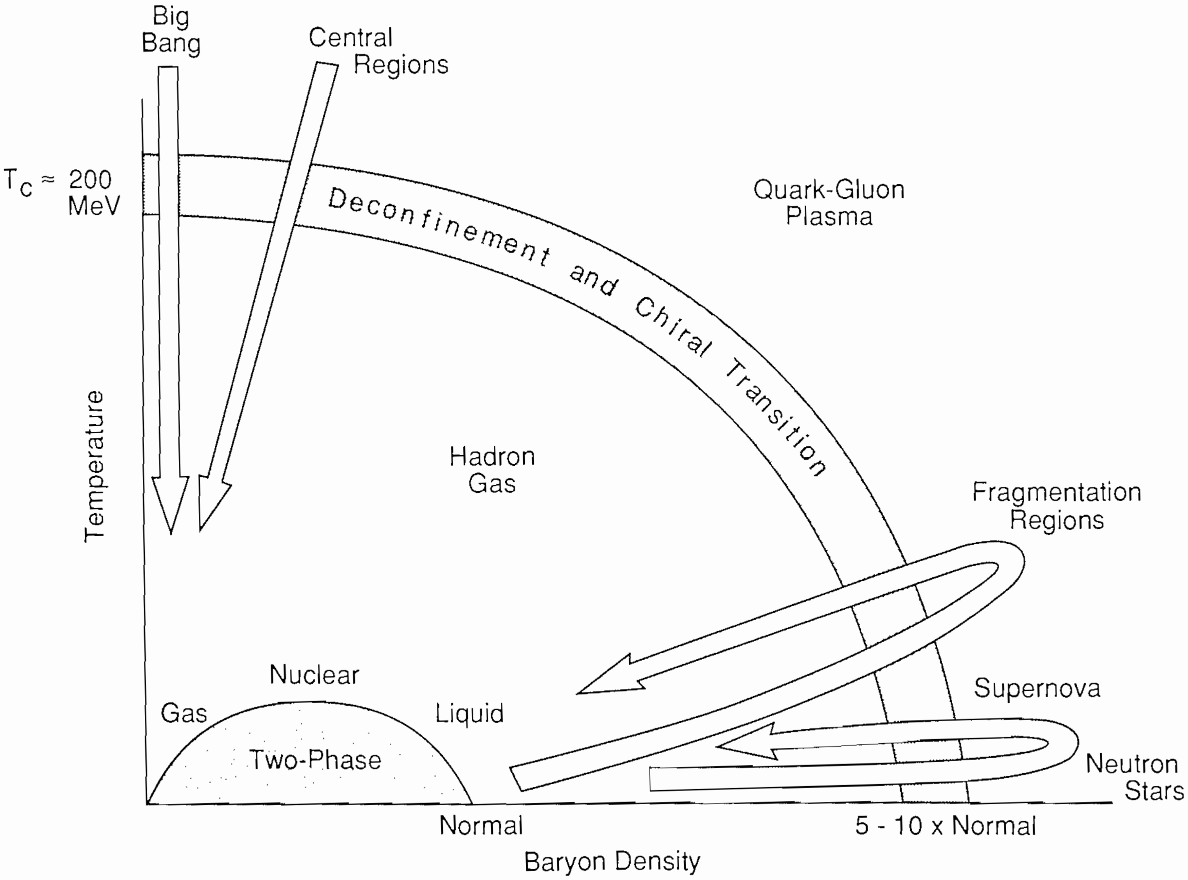

Figure 24: Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase," including a gas-liquid phase-transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultrarelativistic heavy-ion collisions.

collisions. They also provide an important baseline from which new observations can be evaluated. Deviations of new data from predictions based on such models can be used to identify observables most likely to reflect new physics. The development of several independent extrapolation models along these lines allows us to calibrate the theoretical uncertainties associated with "conventional" hadronic physics. Current efforts in developing such models to include initial- and final-state interactions are closely coupled to the ongoing AGS and SPS experiments and will provide essential tools for planning and evaluating future experiments at RHIC energies.

Additional theoretical motivation for exploring nuclear collisions at the highest possible energies has been provided by new calculations of particle production by hard-scattering processes. At RHIC energies ($(100+100)A$ GeV in the CM frame), the number of quarks and gluons that can participate in hard collisions is so large that the resulting increase in the number of energetic secondary particles produced yields a doubling of the already large energy density expected from calculations using the models noted above. Therefore, these processes may lead to energy densities $\sim$ 100 times greater than those in ordinary nuclei. This represents an order of magnitude increase over the energy densities expected with the highest SPS energies, where such hard-scattering processes add little to the energy density created. The investigation of these hard-scattering processes makes use of the information gathered over the last few years concerning the behavior of quarks in nuclei. The modifications to the behavior of quarks when their parent nucleons are themselves contained in nuclei, and the relevant experimental measurements, are discussed in Section 3. This information is vital not only for estimating the expected energy-density increase but also for understanding the expected behavior under "normal" circumstances, of several of the probes of dense matter mentioned below.

A comprehensive picture of useful experimental probes for these new states of matter has emerged over the past several years. These can be broken down into three broad categories, as follows.

Global Event Parameters

These can be deduced by measuring the momenta of produced particles and by looking at how close those particles are to one another in momentum. The former is an indicator of the temperature, while information from the latter can be transformed into information on the spatial and temporal extension and on the density of the emitting system.

Indicators of a Phase Transition

The heavy vector mesons, J/ψ and ψ' and the upsilon states, are composed of heavy quarks and antiquarks. In normal collisions, these quark-antiquark pairs are produced and then separate to a distance characteristic of the size of the final meson state, thus forming the meson. In a quark-gluon plasma, the members of the pair lose contact owing to the presence of all the other free quarks and gluons: the final mesons are formed only rarely. This results in a measurable decrease, or "suppression", of the number of such vector mesons produced if a quark-gluon plasma is formed, relative to the number produced in a normal reaction. Such studies depend upon the input from studies of J/ψ, ψ' and upsilon production in high-energy p-A collisions (see Section 3) for an understanding of apparent suppression effects due instead to absorption in nuclear matter or changes to the behavior of gluons when they are in nuclei.

The establishment of chemical equilibrium in a hot plasma will result in the creation of a large number of $s\bar{s}$ quark-antiquark pairs because the mass of the strange quark is similar to the deconfinement temperature. It is then energetically favorable to create strange quark-antiquark pairs. This will greatly enhance the number of strange baryons, or hyperons, such as Λ and $\bar{\Lambda}$, and strange mesons, such as K^+ and K^-, that are produced. There will also be a "distillation" of strangeness in baryon-rich regions due to the excess in those regions of u and d quarks over their respective antiquarks: an $\bar{s}$ quark will much more easily find a u quark to form a K^+ meson, which then escapes, than will its corresponding s quark find a $\bar{u}$ quark to form a K^- meson.

Direct Information from the Plasma

Leptons (electrons and muons, for example) and photons do not experience the strong interaction. Therefore, those produced in the collision of relativistic nuclei will emerge from the interaction region nearly unaffected by their passage through the dense nuclear matter formed in the interaction region. They therefore carry information about the conditions at their point of formation. This information is contained in their momentum spectra, which are related to the temperature; in their abundance, which is related quadratically to the number of objects present; and in their direction, which is related to the degree of thermalization of the strongly interacting system. Such measurements are under way at the Bevalac using the Di-Lepton Spectrometer where for example the properties of pions created in hot nuclei will be studied.

One can also measure the propagation of energetic quarks and gluons themselves through dense matter. In contrast to leptons and photons, the propagation of these is greatly affected by the density of the strongly interacting matter that they must traverse. These energetic quarks and gluons usually appear in experiments as two diametrically opposed jets of energetic hadrons. The presence of dense hadronic matter will distort this pattern: one jet is likely to be smeared out in solid angle to the point of being not detectable above the "background" of the rest of the produced hadrons. An understanding of how such jets propagate in normal nuclear matter and turn into the observed hadrons is required to interpret the above results. The necessary data are best obtained in hadron-production experiments using electron beams such as are available in high-energy storage rings, or will be available at CEBAF.

Understanding the particulars of these various probes and the contributions of background processes that can mimic the expected signatures will form a central part of the theoretical effort in this area over the next several years. It is expected that a quark-gluon plasma will manifest itself in the behavior of most of the above probes, giving a strong discriminant against alternative explanations of observed phenomena.

Advances in Experiment

Major advances in the design, construction, and operation of experiments with ultrarelativistic nuclear collisions have been made in the past several years. Three large experiments at the AGS and six at the SPS have been brought into operation. Beams of light ions (O, Si, and S) have been accelerated successfully at the AGS and SPS. A key set of measurements has revealed a number of interesting phenomena. These experiments explore the intermediate center-of-mass energy range of 3-10A GeV. They are important forerunners of future experiments with heavier nuclei and higher energies. First results confirm the assumptions made in the 1983 Long Range Plan about extremes of energy densities, which formed the basis for the recommendation for constructing a relativistic heavy-ion collider. In addition, new detector concepts needed to deal with reactions that produce hundreds to thousands of particles, were tested in these experiments. Related concepts are being developed to deal with the lower, but still large, multiplicities of secondary particles involved in heavy-ion reactions at bombarding energies of several tens of MeV to a few GeV, as noted in Section 6.

Measurements made to date are of two major types. First, there are systematic global measurements of observables, such as the multiplicity of produced particles and the angular distribution of the total energy carried by those particles (the so-called transverse energy which is just a particle's energy multiplied by the sine of its angle with respect to the beam direction). From these measurements one can estimate the entropy and initial energy density. Second, there are measurements of specific observables that probe different aspects of the dynamics. A sample of the extensive data on transverse energy distributions is shown in Fig. 25. The transverse energy is a measure of the efficiency

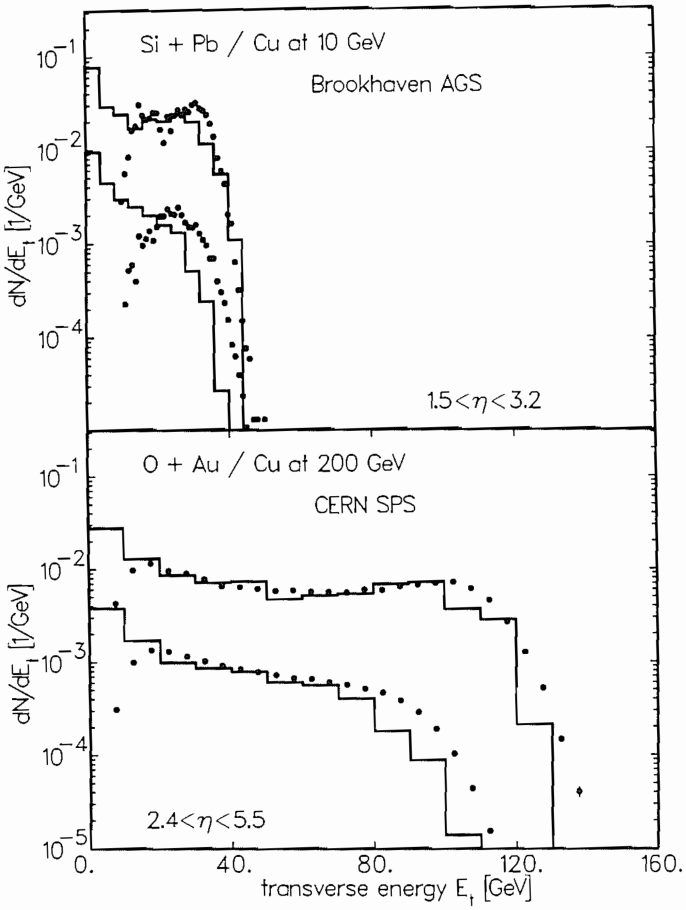

Figure 25: Transverse energy production in high energy heavy-ion collisions into various regions of space defined by the indicated pseudo-rapidity (η) intervals. Pseudorapidity is a logarithmic measure of angle which is convenient to use with relativistic particles. The points are measured data, and the histograms show the results of a Monte Carlo calculation based on interacting color strings. The data were taken with a beam of silicon ions at E/A = 10 GeV at the Brookhaven AGS and with oxygen ions at E/A = 200 GeV at the CERN SPS. In each case the results are shown for two different target nuclei.

of the reaction for converting the kinetic energy of the beam nuclei into random motion transverse to the beam axis. At RHIC energies, transverse energy production is proportional to the energy density initially reached in the collision. Based on data as in Fig. 25 it is estimated that energy densities of 1 GeV/fm^3 or higher were created in nuclear collisions at top SPS energies. At such high energies, the approaching nuclei are much more strongly compressed in the direction of their motion – a consequence of the theory of special relativity – and this should lead to a considerable further increase in the energy density. The overall agreement of string-model calculations with the trends of the measured transverse energies in Fig. 25 indicates that the basic elements of high-energy nuclear dynamics are under control and gives additional confidence in the conservative extrapolations to RHIC energies, where energy densities of at least 20 times, if not 100 times, that in the core of a heavy nucleus are expected. Such energy densities considerably exceed the best estimate of about 2 GeV/fm^3 needed for plasma formation.

In the second category of measurements, several studies have revealed particularly striking new phenomena. We highlight here only three of the most interesting findings that have generated the most debate and theoretical scrutiny. Those data are shown in Fig. 26. A high abundance of strangeness, a suppression of heavy vector mesons such as J/ψ, and a very large decoupling volume are three of the characteristic signatures expected from the production of a quark-gluon plasma state. Figure 26 reveals that all three effects are present to some extent at AGS and SPS energies. The interpretation of these data is still under active debate. A coherent picture of possible background processes is beginning to emerge. For example, associated $K + \Lambda$ production in final-state rescattering of nonstrange mesons with baryons must be taken into account in the interpretation of the K/π ratio. The momentum spectra for J/ψ production must be corrected for the dissociation reactions the J/ψ suffer as they traverse dense hadronic matter. Similarly, the large decoupling radii determined via pion interferometry must be corrected for the decay of long lived resonances. It is the deviation from the trends arising from such background processes that must be looked for in future experiments.

In the next several years, it will be essential to continue an intensive experimental effort at the AGS and SPS to lay the proper foundation for future studies with RHIC. There are still many elements of the basic reaction mechanism that need clarification. For example, the momentum distribution of the nucleons emerging from the collision needs to be determined to test our understanding of the nuclear stopping process. Reactions with the heaviest nuclei in this energy domain will be of fundamental interest for probing the right hand side of the phase diagram and extending the knowledge gained from lower-energy studies at the Bevalac. Detailed measurements of electromagnetic probes, particle spectra, and abundances, especially long-lived resonances such as ω and ϕ, are essential. Finally, it will be important to carry out searches for long-lived strange quark-matter droplets and other possible exotic states, such as the double-strange H particles, that may be produced in the novel conditions of ultrarelativistic nuclear collisions. In order to address these issues, gold beams will be made available at the AGS, and plans have been made to accelerate lead beams at the SPS. Major upgrades to existing experiments and new large experiments are being designed to utilize these heavy beams. These experiments will offer a first view of very dense matter in truly large systems and are essential for the continuation of the present intellectual vitality of the field.

The main thrust of the experimental program at RHIC will be to study the properties of ultradense matter, with detection and study of the quark-gluon plasma as the centerpiece. To this end, the design, development, and construction of detectors for use at RHIC need to be pursued vigorously over the period prior to operation of RHIC. An active program of detector workshops has been carried out over the past 5 years and has resulted in the initiation of a program of detector R&D aimed at mastering the difficult techniques needed for experimentation at RHIC.

Besides the main thrust of RHIC to probe ultradense matter, opportunities will arise to perform interesting experiments of a complementary nature. For example, utilizing the versatile capabilities of RHIC to collide protons with nuclei, experiments

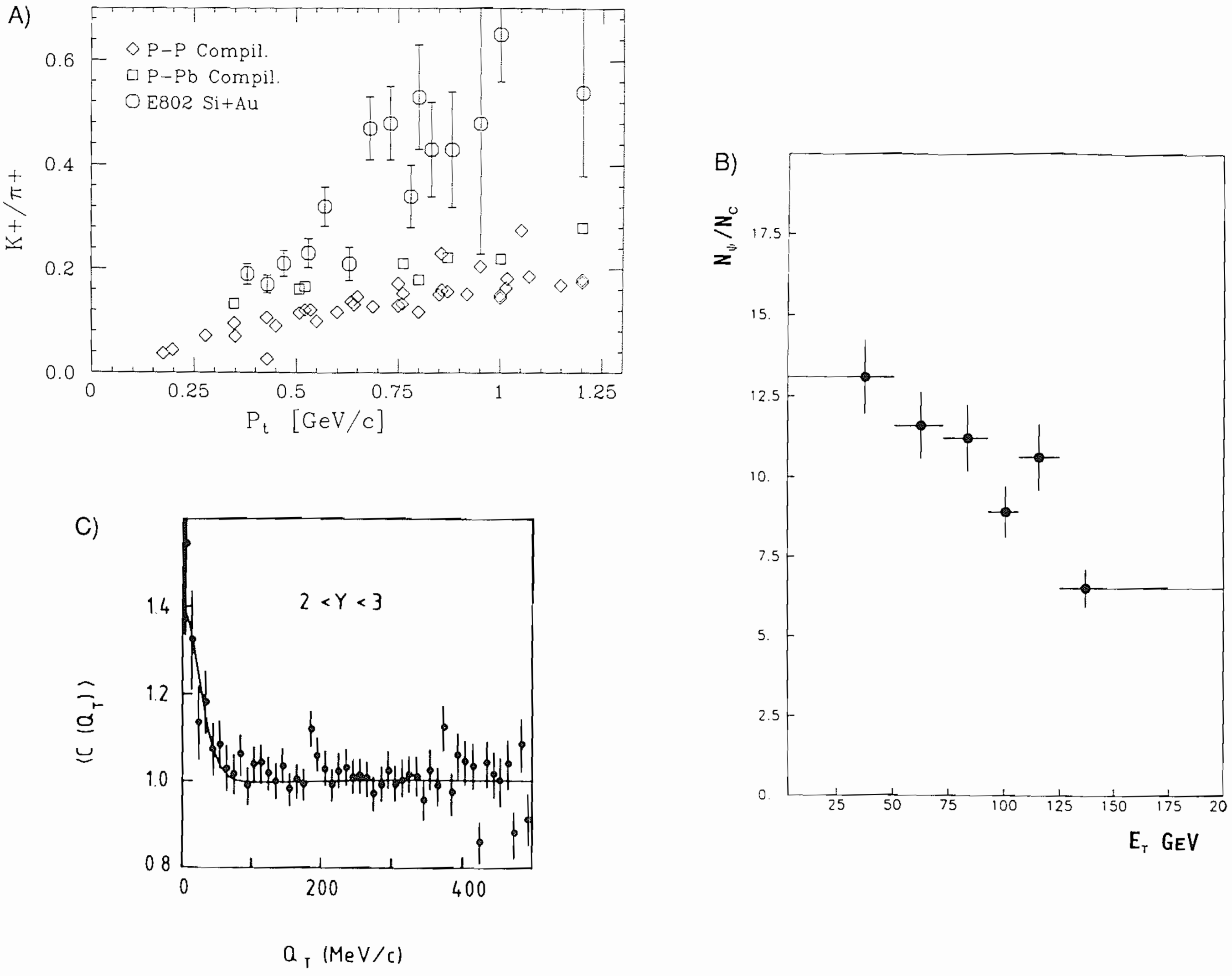

Figure 26: Some measurements of specific observables in which new phenomena may be in evidence in high-energy nucleus-nucleus collisions:

(A) Data from the E802 spectrometer at the Brookhaven AGS, showing the ratio of K^+ to π^+ meson production as a function of transverse momentum in ^{28}Si+Au collisions at $E/A = 14.5$ GeV. The production of strange mesons is enhanced in these collisions when compared with the results from proton-proton and proton-Pb collisions at similar energies.

(B) Data from the muon-pair measurements of the NA38 collaboration, showing the suppression of J/ψ mesons in collisions of large transverse energy for $E/A =$ 200-GeV ^{16}O+U interactions. Here $N_{J/\psi}$ is the number of J/ψ mesons observed for a given transverse energy interval, and N_c is the number of muon pairs seen in the continuum spectrum that underlies the J/ψ resonance peak.

(C) Data from the streamer chamber measurements of the NA35 collaboration at the CERN SPS, showing the correlation function at small relative momenta for pairs of negatively charged particles (mostly pions) produced in ^{16}O+Au collisions at $E/A = 200$ GeV. The abscissa is the relative momentum in the direction transverse to the beam. The data are for particles produced nearly at rest in the appropriate center-of-mass system, as indicated by the particle rapidities y. Rapidity is a convenient logarithmic measure of particle velocity, and y= 2.4 corresponds to a particle at rest in the center of mass. The observed peak arises from an interference effect among identical bosons (pions in this case) produced in each collision. The widths of such peaks give a rather accurate measure of the space-time volume from which the observed particles are radiating.

can be done that take advantage of the very large center-of-mass energy available in a collider to study those gluons and quarks that carry a small fraction of the momentum in a nucleon embedded in a nucleus. In addition, with the use of internal targets, experiments utilizing proton beams in the (fixed-target) energy range of 25-250 GeV and with luminosities in excess of 10^{32} cm^{-2} sec^{-1} could provide an attractive means for probing the distribution of quarks in nuclei that carry a larger fraction of the momentum.

Collisions of heavy ions at RHIC also offer the possibility to study exotic states of nuclear matter. Owing to the extremely high multiplicity of secondary particles produced in ultrarelativistic heavy-ion collisions, it is possible that heavy antinuclei and nuclei carrying several units of strangeness may be created. RHIC would also offer a unique environment for the generation of collective hadronic modes, such as pion condensates or kaon condensates, due to the very large number of these mesons that are produced and the consequent high probability of geometrical overlap.

Summary

Beyond the mid-1990s RHIC will provide the unique facility to probe matter at the highest energy densities accessible in the laboratory. A new kinematic regime will then become available for study in which the hot, dense matter produced in the most violent collisions is essentially baryon-free, i.e., is composed of about equal numbers of quarks and antiquarks, when nuclei are collided at these energies. It is in these collisions that we can explore, with precise and detailed measurements, states of nuclear matter that approximate the conditions of the early universe. It is for these collisions that the behavior of the hot nuclear matter formed can be compared most directly with thermodynamic calculations based on QCD. Here too, the elementary collision energies are high enough that hard-scattering processes occur with a sufficient cross section to allow experimental contact with the predictions of perturbative QCD. With a full range of nuclear beams, a large kinematic lever arm, and sufficient luminosity for the most sensitive experiments, a very wide range of phenomena will be investigated by many experiments operating simultaneously in a dedicated facility. The unprecedented opportunities for new discoveries have attracted a large international community since 1983 and continue to provide the compelling motivation for identifying RHIC as essential for the long range vitality of nuclear science in the United States.

II.8 Precision Tests of Fundamental Interactions

Introduction

The nucleus has been a wellspring of information on the fundamental symmetries of nature. In the past three decades, studies of nuclear beta decay showed that the weak interaction maximally violates reflection symmetry, demonstrated the vector-axial-vector character of the weak-interaction current, and provided the best evidence for conserved vector currents. These observations formed the experimental foundation for the unification of the weak and electromagnetic interactions into the electroweak theory. Today the nucleus continues to serve as a laboratory for testing the Standard Model of the weak, electromagnetic, and strong interactions and for probing for new physics beyond it.

The nuclear physicists who study fundamental interactions belong to a vital branch of our science. Although united by a common set of physics goals, they pursue their research with a diverse set of experiments, ranging from table-top activities to extensive setups at the largest accelerator laboratories. Consequently, this field is not uniquely related to any specific facility. This diversity of approach produces results that are frequently of interest to the entire physics community.

The Minimal Standard Model

Our present description of the fundamental particles and their electroweak and strong interactions is the Minimal Standard Model (MSM). This beautifully simple model assumes neutrinos to be massless, the numbers of baryons and leptons to be conserved, charged currents to be composed only of vector and axial-vector components, a universal coupling of the e, μ and τ leptons, and only three generations of quarks and leptons. The model incorporates the violation of CP symmetry with a single parameter. Here, CP represents the combined effect of charge conjugation C (replacing a particle by its antiparticle), and the parity operation P (spatial reflection).

We have yet to find a flaw in the MSM, and it has recently again proven itself dramatically by explaining a large number of new results obtained at the giant LEP and SLC accelerators from the decay of the Z bosons, one of the carriers of the weak force. However, we are confident that it is incomplete because so many of its parameters take on apparently arbitrary values. The measurements performed in recent years make it evident that any deviations from this model must reflect effects that originate at extremely large mass scales. The inherent interest in the accurate and sensitive tests of the MSM discussed below arises from their sensitivity to new physics at mass scales beyond the direct reach of existing or planned accelerators.

Extra Generations

The three quark families of the MSM are mixed in a way that is characterized by the Kobayashi-Maskawa (KM) matrix. New levels of accuracy, now sufficient to examine the unitarity of the KM matrix and impose strong constraints on contributions from possible fourth and higher generations, have been obtained in measurements of neutron and muon weak decays and in measurements and calculations of superallowed nuclear beta decays.

CP Violation

The KM mixing matrix can accommodate CP violation within the three-generation Standard Model by means of an otherwise undetermined phase. In addition, a second CP-violating phase is introduced by QCD. The magnitude and form of CP violation are therefore constrained, but not explained, within the MSM. Measurements of the neutron electric dipole moment in the past two years at the Institute Laue-Langevin in France and at the Gatchina reactor in the Soviet Union have reached a sensitivity of 10^{-25} e-cm, still well above the level associated with the KM phase but sufficient to rule out a number of otherwise promising alternatives. In particular, these measurements place the best limit on the CP-violating phase ($\leq 10^{-10}$) introduced by QCD. A recent measurement of the CP-violating parameters in neutral kaon decays at CERN is consistent with the MSM prediction. However, this result has yet to be confirmed. The sensitivity achieved in these experiments has now reached the level where new insight might be obtained on the origin of CP violation. Anticipated improvements of factors of 10 in the neutron electric dipole moment and factors of 100 in atomic electric dipole moments, new searches for time-reversal violation in neutron resonances in heavy nuclei, as well as improved measurements of correlation coefficients in beta decay, could further constrain possible models for CP violation.

Lepton Mixing

The mixing that we observe among the quark families strongly suggests that the leptons may also mix at some level. The prototype experimental studies of lepton mixing are the search for the decay $\mu \rightarrow e + \gamma$ and $\mu \rightarrow e$ conversion in the field of the nucleus. Limits on the branching ratios for both processes are about 10^{-11}. Major new efforts to search for $\mu \rightarrow e + \gamma$ (MEGA at LAMPF) and $\mu \rightarrow e$ conversion (at PSI in Switzerland) will extend the branching ratios for rare muon decays by several orders of magnitude.

Ongoing experiments on rare kaon decays at BNL, Fermilab, and KEK (in Japan) have made great progress and are also becoming sensitive to branching ratios of about 10^{-11}. Some of these decays are completely forbidden by the MSM, while others are sensitive to higher-order contributions within it. At the 10^{-11} level, experiments are at the threshold of sensitivity to probe top-quark properties (mass and couplings) and direct CP-violating amplitudes. To go beyond this threshold and to explore possible new mass scales greater than 100 TeV requires the statistical improvements offered by a high-intensity kaon factory. A nonzero result in any of the forbidden kaon or muon transitions would be of enormous significance, demonstrating that new interactions or new particles exist outside of the MSM.

Neutrino Mass, Oscillations, and Couplings

The MSM is constructed in a way that does not permit neutrinos to have mass. However, as no fundamental requirement for massless neutrinos appears to exist, evidence for nonzero masses has been aggressively sought through direct kinematic measurements, the search for changes of one neutrino species into another ("neutrino oscillations"), and neutrinoless double β decay. Discovery of neutrino mass would be a clear signal that the MSM is incomplete.

In the past decade, limits on lifetimes for neutrinoless double β decay have been extended by two orders of magnitude, with no evidence as yet for this decay mode. With significant improvements in the sensitivity obtained in these experiments, two-neutrino double β decay, a second-order process allowed in the MSM, has recently been observed for the first time in the laboratory. The measured lifetime of ^{82}Se, 1.1×10^{20} years, is in agreement with theory and with geochemical observations. Large-scale theoretical nuclear structure calculations play an important role here. The experiment at the University of California at Irvine required the development of a time-projection chamber fabricated of ultrapure materials. An example of a double β decay event is shown in Fig. 27, along with the measured electron energy spectrum. A new generation of double beta decay experiments is beginning that will use large quantities of enriched isotopes, such as ^{76}Ge, ^{100}Mo, and ^{136}Xe. These new detectors will extend the sensitivity to neutrinoless decays by a factor of 100, thereby probing Majorana neutrino masses to about 0.1 eV.

Several earlier indications of neutrino oscillations (with the exception of the durable solar neutrino problem) have now been conclusively refuted by new measurements. A recent important theoretical discovery has been the demonstration that flavor oscillations of solar neutrinos can be greatly enhanced by scattering from solar electrons. Solar neutrino experiments, such as SAGE (Soviet-American Gallium Experiment), GALLEX (European Gallium Experiment), and SNO (Sudbury Neutrino Observatory), are very sensitive probes of neutrino masses and mixing angles, and may establish whether or not neutrino oscillations are responsible for the solar neutrino problem. In the near future, terrestrial studies of neutrino oscillations could produce new results complementing those expected from the solar neutrino experiments. Feasibility studies are under way for a 1-kiloton scintillation detector for neutrinos, to be sited about 10 km from an existing reactor. Such a detector could provide sensitivity to neutrino oscillations at relatively large mixing angles for the entire range

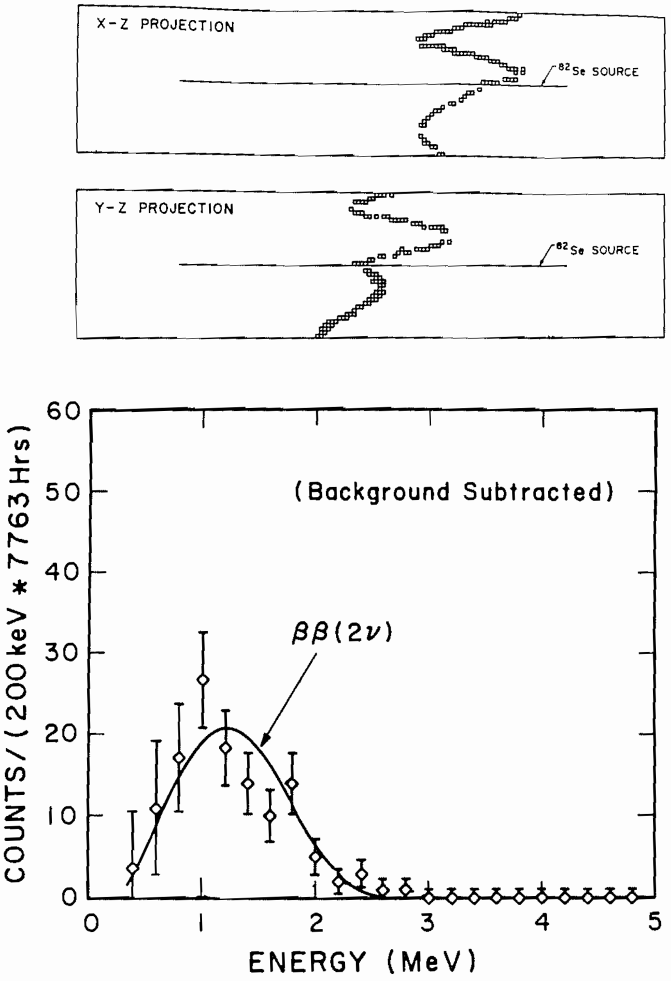

Figure 27: (Top) A candidate double-β-decay event in ^{82}Se, originating in the source (the line crossing the center). Two electrons can be seen spiraling away in the vertical magnetic field in two views.
(Bottom) The background-subtracted electron energy spectrum compared with theory.

of neutrino masses between existing limits and the region to be studied by the solar neutrino detectors.

Neutrino flavor oscillations can occur if neutrinos have mass and if lepton family number is violated. If, however, lepton number is well conserved, a finite neutrino mass can only be observed in direct kinematic searches. The direct upper limits on the masses of the μ and τ neutrinos have steadily fallen, but there are conflicting claims made regarding an electron neutrino mass of about 30 eV. A new measurement will shortly reach a sensitivity of 10 eV or less.

An important confirmation of the MSM was provided by an electron-neutrino electron ($\nu_e - e$) scattering experiment at LAMPF. The predicted destructive interference between the charged and neutral weak currents of the MSM was clearly observed (see Fig. 28). This additional exchange coupling for the electron neutrino when scattering from electrons is what gives rise to the enhanced neutrino oscillation in matter. A precise determination of the main parameter of the MSM, the mixing angle θ_W, can be provided by a comparison of muon and electron neutrino scattering from electrons using the proposed Large Cerenkov Detector (LCD) at LAMPF. This result, together with precise measurements at higher energies, provides an accurate determination of radiative corrections to θ_W, which are sensitive to the masses of the postulated Higgs particle and the top quark. Finally, we note that the development of detectors sensitive to the neutral-current interactions of supernova neutrinos could yield much-improved limits on the μ and τ neutrino masses following the next stellar collapse within our galaxy.

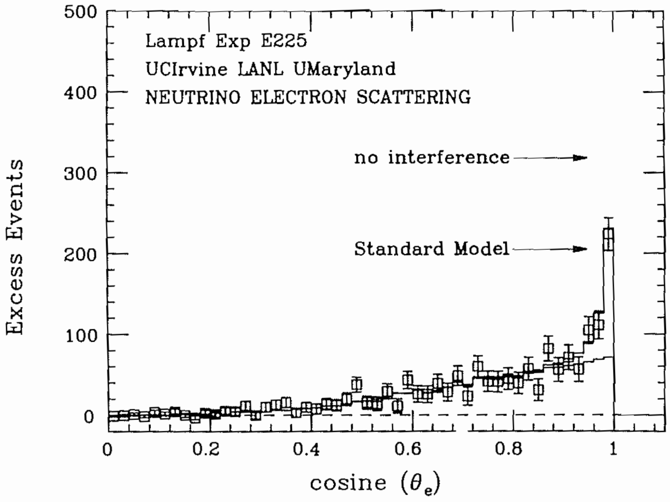

Figure 28: Excess events (cosmic-ray events subtracted) observed as a function of scattering angle between the observed electron direction and the neutrino source. The ν_e electron peak is contained in the sharp peak at the right. The broader distribution is due to $\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$, the first direct observation of a neutrino-nucleus process.

Parity Violation

Parity violation is a well-established ingredient of the weak interaction mediated by the W and Z bosons. Recent experiments at Bates have measured parity violation in the scattering of polarized electrons from ^{12}C. This result is sensitive both to θ_W and the presence of strange quarks in the nucleus. Because the strong and electromagnetic forces conserve parity, hadronic parity violation is a signature of the action of the weak force between nucleons. It therefore probes hadronic dynamics at very short range and allows the investigation of the structure of nucleons and mesons within nuclear matter. Nuclear parity-violation measurements have reached impressive levels of sensitivity, observing effects that are 10^{-7} times smaller than allowed processes, in polarized proton scattering from hydrogen. There is good agreement between calculations and experiments at low energy, but problems persist in understanding experimental results at higher energies. A surprising development in the last few years is the discovery that the isospin-changing $\Delta I = 1$ neutral-current parity-violation enhancement in nuclei is much smaller than expected and has yet to be observed.

Fundamental Issues Outside of the MSM

Positron Lines

An experimental observation whose significance is not yet clear is the discovery in heavy-ion experiments of a source of electron-positron pairs with sharply defined kinetic energies. At least three such lines have been found. They appear to have properties largely independent of the details of the colliding pair of nuclei. Although the discovery was made more than eight years ago and has stimulated considerable experimental and theoretical effort, the source of the sharp lines remains unknown. Some features of the data are consistent with the decay of neutral particles produced almost at rest in the center of mass, but the absence of corresponding resonances in the e^+-e^- cross section and the lack of any discrepancy in the anomalous moment of the electron beyond the QED prediction are very puzzling. Ten-fold improvements in experimental sensitivity are feasible both in the heavy-ion and e^+-e^- experiments, and new initiatives are under way at several laboratories.

Forces of Macroscopic Range

The possible existence of non-Newtonian gravitational couplings has stimulated a number of beautiful measurements (carried out generally by nuclear and particle physicists), resulting in an improvement in the limits on such couplings by a factor of 300. The idea that such forces might exist, stimulated by a reanalysis of the celebrated Eotvos experiment, remains an important and exciting field of investigation, although a force of the size and range originally suggested has been conclusively ruled out. These experiments have already proved to be important tests of conventional theories of gravitation by surpassing the sensitivity of Dicke's classic equivalence-principle test.

Evolution and Future Needs of the Field

This field is distinctive in its use of a wide variety of techniques and facilities, often combined with those from other fields. As a result, recent years have seen the development of completely new areas of investigation, such as e^+-e^- resonances, non-Newtonian gravitational couplings, and tests of time-reversal invariance by neutron scattering. There is, as well, a tradition of healthy interaction between experimentalists and theorists, which has promoted important new theoretical work in testing the unitarity of the KM matrix, exploring the origin of CP violation, and reducing nuclear structure uncertainties in symmetry tests. There is no doubt that these areas will be pursued and that new ones will emerge during the next five years.

The diversity of the field means that its health depends on a number of facilities. In particular, future developments at LAMPF, Bates, and CEBAF are of considerable importance to it. Several improvements to LAMPF and the construction of KAON would permit a number of sensitive tests of the MSM, as well as experiments with neutrino beams and studies of weak nuclear matrix elements with hyperons. In several years, improved intensities for unpolarized and polarized beams at the Brookhaven AGS booster, a facility supported by high-energy physics, could also prove important. Also, development of improved polarized electron beams at Bates and CEBAF is required for a new generation of parity-violation experiments.

It is important to recognize that, in addition to the steady development of existing facilities, there are opportunities offered by large detectors. MEGA, SNO, LCD, and the 1-kiloton scintillation detector for neutrino oscillation studies are examples of detectors that have been built or are in the planning stage. Both accelerator- and non-accelerator-based detectors enable this field to pursue new physics opportunities and provide new challenges to the MSM.

A facility judged to be of major importance to this field is a source of cold and ultracold neutrons. The lack of first-rate sources in the U.S. is limiting basic experiments on parity violation, time-reversal violation, and the lifetime, electric dipole moment, and beta-decay angular correlations of the free neutron. High-flux cold neutronsources based on cryogenic moderators and total-reflection guides would themselves allow significant improvements in tests of fundamental symmetries, but it has recently been shown that ultracold neutrons (i.e., those for which gravitational deflections are important) are superior in virtually every aspect. An excellent facility could be developed at a new reactor proposed by Oak Ridge National Laboratory for condensed-matter studies. Cold and ultracold sources at such a reactor would provide ten times the flux of the best existing (European) facility. Possible additions to condensed-matter facilities at NIST or the use of intense pulsed-neutron facilities could also be considered.

II.9 Nuclear Physics and The Universe

Nuclear reactions and decays are the primary sources of the energy driving the evolution of stars and are responsible for the synthesis of all the chemical elements. As such they play a fundamental role in determining the basic structure and evolution of the universe. Nuclear physics provides sensitive signatures for probing complex astronomical and cosmological environments. In return, these environments provide unique opportunities for learning about nuclear physics under conditions that are still beyond the reach of terrestrial laboratories (e.g., at the center of the sun, in a supernova explosion, or in the hadronization phase transition of the early universe).

Stellar Astrophysics

Solar Neutrinos

Solar neutrinos are byproducts of the nuclear reactions generating energy at the center of the sun. Because of their minuscule interaction with matter, the importance of these neutrinos as a detailed monitor of the nuclear reactions occurring in the solar interior has long been recognized. Four years ago, Mikheyev, Smirnov, and Wolfenstein pointed out the possibility of another remarkable property of these neutrinos: flavor oscillations between the various lepton families (e.g., $\nu_e \Leftrightarrow \nu_\mu$) may be greatly enhanced by the scattering of neutrinos by solar electrons and terrestrial electrons (the latter could give rise to observable day/night effects in solar-neutrino detection rates). Solar neutrinos are unique probes, both for measuring conditions in the solar interior and for searching for possible lepton-family mixing and for neutrino masses as small as 10^{-4} eV, a sensitivity well beyond that currently attainable in any terrestrial experiment.

The classic ^{37}Cl experiment using 100,000 gallons of C_2Cl_4 as a neutrino detector finds a flux of high-energy solar neutrinos that is at least a factor of two smaller than that predicted by the current standard solar model coupled with the standard model of the electroweak interaction. The conversion of the Japanese neutrino detector Kamiokande-II into a solar- and supernova-neutrino detector has recently led to an independent measurement of the flux of solar neutrinos from the beta decay of ^{8}B (0.46 ± 0.13 of the prediction of the standard solar model), which agrees with the ^{37}Cl result; the directionality clearly established that the neutrinos came from the sun. Because these two experiments are primarily sensitive to the neutrinos from the decay of ^{8}B produced through the very temperature-dependent $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction, their results suggest *either* neutrino oscillations into flavors to which these detectors are not sensitive *or* the need for improvements to the existing standard solar model in order to reduce the model's prediction of $\sim 15 \times 10^6$K for the sun's core temperature.

A key challenge has been to find ways to distinguish between these two possibilities. Several new experiments are needed in order to measure the various components of the solar neutrino spectrum.

(A) There is great enthusiasm in Canada and the U.S. for a proposal to build the Sudbury Neutrino Observatory (SNO), a heavy-water Cerenkov detector in the INCO nickel mine. This detector, shown in Fig. 29, consists of 1000 metric tons of D_2O and would measure both charged-current and neutral-current disintegration of the deuteron ($d + \nu_e \rightarrow p + p + e$ and $d + \nu_x \rightarrow p + n + \nu_x$) and would thereby be able to observe directly the presence of any $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$ oscillations. (B) The long-awaited SAGE and GALLEX gallium detectors are now almost operational; these detectors will be sensitive primarily to the low-energy neutrinos from the $p + p \rightarrow d + e^+ + \nu_e$ reaction, whose predicted production rate is much less dependent on the details of the solar model.

Explosive Hydrogen and Helium Burning

Explosive nucleosynthesis is thought to be responsible for the production of terrestrial ^{15}N and the excess ^{22}Ne seen in many meteorite samples, as well as the O, Ne, Mg, etc., elemental overabundances observed in nova ejecta. The temperatures and densities involved in these events are sufficiently high so that proton and alpha-particle-induced nuclear reactions, such as $^{13}\mathrm{N}(p,\gamma)$ and

$^{15}O(\alpha,\gamma)$, can compete with β decay. In order to understand the origin of the material making up our solar system (the site, temperature, density, etc., of its nucleosynthesis), it is necessary to determine the detailed characteristics of the important nuclear reactions in these explosive processes.

The NSAC 1983 Long Range Plan emphasized both the importance of measuring such reactions and the technical challenges associated with their *direct* study, which would require the use of short-lived radioactive targets or beams. However, it has been shown that standard nuclear spectroscopy techniques can determine many of the relevant nuclear reaction rates without the need for radioactive beams and targets. The widths of the resonances can be measured by making use of other nuclear reactions to form the important resonant states and then measuring their decays into specific channels. For example, experimental measurements have been carried out to determine the $^{13}N(p,\gamma)^{14}O$ reaction rate by using complex reactions, such as $^{12}C(^{3}He,n)^{14}O^{*}$, $^{1}H(^{14}N,n)^{14}O^{*}$, and $^{14}N(^{3}He,t)^{14}O^{*}$, to form a specific $^{13}N(p,\gamma)$ resonant state in ^{14}O and by then measuring its $^{14}O^{*} \rightarrow {}^{13}N + p$ and $^{14}O^{*} \rightarrow {}^{14}O + \gamma$ decay rates.

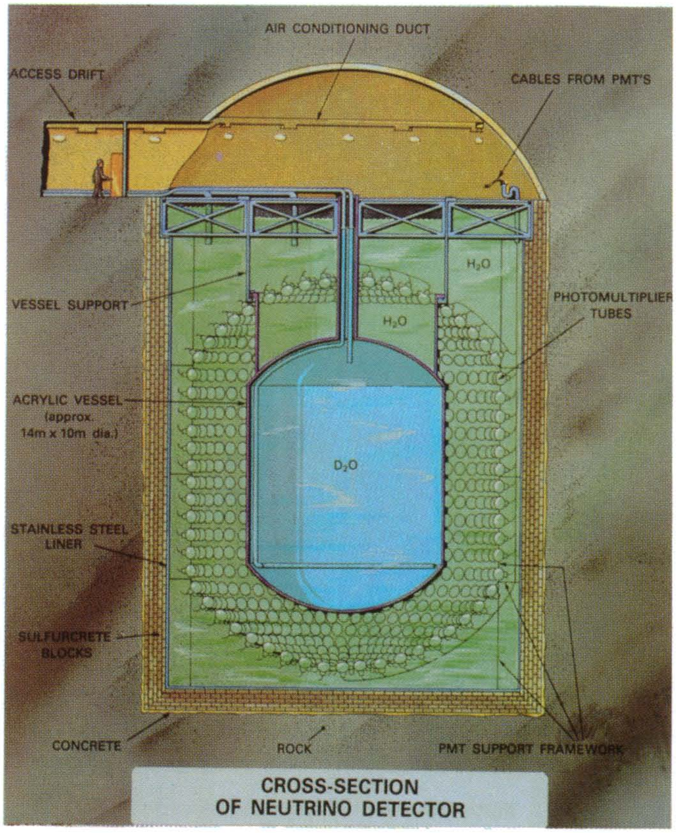

Figure 29: Cutaway view of the Sudbury Neutrino Observatory (SNO) and its heavy-water detector.

While these spectroscopic studies are able to determine the important resonant reaction rates, the measurement of any nonresonant contributions would require facilities for producing very intense radioactive beams in the energy range from 0.3 to 2 MeV per nucleon. At the present time, several special-purpose projects are under way (e.g., a ^{13}N beam at Louvain-La-Neuve and ^{7}Be and ^{8}Li beams at Livermore and at Michigan/Notre Dame). These instruments will provide a measure of the physics that can be done with such a facility and will provide the information necessary to determine if it is warranted to build a dedicated facility for the needs of nuclear astrophysics.

Important related studies will also require the use of balloon flights and space probes such as the Gamma Ray Observatory to search for and study the distribution of additional γ-ray sources in the interstellar medium.

Supernovae

A supernova explosion occurs as the final evolutionary stage of a massive star when its nuclear fuel is exhausted. At the present time, the key issues involved in understanding the processes that occur in supernova explosions are the nuclear equation of state at extremes of density, temperature, and isospin; the weak interaction rates of exotic nuclei far from the valley of stability; the nuclear reactions that govern the presupernova evolution of the star; and the heating and transmutation of nuclei in the star's mantle by the shock wave and the supernova neutrino flux.

Supernovae are the major engine driving the long-term chemical evolution of the galaxy, ejecting into interstellar space the nuclei produced in the presupernova hydrostatic burning phase as well as the nuclei produced by shock-wave heating during the explosion. Detailed knowledge of the nuclear reactions that occur during the star's presupernova evolution and during the explosion is essential for our understanding of these processes. Continued improvements in the sensitivity and precision of laboratory measurements of nuclear reaction rates and decay properties have had a significant impact on this problem. Very recently it has also been shown that the interactions of the supernova-neutrino flux with nuclei in the mantle of the star yield a third nucleosynthesis mechanism: neutrino spallation and subsequent nuclear processing appear to account for the galactic abundances of ^{7}Li, ^{11}B, ^{19}F, and a number of other odd-A nuclei.

Supernovae have always seemed a likely site for the r-process, rapid neutron capture leading to the synthesis of many of the heavy nuclei. The exotic conditions that lead to the r-process (neutron concentrations of $10^{18}/\mathrm{cm}^3$, maintained for at least 3–5 seconds) can be achieved under certain conditions, but the resulting nucleosynthesis appears to be too small to account for the observed abundances of these nuclei. Of particular importance in defining the conditions under which the observed solar-system r-process material was formed are the properties of the *very* neutron-rich "waiting-point" nuclei, at the neutron magic numbers (i.e., $^{80}\mathrm{Zn}[Z = 30, N = 50]$, $^{130}\mathrm{Cd}[Z = 48, N = 82]$, and $^{195}\mathrm{Tm}[Z = 67, N = 128]$), whose lifetimes and neutron-capture cross sections determine the time scale of the r-process. We have just recently achieved sufficient sensitivity using on-line mass separators to measure directly the decay half-lives and energies of both ^{80}Zn and ^{130}Cd. The observation of Supernova 1987a (see Fig. 30), and particularly the serendipitous prompt detection of its neutrinos (which set a kinematic limit of ~25 eV on the ν_e mass, comparable with the best values from tritium β-decay measurements), as well as the subsequent detection of the γ rays from the decay of its ^{56}Ni, have focused considerable attention on efforts to understand the mechanism by which collapsing stars eject their outer shells. A better delineation of this mechanism will require not only a better knowledge of the precollapse evolution of these stars but also a better knowledge of the nuclear weak-interaction rates during the collapse, neutrino diffusion and energy transfer, and the nuclear equation of state appropriate for the neutron star. The neutron star itself is a laboratory for testing the nuclear equation of state under extreme conditions of density, isospin, and rotation; for example, if confirmed, the observation of the pulsar corresponding to SN1987a with a period of only ~500 μsec would place profound constraints on the stiffness of the nuclear equation of state.

At the same time, efforts are under way to make laboratory measurements of some of the required nuclear physics information, such as the compression and flow effects in nucleus–nucleus collisions, which provide information about the nuclear equation of state. Studies with charge-exchange reactions can determine electron capture probabilities that can be used to test nuclear models for the relevant nuclei. It appears that the (^{12}C,^{12}N) reaction (carried out at 100–200 MeV/nucleon) can provide the necessary information with adequate resolution. Another heavy-ion reaction, the (^{6}Li,^{6}Li*) reaction leaving ^{6}Li in its second excited state with $J^\pi = 0^+$; $T = 1$, is sensitive only to the spin-isospin transfer processes and may permit one to measure the matrix elements of the spin-dipole states responsible for neutrino heating via neutral currents.

Big Bang Nucleosynthesis

When coupled with inflationary scenarios that imply that the universe is exactly closed, the nuclear physics of the homogeneous Big Bang (particularly its production of deuterium, helium, and ^{7}Li) appears to require that most of the mass in the universe is not baryonic. An exciting recent development has been the realization that during the Big Bang there might have existed large density fluctuations, triggered by the QCD phase transition, which could have significantly altered primordial nucleosynthesis by generating separated neutron-rich and proton-rich regions. Under such conditions, the observed deuterium and helium abundances need not so strongly constrain the baryonic mass density, and the possibility is opened that the dark matter of the universe could be baryonic.

However, this new scenario also makes other predictions that may conflict with what we observe in nature. For example, inhomogeneous-Big-Bang nucleosynthesis appears to overproduce ^{7}Li and leads to its own distinctive r-process production of heavy elements for which there is not yet any evidence in old, metal-deficient stars. Motivated by the possibility that the primordial QCD phase transition (if sufficiently violent) could have clear obser-

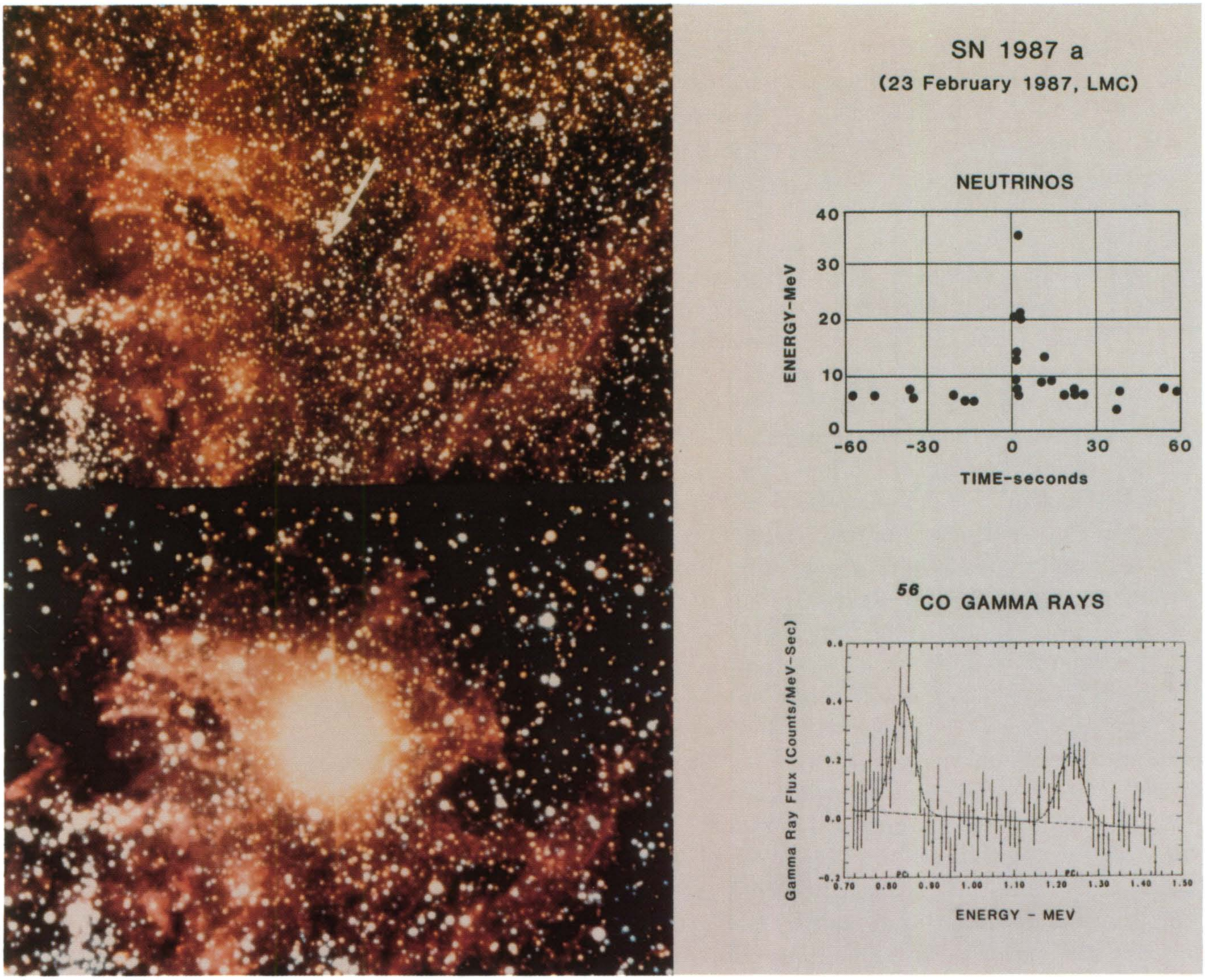

Figure 30: SN 1987a, in the Large Magellanic Cloud (indicated by the arrow *above* the bright star), together with a plot of the arrival time of its neutrinos at the Kamiokande-II detector and a plot of its γ spectrum, showing the 0.85- and 1.24-MeV lines from the decay of ^{56}Co synthesized in its explosion.

vational consequences in the present epoch, laboratory measurements of the rates of the key nuclear reactions in an inhomogeneous Big Bang are just now being initiated at fledgling radioactive-beams facilities (e.g., reactions such as $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$, which can bridge the $A = 8$ gap if it is fast enough to compete with ^{8}Li β-decay and the $^8\mathrm{Li}(d,n)^9\mathrm{Be}$ reaction). Furthermore, experiments such as those that will be carried out at RHIC to determine the nature of the QCD phase transition could also help constrain possible descriptions of Big-Bang nucleosynthesis.

Conclusions

Because it is an interdisciplinary field, nuclear astrophysics generates a natural dialog with other fields of physics, astronomy, and cosmology. Developments in nuclear instrumentation have often led to constructive interactions between laboratory nuclear physics and nuclear and particle astrophysics: for example, the use of large, low-background double-beta-decay detectors to search for WIMPs (weakly interacting massive particles) and the coupling of the LAMPF E225 neutrino/muon detector with an array of gamma-ray detectors to study ultrahigh-energy cosmic-ray bursts from Cygnus X-3 and Hercules X-1. Such interdisciplinary collaborations can be extremely fertile and should be actively encouraged.

To continue to play their essential role in these collaborations, nuclear astrophysicists will need continuing access to a variety of cyclotron, tandem, linac, and reactor facilities in order to measure the cross sections and nuclear properties required to understand the nuclear processes that drive stellar energy generation, the chemical evolution of the galaxy, and the primordial Big Bang. In the near future, as these studies begin to focus on more explosive scenarios, these measurements might also benefit from access to a facility capable of producing very high-intensity radioactive beams with energies in the range from 0.3 to 2 MeV per nucleon.

Funding for the SNO project, both for its construction and for active participation in the science that it will make possible, is this field's *highest priority* at this time. At the same time, it is also essential to continue the important U.S. role in the SAGE and GALLEX collaborations. It is also important and cost-effective to continue the operation of the Homestake facility; its almost continuous operation over the past 20 years provides an indispensable baseline for the continuing study of possible temporal variations associated with the solar cycle. In addition to these detectors, as a complementary part of the U.S. neutrino program, it is also important to be able to respond to research and development proposals for studying possible new materials (such as ^{11}B, ^{98}Mo, ^{127}I, etc.) for future neutrino detectors that might be able to measure other aspects of the neutrino spectrum and its time dependence.

Finally, because of the danger that interface projects and proposals might fall in the cracks between more established and better defined fields, it is imperative that adequate flexibility and breadth of view continue to be exercised in reviewing and funding these programs.

III. THE APPLICATIONS OF NUCLEAR PHYSICS

Introduction

Today, nuclear science affects the life of every person in our society. Its impact derives from the direct applications of nuclear properties in medicine, energy production, industrial processes, and strategic aspects of national security, as well as from its use to advance technology and to provide useful tools in many areas of application in industry and in the research in other sciences.

Nuclear energy derived from fission reactors, or fusion, and nuclear defense are perhaps the most visible national aspects for which nuclear physics, as a science and a technology, is indispensable. Both have become public issues over the recent history. However, it is clearly prudent for the United States to retain a very strong scientific competence in both of these areas. In particular, with the increasing awareness of the serious implications of conventional power sources for the global climate, nuclear power may assume renewed importance for the nation's energy supply. This would be aided by new designs which are intrinsically more fail-safe and that would produce far less long-lived radioactive waste than the older reactor designs. In practical terms, this means that a stock of expertise in nuclear detection techniques as well as in factual nuclear physics must be maintained. Training the high-level technical experts is perhaps one of the most important, if less visible, contributions of nuclear physics research to our society. Application of these technologies in society is properly a matter of public policy and as such is driven by a host of complex considerations outside the realm of science.

Medical, environmental, and industrial applications of nuclear science are widely appreciated in society and continue to expand. The quantitative detection of natural radon gas and the evaluation of radiation hazards from this and other radioactive contaminants, as well as the smoke detector using α particle sources, are prime examples of nuclear know-how entering the home of the average citizen. Accelerator technology developed by nuclear scientists is now being applied to medical diagnosis, cancer treatment, and medical isotope production.

In industry, particle beams play increasingly crucial roles in materials fabrication, elemental and structural analysis, and radiative sterilization of various products, including food. There is a host of devices (some to be discussed below) invented by nuclear scientists that find direct and indirect application in the nation's commercial sector.

The issue of competence in nuclear science, referred to above, was dramatically underlined recently by the sudden need for reliable low-level neutron measurements in connection with the claims for "cold fusion".

Nuclear research has also benefited other areas of study often far removed from nuclear physics. For example, many of the important techniques used in materials science were developed in nuclear physics. The use of low-energy neutron beams is a boon to both materials science and biology for unravelling the underlying atomic structure of complex substances. The development of high-intensity beams may soon allow researchers the opportunity to go beyond structure and begin to investigate time-dependent dynamic processes in both of these fields at a microscopic level. Elemental and structural studies at the atomic level have also become invaluable tools within the disciplines of art history, archeology, paleontology, and geology. Nuclear techniques have often provided the decisive evidence on the specific issue in question. The widely varying lifetimes of radioactive nuclei, along with a knowledge of how they are picked up by various processes and substances, allow these nuclei to become unique "clocks" for measuring time scales as diverse as the age of the rocks in the earth, the life span of fossil remnants, the age of archeological artifacts, and the period during which a particular painting was rendered. These are all more or less unforeseen benefits of the study of nuclei and their properties.

Research on the processes by which nuclear reactions build up the chemical elements via nucleosynthesis in stars has provided a rather clear view of how the chemical elements came to be formed, and their relative abundance became what they are. As this is the very *stuff* we are made of, such knowledge is surely an important aspect of our quest to understand our origins and to reveal the order of the universe.

Hence, nuclear physics continues to contribute directly to our material well-being, to enrich other essential fields of study, and provides us with the means of addressing, on occasion, questions of broad cultural interest.

Applications of Neutrons

Beams of neutrons ranging in energy from ultracold to epithermal are used by materials scientists to study the structure and dynamics of materials. These neutrons are generated either by nuclear reactors or by accelerator-driven pulsed sources. In the U.S. there are two pulsed sources: one at Argonne National Laboratory using the former ZGS injector system, and one at Los Alamos National Laboratory employing a 10% fraction of the LAMPF beam. Other such facilities are operated in England and Japan.

Steady-state reactor sources and pulsed sources have overlapping as well as unique capabilities. The availability of both allows the broadest range of experiments on samples of great interest, including high-temperature superconductors, synthetic rocks, and dinosaur bones.

The texture (alignment of the constituents) of a material has a direct bearing on its mechanical properties. For example, a few years ago officials of the British Railway System noted that their rails were wearing away at an excessive rate, owing to flaking at the rail surface in contact with the wheels. Close study of the texture of the rails via neutron scattering at an English reactor revealed the problem and suggested a treatment to improve the surface texture of the rail. This endeavor is ongoing.

Similar studies are now being undertaken on many components subjected to stress. Two examples are turbine blades and jet engine mountings. Studies of this type will lead to improved selection and treatment of materials.

Texture studies via neutron scattering have also been performed on the leg bones of the largest dinosaur yet discovered, the Seismosaurus. These studies showed that the mineral structure in the bone had a texture that would lead to maximum strength under compression, which is just what one would expect for such a bone! Thus, the bone had retained its original texture for over a million years, despite the possibility that the textured material could have been replaced by intruder minerals.

The extraordinary penetrating power of thermal neutrons, coupled with their strong scattering from hydrogen nuclei, has made them a crucial tool for detecting and precisely locating oil leaks deep within complex engines, and it allows the leak to be investigated while the engine is operating. For the same reason, thermal neutrons can also sense the presence of water. Neutron scattering is being used to detect the presence of condensation within the honeycombed aluminum structures now used in the aircraft industry. The condensed water would react and yield aluminum oxide, which is appreciably weaker than aluminum and could lead to component failure.

Neutrons are proving to be highly sensitive diagnostic tools for the presence of certain elements, making use of specific γ radiation produced in neutron capture or inelastic neutron scattering. These are used for the measurement of the sulfur content of coal, right on the conveyor belt to the power station. Coal from various sources is mixed so as not to exceed a maximal sulfur content. More recently, the same method has been applied to the detection of nitrogen from explosive materials in airline luggage.

A particularly timely and interesting use of neutrons relates to the recent success in increasing the current-carrying capability of crystals of the high-temperature superconductor $YBa_2Cu_3O_7$ about one hundred fold, from 6500 to 620,000 A/cm^2, at 77 K. The neutrons irradiate the crystal and create lattice dislocations; these serve to pin down the magnetic flux lines that are created in the material by the electric currents. If these flux lines are allowed to move around, they heat up the material and, above a certain temperature level, prevent superconductivity.

Thus, neutrons are playing an ever larger role in our industrial society. In each of these applications, nuclear science technology contributes first to the production of the neutron beams, whether from reactors or fission neutron sources or low-energy particle accelerators, and then to the detectors, such as the sensitive large-area detectors that are needed to cover large practical objects.

Finally, one needs to have the basic nuclear data, such as interaction cross sections and specific nuclear transition energies, in hand. The national nuclear data effort collects, evaluates, and catalogs data on neutron and other nuclear cross sections, nuclear energy levels, and decay properties of nuclei. It provides an important source of information for research and applications.

Muon-Catalyzed Fusion

With the growing realization that the fusion of hydrogen isotopes into helium with the attendant release of appreciable energy cannot be accomplished in any simple way, nuclear physicists continue to look for novel ways of achieving this desirable fusion.

A startling result is the observation that a single muon can catalyze the reactions of 150 deuterium-triton fusions before either sticking to a He nucleus (which is a reaction product) or decaying away by virtue of the muon's 2.2×10^{-6}-sec lifetime. A muon is a short-lived particle about 200 times heavier than an electron. Hence, negative muons can bind to hydrogen nuclei and shield their positive charge, thus allowing fusion to occur readily. The use at LAMPF of high-pressure, high-temperature target vessels for d-t mixtures has shown a strong dependence of the cycling rate on temperature. Data have been obtained up to 800 K. Remarkably, the fusion rate continues to increase with temperature over the entire pressure range. Thus the muon, with a rest mass of 105 MeV, is capable of causing fusions that develop a total of 2640 MeV. The reason that muon-catalyzed (d, t) fusion occurs so rapidly is that there is an accidental resonance in the $t_\mu - d_2$ trimolecule very near threshold. The physics of this process is currently being investigated throughout the world, with LAMPF playing a leading role. A wide range of $d - t$ mixtures at various pressures and temperatures is needed to continue investigating this potentially interesting catalysis of fusion.

Atomic Physics

The negative hydrogen ion is a unique system for studying the correlations that can result from the electron–electron interaction. In this system the electron–electron interaction is as strong as that due to the central field created by the proton. The negative hydrogen ion has only a single bound state, the ground state; hence, studies of it necessarily involve exciting H^- into the continuum. The resonant states of the H^- ion lie above 11 eV in the vacuum ultraviolet, for which there are no high-power lasers. Nevertheless, photodetachment studies can be performed using Doppler shifts associated with the relativistic (800-MeV) LAMPF H^- beam interacting with a laser beam in the visible region. Using this technique, resonances have been investigated, and the first observation of photo-double-detachment of H^- was recently reported. Resolutions of 10^{-3} eV in excitation energy over the range 2 to 20 eV are achievable, making possible the investigation of near-threshold behavior, resonances at high principal quantum number, and multiphoton ionization of H^-.

Molecular Physics

The accelerator and detector technology of nuclear physics is being applied in a novel approach to the determination of the structure of certain molecules. Beams of molecular ions are accelerated to velocities high enough (about 1% of the speed of light) to cause their dissociation when they pass through a thin (typically ~30 nm) Formvar foil. This is schematically shown in the top part of Fig. 31. The electrons that bind the molecule together are stripped away within about 10^{-16} sec after penetration into the foil. This time scale is short compared to the characteristic motions within the molecules. There then ensues a "Coulomb explosion" between the (now unbound) atomic ions inside each incident projectile. Because of the high center-of-mass (c.o.m.) velocity these ions fly forward into a narrow cone around the beam direction. Several meters downstream, the fragments strike a position- and time-sensitive detector that determines their transverse and longitudinal velocities in the c.o.m. frame with high accuracy. The original position within the projectile can then be computed for each group of fragment ions. From an ensemble of such measurements, one obtains information on bond lengths, vibrational motions, and intramolecular correlations within the molecular-ion species that constituted the accelerated beam. The bottom of Fig. 31 shows data for the ion $C_2H_3^+$. In some cases, e.g. for multiply charged species and "floppy" molecular ions, this method is the most practical avenue of approach.

Muon Spin Relaxation and Positron Probes

In solid materials, muons can serve as sensitive probes for magnetic effects. This application has recently acquired increasing importance for the study of the structure of high temperature superconductors in which interactions between electron spins are thought to be crucial. Other applications are to exotic materials such as spin glasses and heavy fermion superconductors. In the μSR technique, beams of polarized positive or negative muons are implanted in the samples of interest. As the muon decays with its 2.2-μsec life time, a measurement of the emerging electrons or positrons provides the time evolution of the μ spin depolarization. This application requires the precise beams of muons that are produced at medium-energy nuclear physics accelerators, such as LAMPF, TRIUMF (in Canada), and PSI (in Switzerland). We mention only one example:

The penetration depth of a magnetic field is a fundamental parameter in the theory of superconductivity. Muon spin rotation is an ideal method for measuring the magnetic field distribution in the surface of the superconductor. Fig. 32 shows the example of the superconductor Tl-Ca-Ba-Cu-O, which has a transition temperature of 120 K, the highest presently known. The data in the top part of Fig. 32 show the rotation pattern of the spin in the external magnetic field of 1 kG, as a function of time. While at T= 180 K the external field penetrates homogeneously into the material and the rotation pattern is perfectly regular, below the critical temperature, i.e., at T=4.9 K, the trapped field becomes inhomogeneous and the spin gets depolarized with time. From the depolarization rate as a function of temperature, shown in the bottom part of Fig. 32, one can deduce the penetration depth as plotted in the figure. The data yield a penetration depth of 1400 Å(140 nm) at temperature T = 0 K.

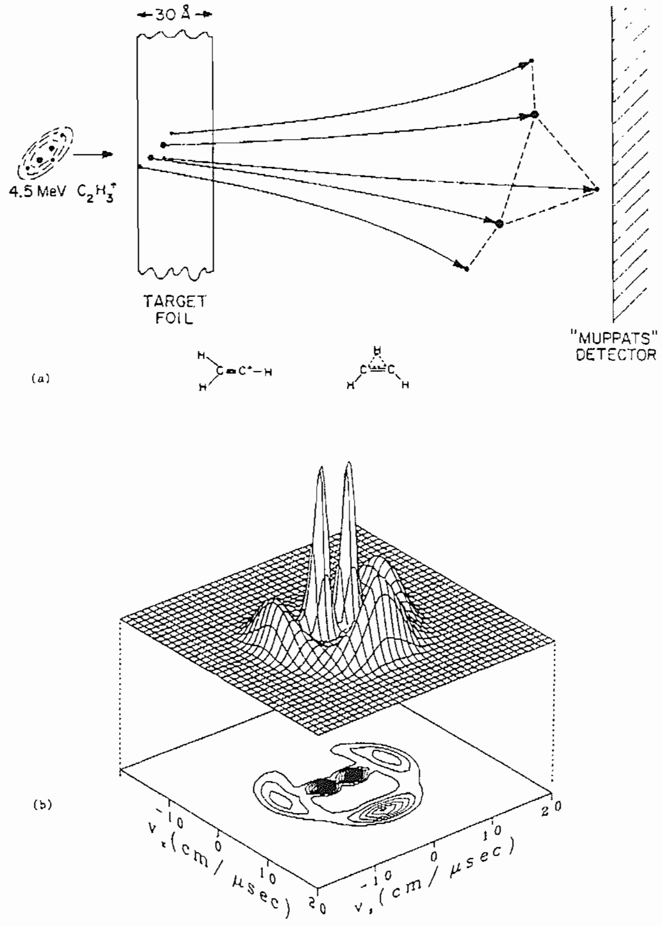

Figure 31: "Coulomb explosion" measurements on the structure of $C_2H_3^+$ ions.
(A) Schematic view of the experiment with 4.5-MeV $C_2H_3^+$ projectiles;
(B) Densities of fragment ions measured in a coordinate system defined by the final c.o.m. velocities of each fragment. The two central peaks are due to the carbon ions. The three protons are grouped around them in a manner demonstrating that the molecular ions are predominantly in the nonclassical "bridged" structure, rather than in the classical form with the protons at the extremities.

Similar in spirit is the use of positron probes in solid-state physics. Positrons are positive anti-electrons that live forever in empty space but die quickly in any material when they come to rest, by annihilating themselves with normal electrons that are always present. Positrons must be produced either from radioactive decays by use of sufficiently long-lived radionuclei, such as ^{64}Cu (usually produced in reactors), or by use of the energetic electron beam from an accelerator that radiates positrons in a suitable moderator. It turns out that positrons can be accumulated in certain moderators and boiled out again, which results in a large increase in directional intensity. These thermal positrons are emitted from the surface with a very low energy spread into a narrow cone. Favored moderators, tungsten and molybdenum, yield peak emission energies around 2 eV. These positrons can then be used to measure the electron momentum distribution at the site in a test material where they annihilate. Additional information can be obtained from the positron lifetime inside the host material where it is dependent on lattice defects via the electron density.

Nuclear Solid State Physics

Nuclear reactions are widely applied to solid-state problems, either for the precise implantation of radioactive nuclei in the form of recoiling reaction products, or as probes for the presence of certain chemical elements in a substrate. They provide ways to obtain precise depth profiles of impurities in materials or to measure local magnetic or electric (quadrupole) fields, which are sensitive to the crystal structure or impurity distribution in materials. These reactions or implantation methods typically use heavy ion accelerators and nuclear detection techniques. From a huge variety of probes and problems, we chose only two examples.

Hydrogen depth profiling has an important application in the detection of unwanted hydrogen, which leads to the embrittlement and early catastrophic failure of metallic pieces, such as rotor blades in jet engines or cooling pipes in nuclear reactors. But it also is a helpful tool in the exploration and development of efficient hydrogen storage materials. Fig. 33 shows the example of the hydrogen

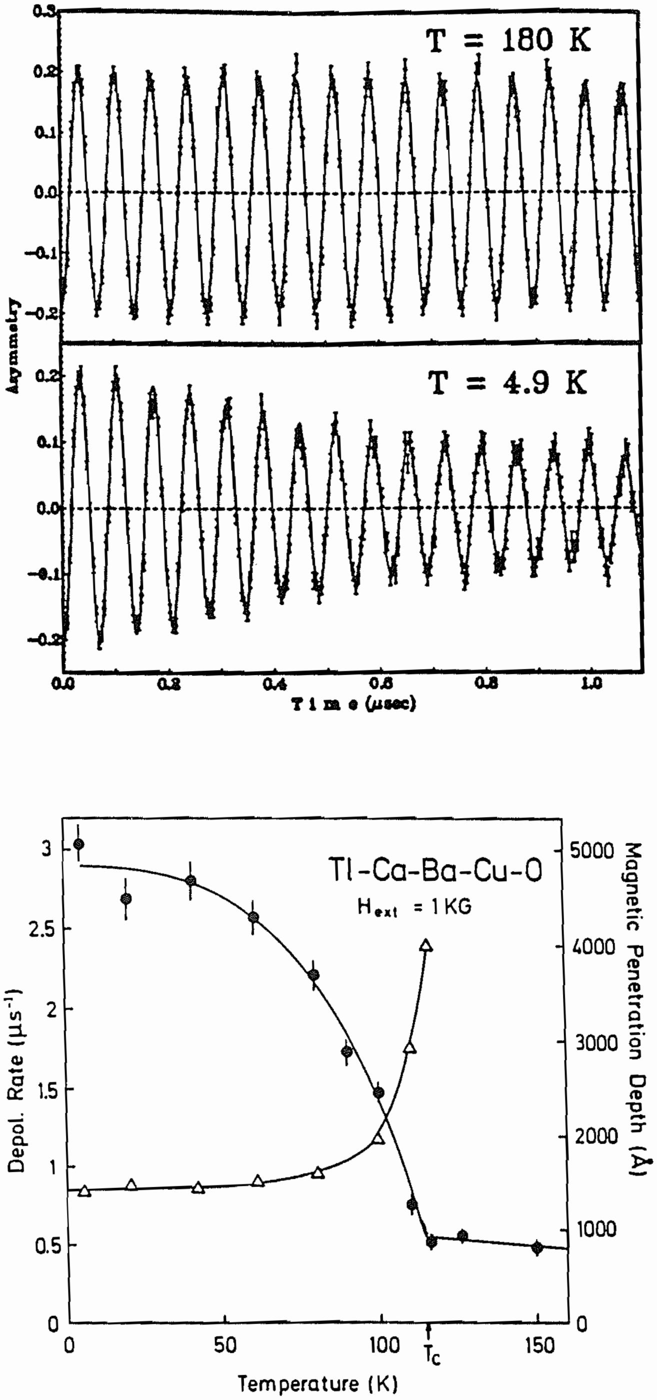

Figure 32: (A) μSR signal observed in Tl-Ca-Ba-Cu-O in a transverse field of 1 kG, above and below the critical temperature T_c= 120 K, as a function of time.
(B) Temperature dependence of the spin depolarization rate (circles) and the London penetration depth (triangles).

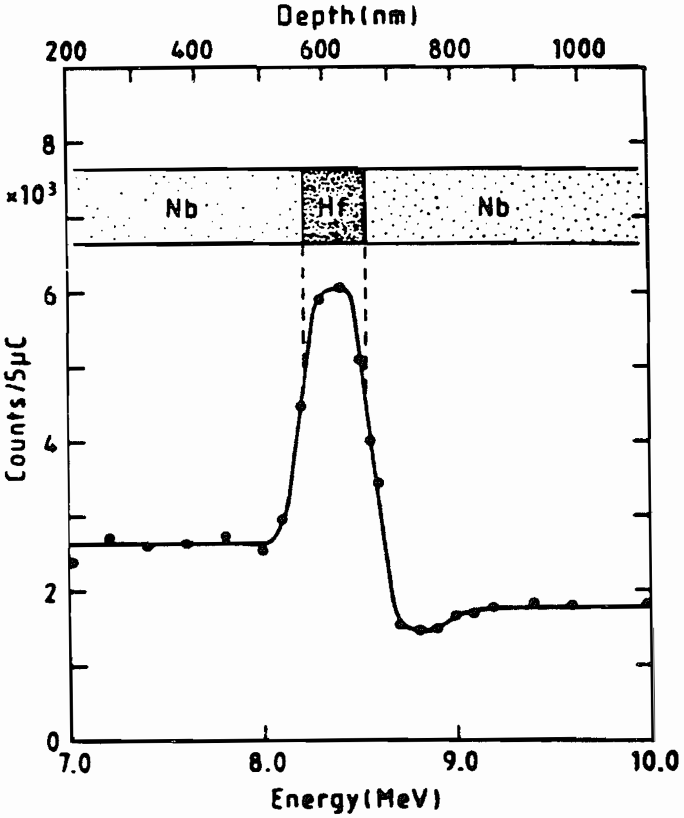

Figure 33: Hydrogen depth profile of a Nb-Hf-Nb sandwich as obtained with the $^{15}N+p$ reaction. The increased hydrogen concentration in the Hf layer is obtained with very good spatial definition.

concentration observed in a layer sandwich of Nb and Hf. It can be seen that the Hf layer, at a depth of 600 nm, stores about three times as much hydrogen as does the Nb layer. A fertile field of nuclear applications to solid-state physics is the method of perturbed angular correlations (PAC), which is very similar to the μSR method described above. An indication of the detail about solid-state structure that is accessible with this method (which has many variations) can be gleamed from the following case, in which radioactive indium nuclei are sensitively detected and identified as sitting at three successive terrace levels of imperfect silver single crystals. The implanted ^{111}In nuclei decay by β and subsequent γ emission. Detection of the β particle specifies the nuclear spin direction of the emitting nucleus. This nuclear spin is made to rotate in an applied magnetic field, and the angular distribution of the γ rays rotates around with the spin.

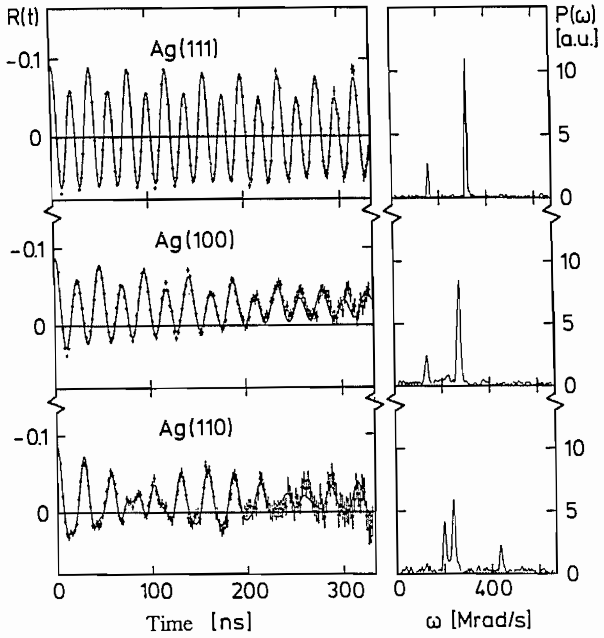

Figure 34: PAC spectra of ^{111}In probes on Ag(111), Ag(100) , and Ag(110) surfaces. The frequencies contained in the perturbed γ-ray angular correlation rotation at left are given in the right side and translate directly into local electric field gradients. They vary from $7.0 \cdot 10^{17}$ V/cm^2 for Ag(110) to $8.6 \cdot 10^{17}$ V/cm^2 for Ag(111). The data were taken at T = 77 K after the sample was annealed above 300 K.

The amplitude of the yield, as a function of time, yields the perturbation due to local electric field gradients. Fig. 34 clearly shows the three different frequencies associated with the varying electric fields experienced by the ^{111}In probe nuclei at the three crystal-terrace levels.

Accelerator Mass Spectrometry

The recognition that a nuclear accelerator coupled with a sensitive magnetic spectrograph can be used to detect and analyze minute traces of elements with unexcelled sensitivity has led to the burgeoning field of accelerator mass spectrometry (AMS). This field has been entirely invented and developed in nuclear physics laboratories. Now it is finding ever increasing use and is shifting to dedicated facilities, with rapidly growing applications in areas of practical needs. About a dozen different isotope ratios of interest are routinely detected in applications to archeology, hydrology, climatology and geology. Again, we list only a few examples.

Radiocarbon Dating:

Observing the ^{14}C concentration in a carbon sample yields the date at which atmospheric carbon was incorporated into the sample if the atmospheric concentration is known for that time period, for example from tree-ring studies. AMS yields results with required sample amounts 1000-fold less than those required for the older decay counting method invented over forty years ago. Two recent, celebrated examples are the age determinations of the shroud of Turin and of an iron smelting fire pit in Newfoundland.

The former object, believed by many to be the burial cloth of Jesus, was dated by AMS to the year A.D. 1325 with an uncertainty of only about 30 years, using only a postage-stamp size piece of the cloth. In the second example, the wood used in an iron-smelting pit in Newfoundland was dated to A.D. 997 with an uncertainty of only 13 years, using minuscule carbon inclusions picked from the iron slag found in the pit. This was the first scientific evidence that Scandinavians were present in America well before Columbus.

Radiochlorine Analysis:

The second most useful isotope measured in AMS, and one that is in the forefront of applications to present-day national needs, is a radioisotope of chlorine, ^{36}Cl, produced by cosmic rays. It is employed to study the integrity of potential sites for the storage of nuclear waste, and aquifer flow rates.This is particularly important because the U.S. government is at this time committed to an underground storage of long-lived radioactive nuclear waste. This isotope has many other geological applications.

Activation Analysis and Dinosaur Extinction

There is now increasing agreement that a large chunk of debris from the solar system struck the earth about 65 million years ago, causing the extinction of most living species, including the dinosaurs. Crucial support for this theory was provided by neutron activation measurements of iridium concentrations. Iridium is found in meteorites with a concentration about 10,000 times higher than that found in the earth's crust. It was noted that the terrestrial clay layer that coincides geologically with the end of the age of the dinosaurs has a sharply increased iridium concentration, and this is found at about 75 locations around the world. Such measurements are made on the ^{192}Ir isotope produced by irradiation at a sensitivity of about 300 parts per trillion, for measurements without prior radiochemical separation. The search continues to establish the occurrence of widespread iridium enhancements associated with other large-scale disappearances of other species, occurring at different geological periods.

Applications in Medicine

Modern medicine makes use of many technologies and techniques derived from nuclear physics. For this reason, nuclear medicine is today a recognized field, and many scientists trained as nuclear physicists later move into careers in this field. The main applications are imaging and diagnosis by nuclear techniques and the use of nuclear beams for cancer therapy. Not surprisingly, these applications have a particularly high visibility in our society. We select here recent developments in imaging technology and in accelerators used for therapy.

Nuclear Imaging:

Positron emission tomography (PET) maps the concentration of positron-emitting isotopes that have been deposited in a human body and determines the precise location of the emitter by detecting two time-coincident decay γ rays that are emitted back-to-back. As a technique it complements the (cheaper) nuclear magnetic resonance imaging (MRI) process by the possibility to incorporate the positron emitter into chemicals that are important for the human metabolism. The elements carbon, nitrogen, and oxygen, which are easily ingested, all have useful positron-emitting isotopes. However, these are very short lived (only about 20 min) and cannot be stored. Thus much of the expense of the technique is associated with the need to have a nuclear accelerator, usually a cyclotron or a linear accelerator, available nearby to produce a steady supply of these isotopes. Intensive research using PET is done on the brain by incorporating the radioactive isotopes into glucose, the basic fuel of body and brain. One can then study how fast that fuel is taken up by various parts of the brain, under different conditions of activity. An example is shown in Fig. 35 from the Washington University School of Medicine. It shows the limbic section of the right brain hemisphere which is associated with emotion and motivation. People that are prone to panic have a greater blood flow and glucose metabolic activity in this section of the right hemisphere than in the left, and the pattern changes during a panic attack. The technology of PET is still improving. New, very fast BaF_2 crystals introduced in nuclear γ ray spectroscopy record the flight-time difference between the two coincidently emitted γ rays with sub-nanosecond accuracy. This additional information results in an improved signal-to-noise ratio and thus a clearer and more sensitive image. A further improvement will be the arrangement of detectors in an almost closed spherical shell, as pioneered by the so-called 4π crystal ball detectors now increasingly in use in nuclear research.

Cancer Therapy:

Cancer radiotherapy uses accelerators conceived for nuclear physics research to produce energetic charged particles or neutrons, which interact with cells in the human body and kill them. Although for certain beams the destruction efficiency is enhanced for malignant,i.e., rapidly growing, cells over that for normal cells, the area of intense irradiation must obviously be confined as much as possible to the tumor. Electron linear accelerators are currently the "workhorses" of radiotherapy, but techniques using neutrons, protons, and heavier ions are being developed because they have fundamental therapeutic advantages over x-ray or electron irradiation. Existing facilities in North America with ongoing neutron trials are located at Fermilab, University of Washington, UCLA, and the M. D. Anderson Hospital in Texas. Charged-particle trials are being conducted at Harvard (protons), Berkeley (neon, carbon, silicon), and TRIUMF (negative pions). Facilities under construction dedicated exclusively for radiotherapy include a superconducting cyclotron for neutron irradiation at Harper-Grace Hospital in Detroit, the Loma Linda University Medical Center proton accelerator, and the heavy-ion accelerator HIMAC in Chiba, Japan.

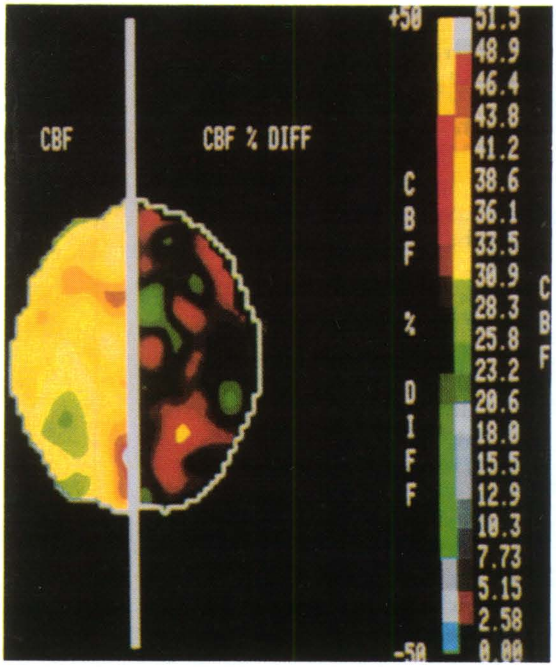

Figure 35: PET image of the limbic region of the brain. The right side has a higher metabolic activity than the left. During a panic attack the pattern changes significantly.

The facilities and experience of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University are being used in the construction of a superconducting cyclotron for cancer therapy (see Fig. 36). The cyclotron will be installed at Harper-Grace Hospital, one of Detroit's leading hospitals. The project uses the cyclotron technology developed in the course of design and construction of two large NSCL research cyclotrons. In the medical application, superconducting technology provides a cyclotron that is much lighter than comparable room-temperature cancer-therapy cyclotrons (25 tons versus several hundred tons). This makes it possible to mount the cyclotron directly on a gantry so that the whole cyclotron rotates on a 14-ft diameter circle about a patient resting on a horizontal table. Patient treatment at Harper-Grace is expected to start in early 1990.

The 70-to-250-MeV proton synchrotron designed and built at Fermilab and being installed at Loma Linda (CA) University Medical Center should be available next year for patient irradiation. Three of five treatment areas are provided with gantries to allow irradiation of patients from any direction. Such gantries were first developed for basic nuclear research at U. Colorado and MSU. The specific en-

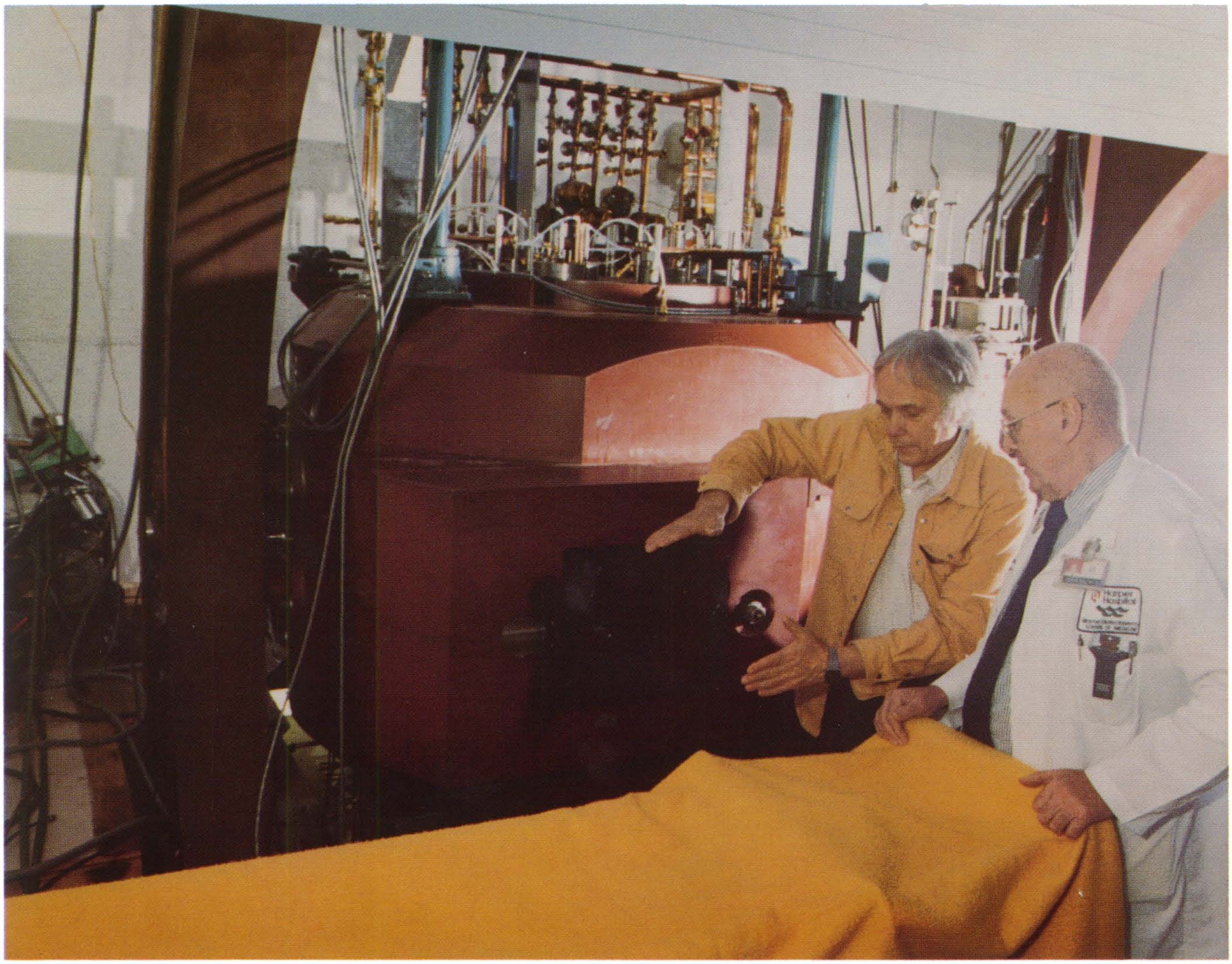

Figure 36: Dr. Henry Blosser, nuclear scientist and cyclotron expert, and Dr. William Powers, chief oncologist, standing beside the patient's table with the superconducting cyclotron just behind.

ergy loss is not as high for protons as for heavy ions or neutrons, but the irradiated volume can be better confined for protons or heavy ions than for x-ray or neutron beams. While this is the first proton accelerator facility designed for "production" proton radiotherapy, the data base of 14,000 patients already treated with protons at facilities around the world assures that treatment can be successful for many types of tumors. About 1000 patients will receive treatment at Loma Linda each year.

Heavy-ion irradiation has the advantages of precise beam control and high specific energy loss near the end of the particle range, thus combining the advantages of proton and neutron beams. A substantial additional advantage of heavy ions is the ability to use radioactive beams to pinpoint the actual stopping point of the therapeutic beam. Uncertainty in the stopping point, due to tissue inhomogeneity and imprecisely measured electron density of the tissue, is a potential source of error in this kind of treatment. In a technique pioneered at the Bevalac at LBL, a beam of (radioactive) ^{19}Ne ions is produced by fragmentation reactions of the primary 500-MeV/A ^{20}Ne beam. The ^{19}Ne beam is then deposited in the patient, and the stopping region is imaged using the PET technique, i.e., by measuring the coincident annihilation photons following positron decay of ^{19}Ne, before the much larger (and thus more dangerous) therapeutic dose is applied. This technique is of critical importance for treatment of cancers in close proximity to vital tissues that must be avoided by the therapeutic radiation. Such a case is shown in Figure 37.

Production of Medical Isotopes:

Many medical applications depend critically on a steady stream of medical isotopes that must be produced on schedule. This requires reliable, high current accelerators. Many nuclear facilities provide such services to the regional medical centers. For example, after passing through the meson production targets the intense LAMPF proton beam is made to further interact with a variety of targets to produce radioactive isotopes for medical research and treatment. An average of 137 shipments per year of these isotopes are being made to 50 institutions. The majority of these institutions are hospitals and clinics. About 20% of the isotopes are provided to private companies that further process and distribute the isotopes to research centers. The LAMPF program supplies more than 30 radionuclides and serves as the sole source for 15 of them.

Industrial Production

Today many accelerator structures or detector concepts developed initially for nuclear research have become significant industrial products. Airline luggage scanners, using large-scale scintillation or neutron counters, are obvious examples. Others are superconducting cyclotrons and the side-coupled linac structures. We cite the latter example as a showcase that seemingly esoteric devices can develop very large markets. Over 100 accelerators based on the LAMPF side-coupled cavity design are commercially produced each year, with a market value in excess of $200,000,000. The accelerators are used to produce intense electron beams for application in both industry and medicine, as exemplified above. Similarly, electrostatic accelerators for solid-state applications have become important commercial items.

In the process of working on superconducting rf cavities, engineers and scientists at LAMPF developed a noncontact, rapid screening system for measuring the transition temperature of high-temperature superconductors. A patent for this device has been obtained and a product has already appeared on the market that promises to greatly speed up

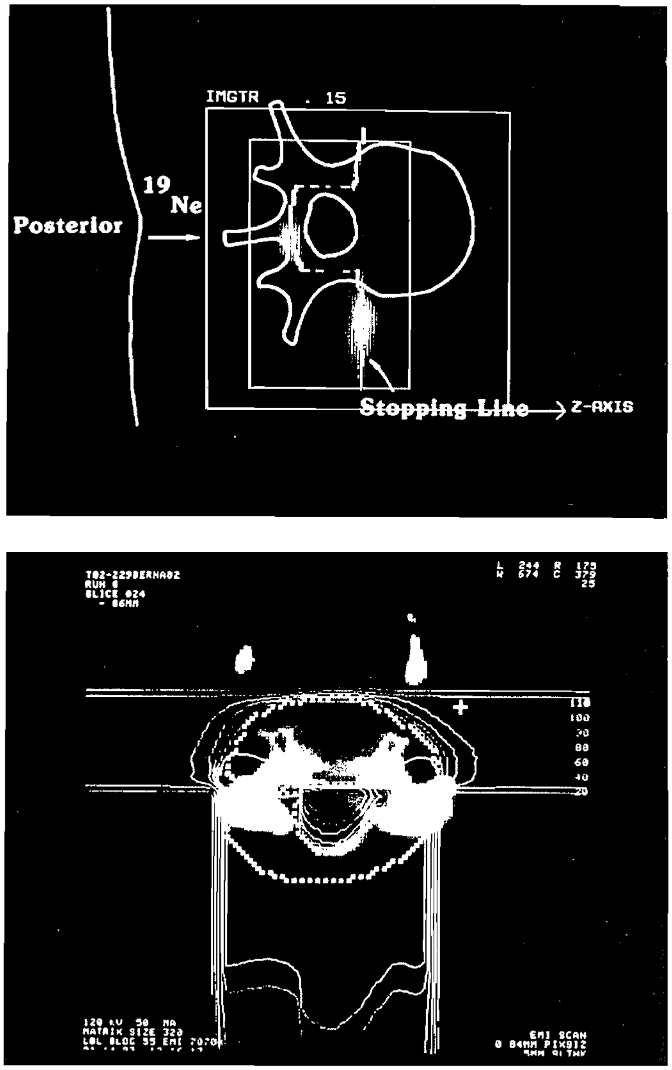

Figure 37: Heavy-ion treatment of a tumor that completely surrounds the spinal cord of the patient.
(Top) Treatment plan:The doughnut-shaped treatment volume indicated by the dotted lines avoids the cord, but the alignment of the field and the knowledge of the range of the beam must be accurate to within a few millimeters to avoid unacceptable damage to the patient. Such treatments are just not possible with x rays or neutrons which do not have the excellent dose-localization of charged particles.
(Bottom) Verification of the accurate placement of the beam by means of ^{19}Ne PET imaging. The beam reaches the indicated stopping line inside the patient. In the center part the beam had to penetrate a energy-reduction plate and thus travels less far. Superimposed on the figure are the vertebral body and, at the center, the spinal cord. This technique has been pioneered at LBL.

the rate at which high-temperature superconducting samples can be characterized.

Nuclear Data for Applications

The Nuclear Data Discipline

The nuclear data discipline forms the interface between the scientific content of nuclear physics and the technology of nuclear applications, most directly of reactor technology. Quantitative results reach the applications engineer in complete, evaluated files of cross sections and related quantities, and in standards such as the ANSI standard for after-shutdown fission-reactor decay heat and the ASTM standard for atomic-displacement cross sections relevant to radiation damage. Measurements and evaluations in the incident neutron energy region up to 20 MeV have been emphasized so far. Charged-particle nuclear cross sections of interest to fusion energy are included. Accuracy requirements on measurements are demanding, and the nuclear models often necessary for the extraction of useful numbers must be comprehensive.

Experimental Program

Most of the needed measurements are provided by research programs that are dedicated to meet data needs of application areas. A few U.S. accelerators are devoted primarily to this work. ORELA, a powerful electron linear accelerator at Oak Ridge, is an excellent pulsed "white" neutron source allowing high resolution measurements from the resonance-reaction region through tens of MeV. FNG, an electrostatic accelerator at Argonne, is the primary source in the U.S. of mono-energetic neutrons for nuclear data measurements. A pulsed spallation neutron source at LAMPF is effective from several hundred MeV down to at least a few MeV. Recent results include:

(1) Fast-neutron differential scattering measurements in the few-MeV region, with accuracies comparable to those of charged-particle results.(2) Significant improvements in the measurement and analysis of neutron resonances, both in structural materials and in the reactor-fuel materials. (3) Discrepancies in the cross section for the $^7\mathrm{Li}(n, n't)$ reaction were removed. This cross section is important for the design of tritium-breeding blankets surrounding fusion reactors.

There also remain important needs. For example: (1) Some capture cross sections need to be remeasured in the nuclear excitation range where resonances are important, for the reactor data base. (2) Neutron and photon emission spectra to at least 20 MeV are needed for materials of importance to fusion energy, to support development of improved models for neutron emission. (3) Charged-particle emission cross sections are needed for 10-to-60-MeV neutrons for carbon and oxygen to enable correct specific energy loss estimates for the neutron radiotherapy application.

Evaluation Program

Evaluated nuclear cross-section and decay data developed in the United States are stored in the Evaluated Nuclear Data File (ENDF/B) system. Version VI of this file is now in final preparation, replacing earlier files released over a period starting about 10 years ago. Complete neutron cross-section sets through 20-MeV energy will be included for 86 important nuclides or elements. Fission product yields, complete decay spectra for the calculation of after-shutdown decay power of a nuclear reactor, and neutron radioactivation cross sections are also included. For the first time, delayed neutron spectra of fission-product precursors will be given. The file also includes R-matrix characterizations of the D + T and D +D reactions, which are most important to fusion applications. The work is coordinated through the National Nuclear Data Center at BNL, and the Cross Section Evaluation Working Group (CSEWG) guides the evaluation and testing efforts. This group includes representatives of user industries, universities, and major nuclear laboratories.

Nuclear Structure and Decay Data

Nuclear structure and decay data have been compiled for half a century in the form of nuclear levels and transitions, so that duplication of effort is avoided and a consistent data base is available. Nuclear structure data for atomic mass numbers through 266 are collected in the Evaluated Nuclear Structure Data File (ENSDF) available on computers. This system forms the basis for the Nuclear Data Sheets. New data on many of the 2200 known nuclides are generated each year. About 20 full-time evaluators, about half inside the U.S., are organized by the International Atomic Energy Agency and reevaluate about 25 A-chains per year. Coordination and support for this activity is provided by the National Nuclear Data Center at BNL.

Continuing nuclear data evaluation will be required for future applications, both because different materials and reactions will need emphasis and because accuracy standards tighten. Specific goals include: (1) For reactor-related data, increased accuracy is needed to achieve longer core lifetimes with smaller amounts of excess reactivity to facilitate passive safety design concepts. (2) Theoretical methods that are predictive in nature will be stressed to satisfy data needs where measurements are not feasible. (3) The scope of ENDF/B should be broadened to consider a wider range of applications than fission and fusion energy production, and to include those more completely.

For the nation to be able to tap the great potential that nuclear energy offers, continuing steady efforts are required such that the knowledge of nuclear processes that basic science develops is compiled and systematized for use by nuclear engineers. The nation must maintain a strong capability in the applied nuclear data area. Intensive international cooperation makes significant progress possible in this domain at current manpower levels. A good start is being made in Western Europe, the United States, and Japan to identify evaluation problems that can benefit from a joint effort.

Attracting bright young scientists to this area on a continuing basis is important. This will be aided if facilities and equipment are kept upgraded, if there is ongoing university involvement in nuclear data efforts, and if innovative physics activities accompany the applied physics measurement programs.

IV. THE TOOLS FOR NUCLEAR RESEARCH

IV.1 Accelerator Facilities

Introduction

The major portion of research in nuclear physics continues to be carried out at charged-particle accelerators. Thus, the continuing modernization, as well as the development and application of new accelerator technology, is of great importance to the field. As was emphasized earlier in this report, nuclear physics has need for several types of primary accelerator beams: electrons, protons, and heavy ions. Each serves a different class of experiments. Neutron beams from reactors complement this group. Today, nuclear physics accelerator technology ranges from the development, design, and construction of accelerators suitable for small and medium-sized university facilities to very large accelerators located at national laboratories. Because of this wide spread of technologies and sizes, as well as the variety of beams used in nuclear physics, nuclear accelerators have found many applications outside of nuclear physics. Indeed, about 99% of all operating accelerators are found in applied areas, most notably in medicine and materials science. It is thus equally important to keep up the appropriate training of students in the necessary skills to manage the increasingly sophisticated machines that are being built. For the latter reason, nuclear physics is particularly fortunate that a number of its accelerator facilities, including three major ones (Bates, MSU, and IUCF) which are operated as national users facilities, are operated by university groups.

New accelerators and upgrades to existing nuclear facilities incorporate several recent advances in accelerator technology. Among these one finds superconducting magnets, superconducting resonators to produce high-gradient radiofrequency fields for acceleration of charged particles, and electron cooling of beams in storage rings.

In this section, we review the facilities that are presently operated principally for nuclear physics research. These fall into two major categories:
(1) larger facilities that operate for substantial outside user communities, and
(2) smaller facilities that mainly serve local groups of scientists.

An increasingly important trend is the shared use of the larger facilities for nuclear and particle physics. Today one finds involvement of nuclear physicists at the high-energy physics accelerators at Fermilab (FNAL), Brookhaven (BNL), and SLAC. Conversely, the major new nuclear physics facilities that are being discussed have an admixture of particle physics opportunities.

The major new facilities proposed and discussed in this plan are the Relativistic Heavy Ion Collider (RHIC) at BNL, and the intense-proton 30-GeV accelerator, KAON, proposed in Canada. We will give brief descriptions of these in the final part of this section, which gives a general long-range outlook over the accelerator needs of nuclear physics.

Major Accelerator Facilities

Electron Accelerators

It is in the area of electron beams that the 1979 and 1983 LRPs had their greatest impact. The pressing need for multiple, high-intensity beams of a continuous-wave time structure suitable for coincidence work had led to the early recommendations for the construction of CEBAF (Continuous Electron Beam Accelerator Facility) as the premier high-energy (4-GeV) continuous-beam electron facility, and for the upgrading of the Bates 1-GeV accelerator through the addition of a stretcher ring. Both of these projects are now under construction and will come on line for research in the first part of the 1990s. This powerful, modern capability, augmented by capabilities at much higher energies at SLAC (including 15 GeV at PEP), should satisfy the research needs for electron beams over the time span of this LRP.

Construction of the **Continuous Electron Beam Accelerator Facility**, begun in early 1987, is well under way in Newport News, Virginia. The facility, which is planned to be ready for experiments in 1994, will provide continuous electron beams with energies between 0.5 and 4 GeV and currents up to 200 μA, divisible into three simultaneous beams serving three separate target areas. To achieve this high energy and high current, the accelerator will use newly developed superconducting resonators operated at liquid helium temperatures.

CEBAF will be used to study the structure of the nuclear many-body system, its quark substructure, and the strong and electroweak interactions governing the behavior of nuclear matter. The combination of energy, beam intensity, and high duty factor, will make this machine a unique instrument for nuclear physics research well into the next century. CEBAF will be a user facility, serving both the national and international communities in the area of electromagnetic physics. The research program will rely on high-precision magnetic detection systems to measure elastic and inelastic form factors, single-nucleon density distributions in $(e, e'N)$ reactions, as well as other final states with pions and kaons. A novel spectrometer (LAS) with a very large angular acceptance will study multiparticle final states. Electromagnetic transition form factors of hadronic systems, resonance production and propagation in nuclei, and multinucleon emission in e-nucleus interactions as well as fundamental form-factor measurements, parity violation measurements, hypernuclear physics, and baryon resonance studies are all possible subjects.

The **Bates Linear Accelerator Center** at the Massachusetts Institute of Technology provides high-quality electron and photon beams with energies of up to 1 GeV. The pulsed S-band electron linac and the isochronous recirculator (shown in Fig. 38) can provide currents in excess of 80 μA at a duty factor up to 1%, for an experimental program recognized worldwide for its contributions to single-arm high resolution electron scattering, to high momentum transfer, high missing energy coincidence studies of the $(e, e'p)$ reaction, and to pion production in nuclei. At present, major emphasis within the electronuclear community has been placed on the measurement of spin observables. A polarized electron source has been constructed in collaboration with Yale University and provides average beam currents of up to 50 μA with about 40% polarization. Spin response functions of nucleons and few-body nuclei, and parity-violating asymmetries have been measured. These will provide a major focus of activity over the next several years.Bates serves a large outside user community, involving over 200 scientists from about 50 universities and national laboratories. About 65% of the research time goes to outside users.

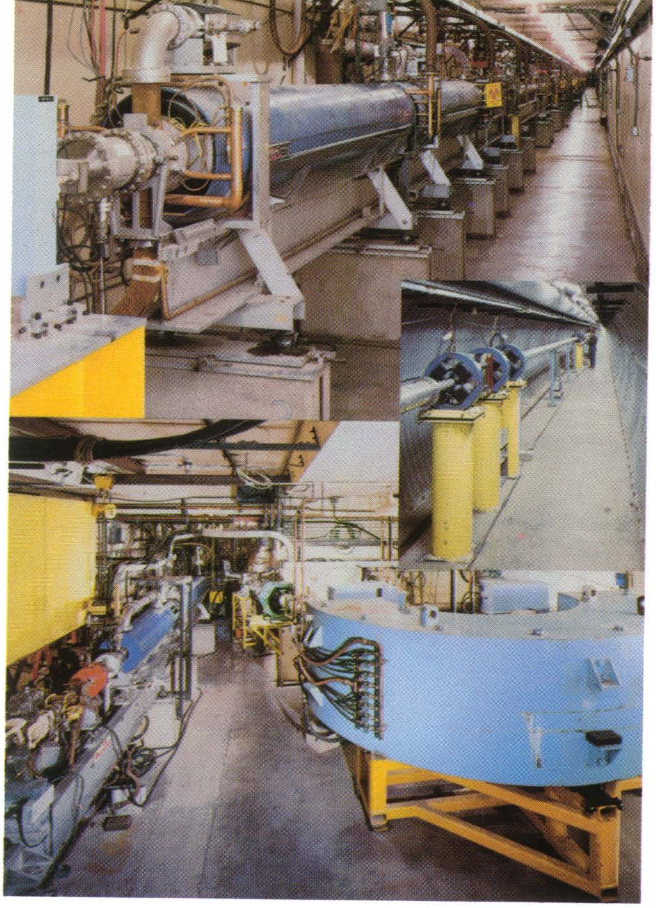

Figure 38: The main accelerator and the isochronous recirculator turn of the Bates Electron Accelerator. Beams bursts from this facility will be stored and time-stretched in the South Hall stretcher ring to provide a 100% duty factor beam of 1 GeV energy.

Construction of the South Hall Ring, which will provide 100%-duty-factor polarized and unpolarized beams, is now under way. The ring is designed to operate in the energy range up to 1 GeV at peak circulating currents of up to 80 mA and average extracted currents of up to 50 μA with an energy resolution as low as 0.04%. It will be fed by the existing accelerator-recirculator system. The 190-m-circumference ring can be operated in either pulse-stretcher or storage modes. Operating in the pulse stretcher mode, the ring will convert the injected pulsed electron beam into a nearly continuous one, thereby improving the ability of experimenters to carry out coincidence experiments by a factor of 100. Operating the ring in the storage mode, internal target experiments will be carried out. This will allow the detection of highly ionizing recoil particles and, with polarized targets and beams, the introduction of full spin capability to the electronuclear program. This combination of spin physics measurements with polarized beams and internal targets will be unique. Present plans call for the South Hall Ring to be available for physics research in 1992.

Proton Accelerators

The availability of proton accelerators has remained relatively stable since the 1983 LRP, but the successful completion of the Indiana Cooler Ring represents a significantly upgraded capability. The 1983 plan had expressed the desirability of constructing a modern 10-to-30-GeV, high beam-intensity machine, and several conceptual designs have been considered over the past five years. The recent Canadian proposal, KAON, for a 30-GeV, 100-μA proton accelerator that could be completed by 1995, has been the basis for enthusiastic discussion during the deliberations for this LRP, resulting in a major recommendation. This machine will be briefly described later.

At this time, the proton accelerator at the **Los Alamos Meson Physics Facility** (LAMPF) is the most powerful of the three pion factories in the world, and the only one in the U.S. It is an 800-MeV proton linear accelerator that can simultaneously produce beams of H^+ and H^-, and of polarized H^-. The H^+ beam, with average beam currents in the 1-mA range, is used to produce secondary beams of pions, muons, neutrinos, and spallation products for basic research, and is also available for applied research and development purposes (e.g., production of sizable quantities of radioactive isotopes). Several different magnetic channels, servicing a variety of experimental detectors, allow researchers to select the energy and particle type of the secondary beam. The polarized H^- beam, at energies from 211 to 800 MeV, is used for nucleon-nucleon and nucleon-nucleus studies and for producing beams of polarized neutrons. The unpolarized H^- beam is used to fill the existing Proton Storage Ring (PSR) for production of intense, pulsed neutron beams in the neutron scattering facility. During a typical year LAMPF provides about six months of beam time to about 50–60 experiments, involving over 400 scientists and students from over 50 different institutions.

Presently, the four main areas of nuclear physics research at LAMPF are: (1) the interaction of pions with nuclei to study details of nuclear structure and to learn more about the pion interaction with and in nuclei; (2) investigation of the spin and isospin degrees of freedom by studying proton interactions with nuclei; (3) investigations of the basic proton-proton, neutron-proton, and pion-nucleon interactions; and (4) fundamental aspects of the electroweak interaction and possible extensions of the Standard Model. The very high instantaneous intensity of the LAMPF beam allows for a unique program in neutrino physics. Near-term and future facility plans include the exploitation of the powerful new capability for exploring spin and isospin degrees of freedom and the commissioning of the MEGA detector, with the purpose of increasing the sensitivity to very rare muon decay by more than a factor of 100. High priority is now placed on construction of a pulsed neutrino source with the PSR, which could be used in conjunction with the proposed large water Cerenkov detector (LCD) to provide a more precise determination of the Weinberg angle to test the Standard Model. Consideration is also given to increasing the primary energy of LAMPF to 1.6 GeV, which would provide much more energetic pion beams.

The **Indiana University Cyclotron Facility** (IUCF) is one of the two major nuclear facilities that are supported by the National Science Foundation and is operated as a National User Facility since 1975. Polarized and unpolarized light-ion beams are first accelerated to 210 Q^2/A MeV by a coupled pair of separated sector cyclotrons. These beams are used for a diverse program of research and also to inject into the recently commissioned electron-cooled storage ring and synchrotron accelerator. The cooled beam in the ring can be accelerated to 560 Q^2/A MeV. The electron cooling results in dramatic decreases in both the longitudinal and transverse phase space of the beam. The circulating beam current is expected eventually to reach several milliamperes, which, when used with suitable internal targets, should yield luminosities of up to 10^{32} $\text{cm}^{-2}\text{s}^{-1}$. Experimental facilities that use beams from the cyclotron include a new K-600 spectrometer, which permits a resolution of better than 20 keV to be obtained with 200-MeV protons, and a 20-cm-long liquid deuterium target to produce polarized neutrons by spin transfer from the incident polarized proton beam. Future plans for the cooler include additional spectrometers for charge-exchange studies and a large-acceptance spectrometer to be used with polarized internal targets. A small synchrotron, which would have several advantages over the cyclotrons as an injector to the ring, is also being studied. A design effort has been initiated to review the opportunities presented by using the very low emittance beam from the cooler to inject into a 56-T·m synchrotron and storage ring.

Heavy-Ion Accelerators

The 1983 LRP called for the construction of a relativistic heavy ion collider. This machine has since been developed as the RHIC project and moved to the point of construction at Brookhaven National Laboratory (BNL). Its swift realization is the major recommendation of this LRP for new construction. Apart from RHIC, the area of heavy ion accelerators has seen advances at all national facilities dedicated to heavy-ion research, over the last five years. Qualitatively major steps forward are the large superconducting cyclotron at Michigan State University (MSU), the successful coupling of a heavy-ion beam to the AGS accelerator at BNL to produce the first ultrarelativistic heavy ion beams in the U.S., and the upgrading of the ATLAS superconducting linear accelerator for the production of high-quality uranium beams.

The **National Superconducting Cyclotron Laboratory** (NSCL) at Michigan State University is the second major nuclear facility funded by the National Science Foundation. NSCL has operated as a national user facility since 1983 and has served about 330 scientists and graduate students. It is dedicated to research with heavy ions of medium energy and to the continuing development of superconducting cyclotrons. Two of these, the K-500 and K-1200, are independently available for research. The recently completed K-1200 machine, the largest superconducting cyclotron in the world, is designed to accelerate light ions to 200 MeV/A and the heaviest nuclei to about 80 MeV/A. A superconducting high frequency (28 GHz) electron cyclotron resonance (ECR) ion source is under development and would help to reach the highest energies specified. Major experimental facilities include a 4π detector for recording large multifragment breakup events, a reaction mass spectrometer for studying nuclei far from stability, and a low-resolution spectrograph for mass measurements and giant resonance studies. An additional 4π detector (the Miniball) designed to study the decay of hot nuclei is nearing completion. A proposal has been submitted for a high-resolution ($\delta p/p = 10^{-4}$) spectrograph with large solid angle (10-20 msr) for nuclear structure studies. A broad research program ranges from studying the thermodynamic properties of nuclear matter via colliding heavy nuclei, through the excitation of giant inelastic and charge-exchange resonances, to the properties of nuclei far from stability and their astrophysical implications. The latter will profit from a superconducting beam analysis and transport system that will separate and identify recoiling exotic nuclear reaction fragments with high selectivity.

The **88-Inch Cyclotron** at the Lawrence Berkeley Laboratory is a variable-energy isochronous cyclotron with spiral-sector focusing. With the addition of an ECR source in early 1985, the energy and the mass range of available beams were substantially increased. For light ions, energies of 35 MeV/A, and in excess of 5 MeV/A for masses up to about $A = 150$, are being provided for experimental programs in nuclear science as well as in other areas, such as atomic physics, surface physics, radiation damage in semiconductors, and biomedicine. The basic research program is focused on several topics, including investigations of heavy-ion reaction mechanisms, production and study of exotic nuclei far from stability, structure at high angular momentum, nuclear astrophysics, and the chemical and physical properties of the transuranic elements. In particular, a 21-element array (HERA) of BGO Compton-suppressed high-resolution germanium detectors has been in use for several years to study nuclei at high spin. A 40-element total-energy-multiplicity inner ball of BGO is now in operation with HERA. This is a premier high-resolution γ-ray facility in the U.S.

Future accelerator improvements include a new ECR source, operating at 14 GHz, to provide beams up to $A = 200$ at the Coulomb barrier. This device, started in the fall of 1988, is expected to be in operation in the fall of 1990 for research. Beyond this, a conceptual design study for a 28-GHz superconducting ECR source driven by a gyrotron is in progress and could be available for the research program at the 88-Inch Cyclotron in the mid-1990s. Beams of uranium above the Coulomb barrier, together with substantially increased beam currents, would result from coupling such a device to the existing machine.

The **Holifield Heavy-Ion Research Facility** at Oak Ridge National Laboratory is a major national user facility for research with heavy ions. The facility includes a tandem accelerator, which is now routinely operating at a voltage of 25 MV (highest of any electrostatic device in the world), and the Oak Ridge Isochronous Cyclotron (ORIC), which serves as an energy booster for heavy ion beams from the tandem. This facility can supply beams all the way up to uranium. These projectiles are used to study nuclear structure and nuclear behavior under a variety of extreme conditions, such as high excitation energy (hot nuclei) and large angular momentum, as well as to create nuclei far from stability. In addition, nuclear reactions and the dynamical processes by which they come about are explored in terms of bombarding energy and impact parameter. Smaller research efforts in atomic physics and applications of nuclear science are also carried out.

To carry out this rich research program, major pieces of experimental equipment are in use at the facility. Examples include two magnetic spectrometers, a velocity filter, and a multielement array of charged-particle detectors with a large dynamic range (HILI), all of which can be used to study nuclear reaction dynamics. A 72-element, 4π NaI gamma-ray system (Spin Spectrometer) has been actively used in the study of nuclei at high spin. Up to 20 of the Spin Spectrometer elements can routinely be replaced with Compton-suppressed high-resolution gamma-ray Ge detectors. In addition, small charged-particle detectors (such as the Washington University Dwarf Ball) can be placed inside the Spin Spectrometer to perform coincidence measurements between γ rays and associated charged fragments. The UNISOR (University Isotope Separator at Oak Ridge) magnetic isotope separator project with a nuclear orientation facility is located at Holifield and carries out a program of research on nuclear properties, particularly for nuclei far from stability. A major new piece of equipment, the recoil mass spectrometer (RMS), built in conjunction with a university consortium, will greatly enhance the capabilities of this facility when completed in the early 1990s. This instrument will select reaction products (for both normal and inverse kinematics) with high mass resolution. The RMS has been designed to accommodate the proposed Gammasphere array either at the target or focal plane position.

The **Argonne Tandem-Linac Accelerator System** (ATLAS) at Argonne National Laboratory is a superconducting accelerator system for heavy ions. It consists of a 40-MV equivalent superconducting linear accelerator, and in its initial phase of operation (begun in 1985), a 9-MV tandem Van de Graaff injector. The system was designed for high-resolution nuclear physics research in the energy range <25 MeV/A, where nuclear structure effects are particularly important. ATLAS can provide very short beam pulses (<150 picosec), a feature that has opened new research opportunities. In order to expand the mass range of projectiles to the heaviest elements, the tandem is now being replaced by a positive-ion injector consisting of an ECR ion source and a superconducting injector linac of novel design. The first phase of this addition is already complete, and by 1990–91 ATLAS will be able to accelerate beams up to uranium with qualities unequaled for nuclear physics research in the vicinity of the Coulomb barrier. The present experimental program at ATLAS includes studies of high-spin nuclear physics, subbarrier reactions, fission and fusion reactions, quasielastic and deep-inelastic reactions, and accelerator mass spectroscopy. A small program of atomic physics and other non-nuclear investigations is also carried out at ATLAS.

Major pieces of equipment include a multidetector γ-ray system (with the capability of associated charged-particle detectors for coincidence experiments) and 2 magnetic spectrographs. Construction of a fragment mass analyzer (FMA) is in an advanced stage. It will allow reaction products to be detected and analyzed, free from contamination by the primary beam. Planning for a new detector system called APEX (ATLAS Positron Experiment) is being actively pursued. This device, a solenoidal magnet with associated detectors, will be used with uranium beams to elucidate the nature of puzzling sharp coincident electron-positron lines seen in a long series of experiments at the GSI UNILAC accelerator (see Section II.8). Present plans call for this device to be ready in the 1991–92 period.

The **Bevalac Facility** at the Lawrence Berkeley Laboratory was until very recently the only accelerator in the world capable of accelerating the complete spectrum of nuclei, from protons to uranium, from low energies around 30–40 MeV/A to relativistic energies of 1–2 GeV/A. As such it has been a pioneering facility. Only now is the just completed SIS facility in Germany starting to provide competition. The Bevalac complex consists of the SuperHILAC (linac) as the injector of heavy ions at 8.5 MeV/A into the Bevatron (a weak-focusing positive-ion synchrotron), where they are accelerated and extracted into several experimental areas for nuclear physics research. In addition, the Bevatron has its own local source as a primary injector for the unique medical radiotherapy/biology program, which runs about 30% of the time.

The central research focus of the Bevalac program is the investigation of extreme conditions in nuclear matter. Measurements of rare processes, such as dileptons (electron-positron pairs), are made in order to learn about the early stages of the collision process, while subthreshold pions, kaons and antiprotons provide valuable information on cooperative effects in nuclei. The process of multifragmentation is studied at intermediate energies to determine how nuclei disassemble when very highly excited. Studies with radioactive beams are carried out to determine their basic interactions with matter and to produce nuclei far from stability. An atomic physics program tests quantum electrodynamics with one- and two-electron uranium.

The Bevalac's major facilities include HISS (a large-volume, superconducting-magnet spectrometer system) and its complement of detectors (time-of-flight detectors, large-volume drift chambers, multiplicity array); a streamer chamber for studying exclusive reactions in 4π geometry; and the dilepton spectrometer (DLS), a two-armed magnetic system for studying electron-positron pairs with invariant masses up to 1000 MeV. A time projection chamber (TPC) is presently being constructed and will be available in mid-1991 as the next-generation 4π detector at the Bevalac to study the physics of the nuclear equation of state.

The **Tandem/AGS facility** at the Brookhaven National Laboratory is also a unique accelerator complex, providing beams of relativistic heavy ions of up to 14.6 GeV/A (the highest energy heavy-ion accelerator in the U.S.) for a program of nuclear physics research. First heavy-ion operation of the Alternating Gradient Synchrotron (AGS), which normally accelerates protons, occurred in 1986. The ions originate in the Tandem, where they are accelerated and injected (after passing through an 1800-foot transfer line) into the AGS. There they are further accelerated and then extracted from the AGS into the various experimental areas for research. At present, fully stripped ions up to Si have been obtained from the Tandem facility for the experimental program of relativistic heavy-ion studies. In addition, there is an active intermediate-energy nuclear physics program using secondary kaon beams operating during the proton running cycle.

The initial physics experiments with heavy ions at the AGS have focused on central and peripheral collisions and on characterizing basic features such as particle spectra, particle multiplicity distributions, energy deposition, energy flow and the stopping of relativistic nuclei in nuclear matter. Fostering an understanding of the formation of hot hadronic matter, being essential for eventual production of a baryon-rich quark-gluon plasma, is central to this program. At present, there are three major experiments on the AGS floor. These include a magnetic spectrometer for measuring particle spectra and correlations, with associated multiplicity and energy-flow measurements, a time-projection chamber to study strangeness production and multiparticle correlations, and a large-acceptance device with electromagnetic and hadronic calorimeters and magnetic tracking to study peripheral and central collision processes. The intermediate-energy program includes the study of hypernuclei and a search for the H particle (a strangeness -2 dibaryon; see Section II. 7).

A booster synchrotron, located before the AGS, is in an advanced stage of construction. Initially designed to increase the intensity of protons for injection into the AGS, it will also be used to extend the mass range of heavy ions available for insertion into the AGS. Partially stripped ions up to gold (A = 197) will be injected into the Booster where they will be accelerated to sufficient energy to strip away all remaining electrons. They will then be extracted from the Booster and injected and accelerated in the AGS. When completed in 1992, the Booster will substantially enhance the heavy-ion physics program at the AGS, because many effects of interest in relativistic heavy-ion collisions are thought to benefit from the interaction of massive globs of nuclear matter.

The Tandem-Booster-AGS complex will later be used as the injection system for RHIC, which could be completed in 1996. As an injector, this complex of accelerators will be required to fill the storage rings of RHIC for periods of only a few minutes , at intervals of about twice a day. Thus, if the scientific priorities are sufficiently high, a fixed-target heavy-ion program at the AGS can continue during the operation of RHIC.

Smaller Accelerator Facilities

There are at present eleven smaller accelerator facilities funded by NSF/DOE. These are situated on university campuses and play a variety of important roles. First and foremost, they allow first-rate nuclear-physics research to be carried out in a university environment. As nuclear physics is a multifaceted discipline, one finds that not all of the important questions can *best* be addressed at the major centers. Indeed, some can *only* be investigated using one of the smaller, more specialized and flexible accelerators. Second, these facilities serve to provide long-term stability, as a visible presence to attract graduate students, and as staging areas for groups that carry out part of their research at the larger laboratories. The technical capabilities offered by the laboratory staff and the availability of beams for calibration of detectors are important elements of this mission.

Most of these smaller facilities have recently had, or are presently undergoing, major upgrades. Three tandem Van de Graaffs, at Florida State University, Stony Brook and the University of Washington, have been coupled to superconducting linac sections yielding heavy ions with energies between 5 and 10 MeV/A from ^{12}C to about A=90.

Upgrades of the Yale and Rochester large Emperor tandems have been completed successfully and operation has been initiated at 22.5 MV and 16 MV terminal voltage, respectively. Texas A&M University (TAMU) has just completed a K–500 Superconducting Cyclotron for light and heavy ions. The Princeton cyclotron facility is currently undergoing a thorough modernization to provide light projectile beams with greater intensity and precision. The pelletron accelerator at Caltech provides a new capability for precise measurements of low-energy cross sections. In each case, these upgrades were planned, designed, and executed by the local faculty, staff, and students. In some cases, these university laboratories have been upgraded by adding special input or output devices to their accelerators, again usually produced by the laboratories themselves. Research on new schemes for polarized ion sources and targets is carried out with great success at TUNL at Duke University, Princeton, and the University of Wisconsin. The University of Pennsylvania laboratory is recognized for its leadership in development of negative ion beams widely used with tandem accelerators. Stony Brook is exploring new rf structures for the acceleration of slow heavy ions. Caltech and Notre Dame have each developed new methods for measurements on radioactive targets.

The instrumental equipment and programmatic thrusts of these laboratories vary considerably. All have a complement of modern equipment for research near the Coulomb barrier. TAMU is designing a state-of-the-art Recoil Mass Spectrometer. A polarized ion source coupled to the new K–500 cyclotron will provide 140-MeV polarized deuteron beams. A pioneering high-intensity polarized ion source has been developed at TUNL and will be used with its tandem Van de Graaff, as well as being the central component of a new low-energy facility. By contributing heavily toward the development of instrumentation, ranging from the small to the very large, these facilities provide a symbiotic relationship between their research and research carried out by the local groups at national facilities.

Other Facilities

As was mentioned earlier, a number of nuclear physics programs use high-energy physics accelerators. Examples are Fermilab, SLAC, CERN and HERA, the latter in preparation. In two cases, these programs have gone further and added to the facility capabilities specific to nuclear physics needs.

The **Nuclear Physics at SLAC** (NPAS) program utilizes an electron beam generated by a portion of the 2-mile-long SLAC linac. An electron injector (called NPI for Nuclear Physics Injector) has been installed to inject electrons into the last 20% of the accelerator. This technique efficiently provides high-intensity pulsed beams at multi-GeV energies for the nuclear physics experimental program. First experiments were begun in 1985 and beam for nuclear physics has been delivered for approximately two months per year since that time.

The NPAS experimental program is centered on measurements of elastic and inelastic electron scattering at high-energy and high-momentum transfer to study the structure of nucleons and nuclei down to the sub-nucleon size of 0.1 fm. Nuclear physics experiments use the extensive facilities of End Station A, which houses three large magnetic spectrometers with cryogenic targets. In addition to the NPAS program, a collaboration has been formed to establish a nuclear physics interaction region in the PEP electron-positron storage ring at SLAC. This facility would consist of a gas-jet target and a large multiparticle forward spectrometer and nuclear fragment detectors to measure many particles in coincidence with scattered electrons at energies of 6–15 GeV. A proposal for this detector (PEGASYS) is being prepared and such a facility could be available for physics research in the early 1990s.

A novel facility is the **Laser Electron Gamma Source** (LEGS) installation at the National Synchrotron Light Source at BNL. Here a beam of polarized light from a laser is backscattered from the circulating electron beam to yield a monoenergetic photon beam with energies of up to 400 MeV.

There are several other facilities operated totally or mainly for nuclear physics research that depend on a larger infrastructure. For example, we note the TRISTAN isotope separator at the Brookhaven neutron reactor, which uses neutron-induced fission of uranium to produce a broad range of neutron-rich nuclei far from the valley of stability for a program on nuclear structure and nucleosynthesis studies. The ORELA neutron facility at Oak Ridge, which is used for the production of neutron reaction data, is a second example.

Outlook for the Next Decade

It is clear that nuclear physics has a broad base of research facilities in place at this time. The major pieces missing are those higher-energy accelerators that are needed to address the quark degrees of freedom in the nuclear medium, and that had already emerged from the 1983 and even the 1979 LRPs as crucial for that purpose. The research agenda outlined in the main body of this report requires those electron, heavy ion and proton accelerators which were projected in the 1983 LRP. This is summarized in our major recommendations given in the summary and in the final chapter.

The first priority is given to the completion of

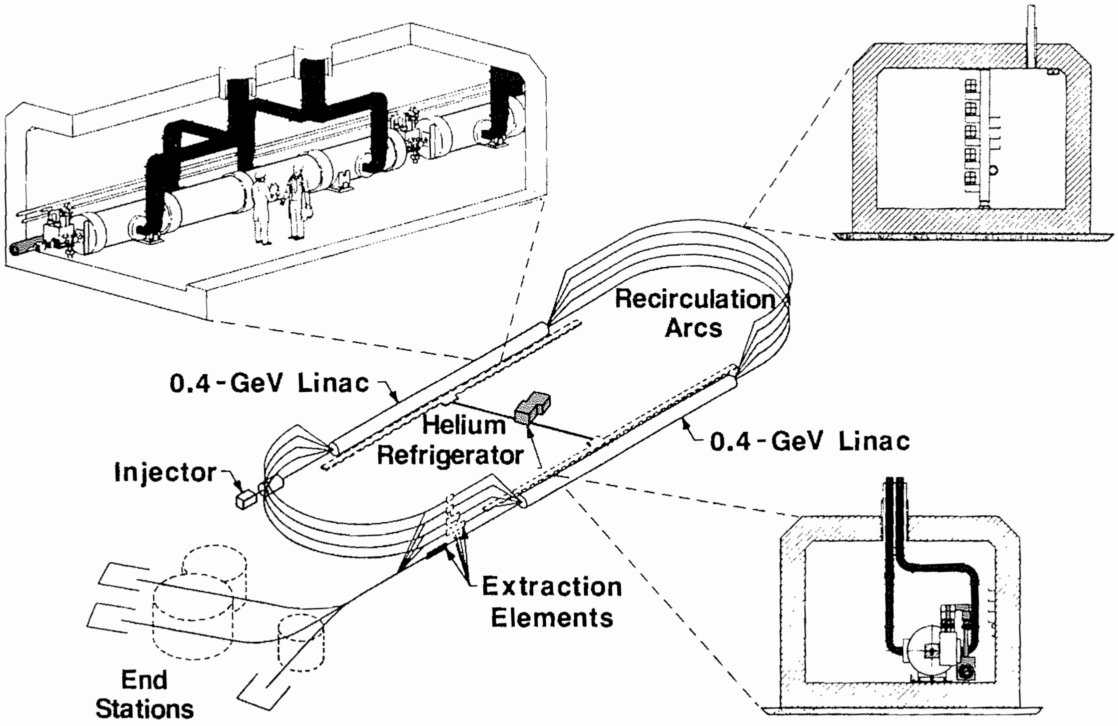

Figure 39: Schematic description of the CEBAF accelerator facility under construction in Newport News, Virginia. The electron beam passes through the two accelerating sections five times, being recirculated four full times around the race track. The beam can be extracted after each pass.

CEBAF as the major electron facility. With its 4-GeV energy, and 200-μA CW beam current serving three target areas simultaneously, CEBAF will provide opportunities for a large user community that is eagerly awaiting the 1994 start up date. A schematic depiction of the CEBAF accelerator is given in Fig. 39. Two superconducting linear accelerator sections, each providing 0.4 GeV energy gain per pass, will accelerate the electron beam over five consecutive passes, to the final energy of 4 GeV. Beams can be extracted after each pass and delivered to three target areas. The heart of the accelerator is a set of superconducting radiofrequency niobium cavities operating at a temperature of 2 K. These are described later in this section.

By 1992 the Bates South Hall electron storage ring will be available with capabilities that complement those of CEBAF, by allowing precision measurements with electrons on the spin degrees of freedom, which are emphasized in the scientific part of this report.

Highest priority for new construction is placed on the Relativistic Heavy Ion Collider, RHIC. At Brookhaven National Laboratory this accelerator has already undergone a thorough design and prototyping phase, in particular with respect to its superconducting magnets, and is ready for immediate construction. If its construction is started in FY91 it could be completed by 1996.

RHIC is a complex system of accelerators, as can be seen in Fig. 40. Heavy ions are produced inside an electrostatic Tandem accelerator and transferred over a distance of about 1800 feet into a booster synchrotron. The Booster's main purpose is to increase the ion energy sufficiently so that essentially all electrons can be stripped off (for gold, typically 77 of 79 electrons will be removed) as the ions emerge and before injection into the venerable AGS synchrotron. When they leave the AGS, the projectile ions will have an energy of about 10.5 GeV/A. Fully stripped, they then enter two rings, which are the heart of RHIC. After a filling time of about 1 minute, to an intensity of about 10^{11} ions per ring, they are accelerated for 60 seconds to a maximal energy of about 100 GeV/A per beam. The beams circle around in the two

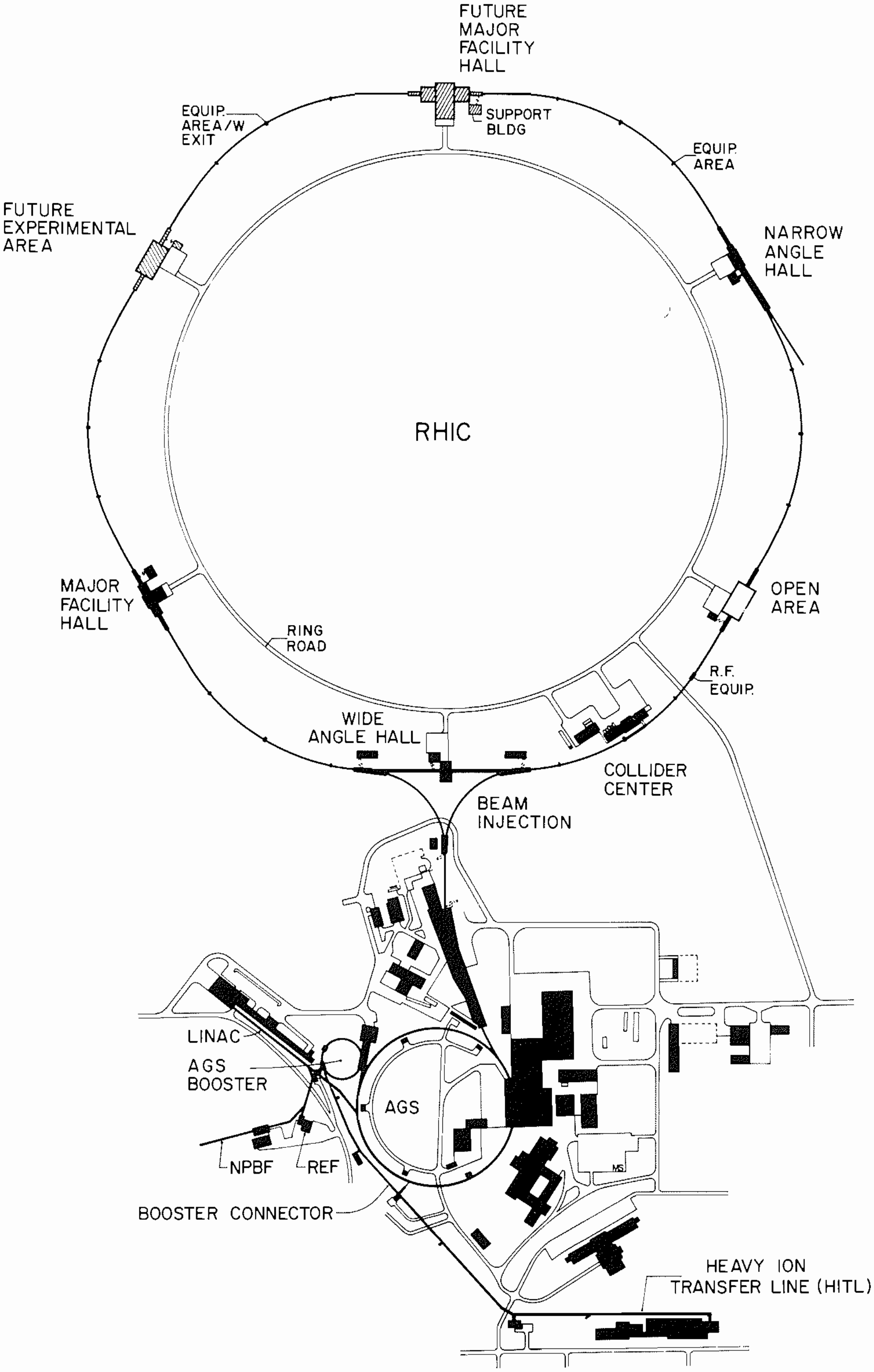

Figure 40: Outline of the Relativistic Heavy Ion Collider, RHIC, and its various preaccelerators. Ions are transferred from the Tandem accelerator at the bottom right of the figure through the Booster and the AGS into the two large RHIC rings. The two rings are so close together that they appear as one on the scale of this figure. The counter-rotating beams intersect in six interaction regions.

rings, 90 cm apart, in opposite directions, held in their pathways by superconducting magnets operated at 3.5 Tesla. The lifetime of the circling beams is estimated to be about 11 hours, so that the whole filling and accelerating process need occur only about twice a day, totaling 4 minutes altogether. The circling beams intersect at six points of which three are presently prepared as experimental stations. This complex system of successive accelerators is able to accelerate all ion species to a wide range of energies from about 1.5 to 100 GeV per nucleon. What makes the facility especially cost-effective is that all stages except the storage rings themselves are already in existence. RHIC will allow a wide nuclear physics program, but its main mission is the preparation and exploration of the quark-gluon plasma, as described in Section II.7. Until the completion of RHIC, i.e., 1996/97, the present AGS-Tandem program and the Bevalac will be important for initial measurements on RHIC physics. For medium-energy heavy-ion physics the new K=1200 cyclotron at NSCL will be the main heavy-ion facility in the U.S.

In the domain of hadronic beams, the Canadian proposal for a 30-GeV, high-current proton facility (KAON) has aroused great interest in the U.S. nuclear physics community. This machine is seen as fulfilling the need, already projected in the 1983 LRP, for an advanced hadron facility. This facility could conceivably become available as early as 1995. The U.S. has been invited to participate in the construction (at a level of $75M out of $\sim$ $500M) and, later, in the experimental program (with operating costs borne by the host country). NSAC has recently recommended that this offer be very seriously considered. The Long Range Plan Working Group (LRPWG) followed this recommendation with a statement of high priority included in this report.

KAON is designed to accelerate a 100-μA proton beam to an energy of 30 GeV. To achieve this intensity the accelerator consists of a sequence of five rings, three rings used for acceleration are interspersed by storage rings for time matching. The initial beam is produced in the TRIUMF cyclotron at an energy of 500 MeV and stored in the accumulator. It is then accelerated in a synchrotron to 3 GeV and stored in the collector, and finally accelerated to 30 GeV and stored in the extender ring, which delivers a slowly extracted beam to a stationary target.

For the near term, the two existing hadron facilities, LAMPF and the IUCF cyclotron-cooler, will be the main work horses for medium-energy nuclear physics with protons. The pion beams of LAMPF will be unique in the U.S., as will be the high energy definition of the IUCF cooler ring.

A number of potential upgrades and "smaller" facilities (although the costs ranged from $20M to $160M), which would serve specific projected needs over the next decade, were presented to the LRPWG. Some of these should be developed further and, if cost-effective, could be considered for funding during the 1990's.

- *Radioactive beam accelerator:* It is becoming increasingly apparent that a facility producing beams of radioactive nuclei that have extreme neutron-to-proton ratios is of high scientific interest and technically feasible. It would allow the study of nuclear structure and astrophysical reactions very far from the line of stable nuclei, and could provide new possibilities of reaching the long-sought island of stability of superheavy nuclei. Such facilities are under advanced consideration in Japan and at CERN in Europe.
- *High energy proton cooler ring:* With the recent success of the electron-cooled polarized proton storage ring at IUCF, the value of a similar storage ring in the 10-to-20 GeV energy range for hadron spin physics might be explored.
- *LAMPF energy doubler:* The Los Alamos Meson Physics facility is evaluating the scientific potential of a doubler stage to its present linac, that would boost the proton beam energy to 1.6 GeV and the intensity to 2 mA. This would make available, among other things, the world's most intense high-resolution pion beams, which would be useful for the detailed study of hypernuclei.
- *High resolution 0.5 GeV/A heavy-ion accelerator:* An accelerator capable of delivering heavy ion beams at energies between 0.5 and 1 GeV/A with excellent energy resolution would permit nuclear structure studies with heavy ions, allow the spectroscopic study of nuclei far from stability, and could be useful to provide insight into the behavior of nuclear matter at and beyond the liquid-gas

phase transition.

- *Very cold neutron beams:* The potential of a facility capable of providing high fluxes of cold and ultracold neutrons for disclosing the fundamental symmetries of nature is well recognized. Interaction with other disciplines that are presently considering such facilities, with a view toward gaining access for nuclear physics, could prove very fruitful.

IV.2 Developments in Technology and Instrumentation

Superconducting Structures

The five-year period since the last LRP has seen great advances in the application of superconducting technology to accelerators. Several projects that were under study at that time have since become operational, and the use of large superconducting magnets and accelerating structures is becoming relatively routine, if still technically challenging. The K–1200 cyclotron at MSU and the Texas A&M superconducting cyclotron, both now operational, vividly illustrate the compactness and reliability of such designs. MSU has also designed and is presently constructing a 1.6-GeV/c beam-transport system utilizing superconducting quadrupoles of a novel cold iron conformal-mapped design. A six-magnet prototype of this beam line has been in routine operation for over a year. Brookhaven has constructed six prototype 9.7-m superconducting magnets for RHIC (Fig. 41). These magnets have an 8-cm bore and operate at a field strength of 3.5 T. They have all been successfully operated and show no quenching until well above their design fields. The magnets employ a single-layer winding of superconducting cable and are well adapted to industrial production.

Superconducting rf technology has matured considerably in the past few years so that, with sufficient attention to production details (cleanliness, surface treatment, purity of material, etc.), one can now commercially produce large structures reliably operating at high field gradients. The largest nuclear physics accelerator project presently under construction, CEBAF, employs 80 meters of such structure. The basic 2-cell, 1-meter niobium structure is shown in Fig. 42. It operates at a frequency of 1.5 GHz with a design gradient of 5 MV/m and a Q at 2 K of $\geq 2 \times 10^9$. The associated 4.8-kW 2K refrigerator will be the largest such unit in existence. The lower-frequency niobium cavities recently developed at the Argonne ATLAS accelerator have recently been successfully employed in their new preaccelerator, where they allowed acceleration of heavy ions with the record low velocity of $\beta \leq 0.01$. This new ATLAS acceleration system, as well as the K–1200 cyclotron facility at NSCL, will utilize superconducting elements for all accelerating and focusing functions.

At LAMPF a single-cell superconducting rf cavity operating at 400 MHz with fields of 5 MV/m will be used to rotate the longitudinal phase space of a secondary pion beam (in which the time structure of the primary proton beam is preserved). In this way, the cavity will reduce by a factor of five the energy spread of the pions in the energy range from 50-100 MeV, leading to either much increased pion fluxes at moderate energy resolution or to considerably higher energy resolution of pion beams used for studying nuclear level structure.

Ion Sources

Major improvements have taken place in ion-source technology, for the production of highly charged heavy-ion beams and intense polarized beams of electrons, protons and deuterons, and for fission- or reaction-product ion sources.

For heavy-ion sources, the Electron Cyclotron Resonance (ECR) source first developed at Grenoble and now employed at ATLAS, Berkeley, MSU, and Texas A&M continues to be developed further, by employing higher-frequency rf drivers. This development promises to produce much more highly charged ions, such as Pb^{35+}, at currents of 1 μA.

Major increases in intensity for polarized proton and deuteron beams have recently been achieved in ion sources that combine atomic beams with the ECR principle for ionization. The best case is the source recently completed at the TUNL laboratory, which produces over 100 μA of H^+ or D^+ beam, as extracted from the ECR ionizer. With a cesium charge-exchange oven added to the system, currents of $\sim 10\mu$A of H^- or D^- are obtained, with polarizations of over 86% of the total beam. This represents an increase by a factor 20 over intensities obtained with Lamb shift sources. The TUNL polarized ion source is shown in Fig. 43. New higher-intensity polarized H^- sources that utilize laser-pumped alkalis are being commissioned at LAMPF, TRIUMF, and KEK. The possibilities of such sources are best illustrated by the KEK result of a $100\mu A$ (peak current) H^- beam with 65%

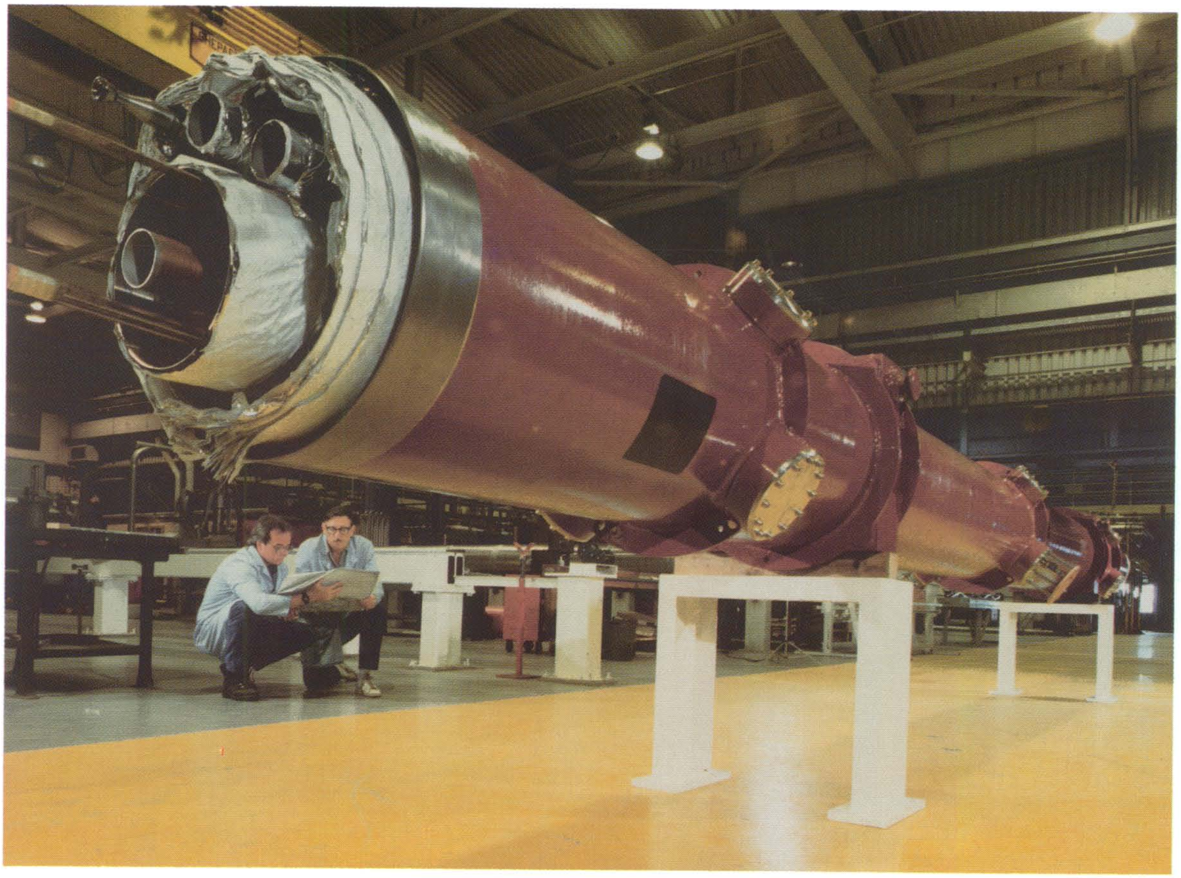

Figure 41: A prototype of a 9.7-m superconducting magnet for RHIC.

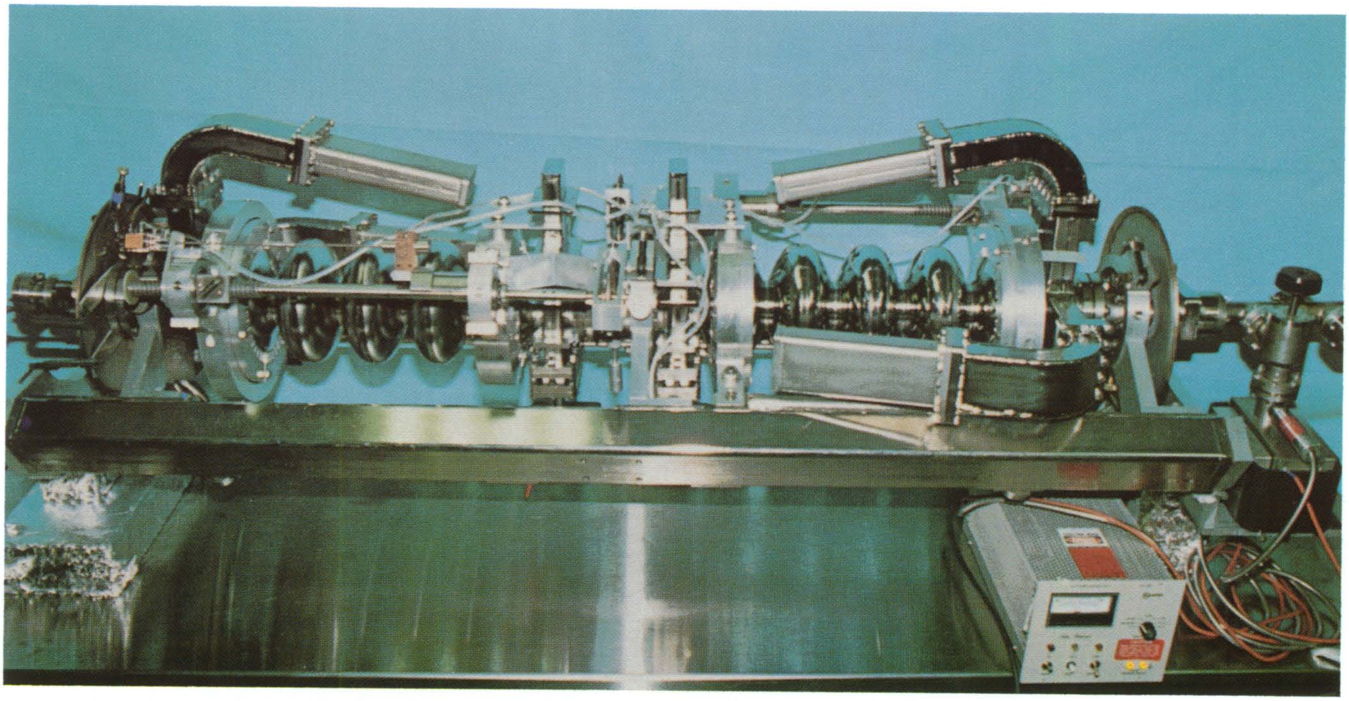

Figure 42: A two-cell, 1-m niobium superconducting rf cavity under development for the CEBAF facility. These structures have produced accelerating fields as high as 7 MV/m at an operating temperature of 2 K.

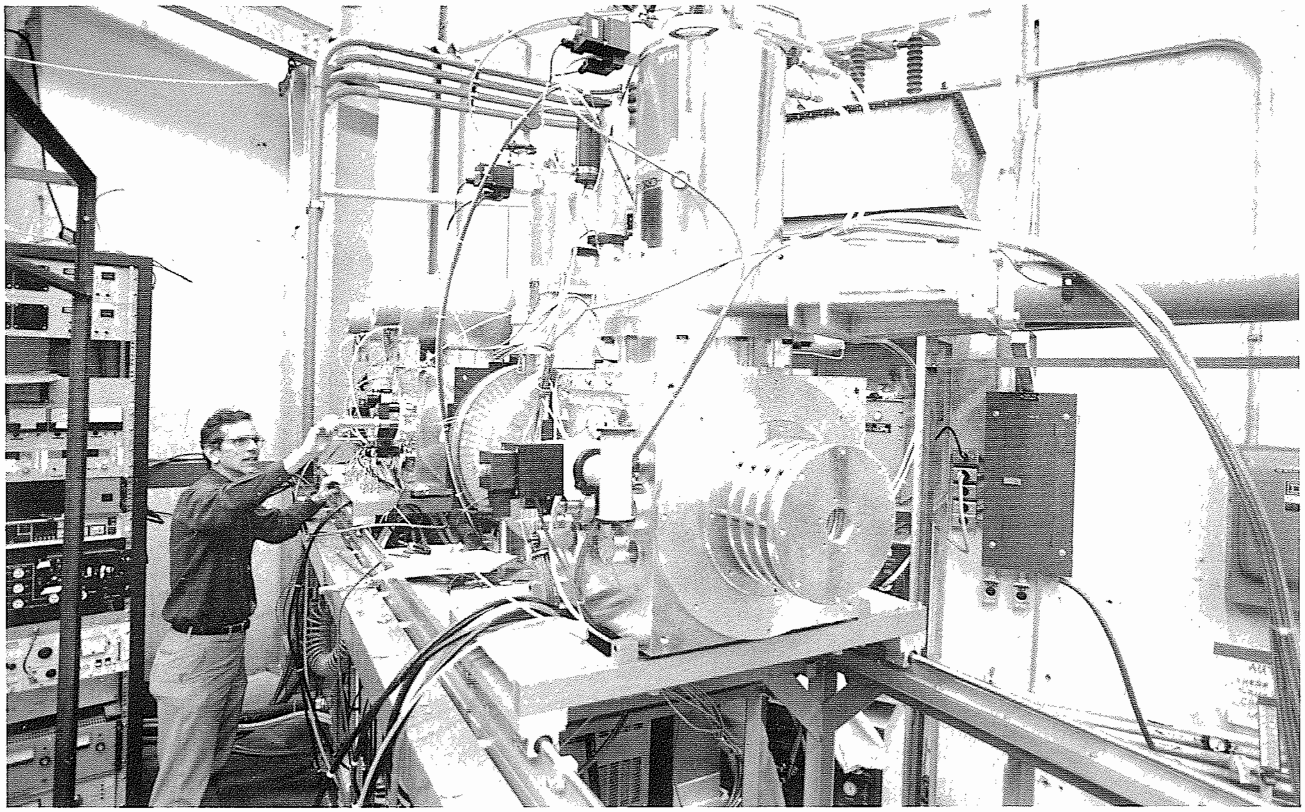

Figure 43: The high-intensity source of polarized protons and deuterons recently completed at TUNL. The atomic beam oven is at the far end of the picture, followed by the spin polarizing sections, the ECR ionizer and, finally, the cesium charge exchange canal. The beam emerges from the flange on the right end of the apparatus.

polarization.

In polarized-electron sources, major efforts are under way at Illinois, Rice, CEBAF, and SLAC to improve the $\approx 40\%$ polarization achieved presently with photoionization gallium arsenide electron sources. Experiments using extremely thin layers achieve values close to the theoretical maximum of 50% for this material. This limitation is due to a solid-state effect, i.e., the degeneracy at the top of the valence band. Other materials not having this degeneracy, such as the chalcopyrites (e.g., $ZnGeAs_2$), are under investigation at CEBAF and Illinois. Another method of achieving a very high degree of polarization is the optical pumping of ^{3}He atoms. This technique is under study at Rice and presently yields currents of a few microamperes with a polarization of roughly 90%.

Improvements in the ion-source technology for beam- or fission-produced radioactive nuclei are critical for any future radioactive beam facility. Recent advances in plasma and thermal sources have produced large increases in yield, leading, e.g., to an 8-fold increase in useful beams at the TRISTAN fission-fragment facility.

Targets

A number of interesting developments have occurred in the field of targets, in response to the needs of the new storage rings and to relativistic heavy-ion beams.

The development for use in storage rings ranges from unpolarized jet targets of diatomic gases (H_2, D_2, N_2) for use at the Indiana Cooler Ring to polarized storage-cell targets of hydrogen and deuterium developed at Wisconsin. Argonne has also developed polarized hydrogen and deuterium targets for use in such machines and an experiment using these is now being carried out at Novosibirsk. Polarized ^{3}He targets offer the best available alternative to a polarized neutron target, and these are being developed at Caltech, MIT, Wisconsin, Harvard, and Princeton. The Caltech-MIT method is to optically pump ^{3}He metastables in a Pyrex cell and then transfer them through a capillary to a copper cell placed in the beam. The Princeton-Harvard-MIT method uses optical pumping of a Rb beam, which then spin-exchanges with the ^{3}He. The Caltech-MIT targets are to be utilized in experiments proposed at IUCF, Bates, CEBAF, and HERA. Progress has continued in achieving high polarization in p, d, ^{6}Li, ^{13}C, and other nuclei for use in external beam experiments. The use of irradiated deuterated ammonia pioneered at Bonn has provided polarized targets with an increased fraction of deuterium (16% vs.9%) and target lifetimes that are not limited by radiation damage. Targets of polarized light nuclei have begun to be utilized in proton and pion experiments at the meson factories.

A major new development in target technology are the so-called "live" targets for use with relativistic heavy-ion beams. A live target represents more than just an inert piece of material with which the beam interacts, by producing a signal that is part of the measurement. While such targets have been used for special purposes in the past, they have become essential parts of most relativistic heavy ion experiments. This is because targets for these experiments must be quite thick, yet allow for the precise determination of the point of origin and the energies of the many reaction products that emerge from an interaction. Thus the material is broken down into a sequence of thin layers. A signal identifies the layer in which a specific reaction event has taken place. In the presence of the intense counting rates produced by relativistic heavy-ion beams, live targets that function reliably represent major achievements.

Beam Cooling

A major achievement since the last LRP is the successful operation of the Indiana Cooler Ring. This device uses the electron cooling technique, first developed at Novosibirsk, in which the (proton) beam to be cooled travels through an intense electron beam of very precise energy definition, to which it imparts its random momentum. Although still in the initial operational phase, the IUCF Cooler Ring has already successfully cooled a proton beam from an initial energy spread of 120 keV to a final spread of only 3 keV (Fig. 44). It has also recently completed the first experimental confirmation of an ingenious scheme, the "Siberian Snake" system, which helps to maintain beam polarization during acceleration in a cyclic machine with intrinsic depolarizing effects. A second important advance in beam cooling bears mentioning. This is the successful application of the electron-beam cooling concept to stored heavy-ion beams demonstrated recently at the TSR ring in Heidelberg. Followed by the first successful use of laser cooling with stored beams of heavy ions, beam temperatures in the range of microKelvins have already been achieved.

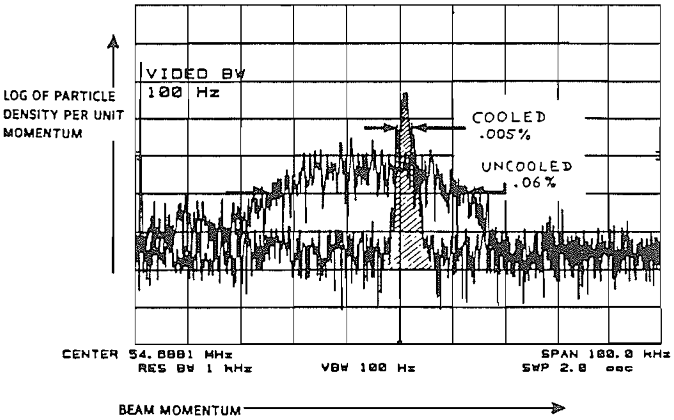

Figure 44: The first spectra, recorded on April 16, 1988, showing the effect of electron cooling on the stored proton beam in the IUCF Cooler Ring. Typical energy spread of the cooled beam is about 3 keV full width at half-maximum.

Detector Instrumentation

Such developments range from the search for new concepts, such as the bolometric detector studies at Princeton University, to the design of large (both physically and in the number of read-out channels) detector systems needed to study the hundreds and, eventually, thousands of particles (at RHIC energies) which are produced in a central collision of two energetic nuclei.

To study nuclear double beta decay, a special-purpose Time Projection Chamber (TPC) has been developed at Irvine. With this instrument, where the source is directly incorporated into the detector, the Irvine group has obtained the superb background rejection needed to study very low-level radioactive processes and has indeed obtained evidence for the existence of two-neutrino double beta decay of ^{82}Se.

Major new detectors have been built to study the debris left over after a central nucleus-nucleus collision at high energies. For example, the 4π detector at MSU, built from a combination of gas ionization detectors and scintillator elements, has a detection sensitivity ranging from protons to very heavy fragments, and will be a key instrument in the quest for understanding the nuclear equation of state at low density. A TPC is being constructed at the Bevalac to study central collisions of heavy ions where 100 to 200 particles are emitted.

Detectors at BNL and CERN have been built to measure the many hundreds of pions and other subnuclear particles produced at very high energies, and an active R&D program is under way to develop new concepts for experiments at RHIC. Part of such a detector can be seen in Fig. 45 which shows an view along the beam through the elements surrounding the target of Experiment 814 at the AGS. These experiments require novel instrumentation. For example, a major breakthrough in particle identification was achieved within Exp. 802 at the Brookhaven AGS by developing a scintillator hodoscope with a time-of-flight resolution of consistently 50 psec, unparalleled in the world. Similarly, new ground was broken by the 814 collaboration at BNL with the development of a novel drift chamber. In this instrument, the trajectories of more than 20 particles simultaneously traversing the drift chamber can be accurately determined (with precision of better than 200 μm) by recording, in addition to the drift times of secondary electrons, the charge induced on an electrode consisting of up to 1000 individual pads.

A detector of similar complexity has been developed and built at the Los Alamos National Laboratory to search for a neutrinoless decay mode of the muon (MEGA). Here it has been necessary to develop technical solutions to the problems of high counting rates, resolution in charged-particle momentum, photon energy, and angular resolution.

Exciting new opportunities are opening up with the development at Stanford and Princeton of special ultra low-temperature bolometric detector systems for use as particle detectors. Such devices promise lower thresholds and better resolution in energy than any other detector presently available. In these devices, the energy of an incoming charged particle is measured by detecting lattice vibrations (ballistic phonons) in crystals at ultralow temperatures (<1 milliKelvin). The present state of the art indicates that resolutions of one part in 10,000 should be achievable for energies in the 1-MeV range.

New magnetic spectrographs of unparalleled precision and solid angle are being designed. For example, the high-resolution spectrometer at CEBAF will have a solid angle of about 8 msr and a resolution in momentum of $\delta p/p = 5 \cdot 10^{-5}$ for a momentum acceptance of 10% at 4 GeV/c. At MSU a new spectrograph has been designed for high-precision spectroscopy with intermediate-energy heavy ions. This novel design is based on superconducting technology; it consists of two large-aperture quadrupole magnets followed by two 75-ton dipoles and could be a prototype for future very large devices. Out-of-plane magnetic spectrometers will provide access to new response functions in electron coincidence studies. A closely related development is the design and construction of recoil mass spectrometers that select and guide nuclear reaction products with unprecedented efficiency to a focal plane, where they are detected and undergo further experiments.

A new neutral-meson spectrometer is being constructed at LAMPF which will provide an energy resolution of about 300 keV at a solid angle of 2 msr. One of the features leading to this order-of-magnitude increase in energy resolution is the use of pure cesium iodide in the calorimeter, which provides an energy resolution comparable to the older sodium iodide material but a much faster signal.

The vitality of the field can perhaps best be judged by the large number of sophisticated detectors that have been developed to final proposal stage recently. These include the large underground Sudbury Neutrino Observatory (SNO) developed in a cooperation between Canadian, U.S. and British scientists and to be built at Sudbury, Canada. In this detector, 1000 tons of heavy water will be used to detect neutrinos from the sun and other sources. A picture of the detector and a description of its use for solar neutrino physics is described in Section II.9. The use of heavy water allows the measurement of the total flux of all three flavors of

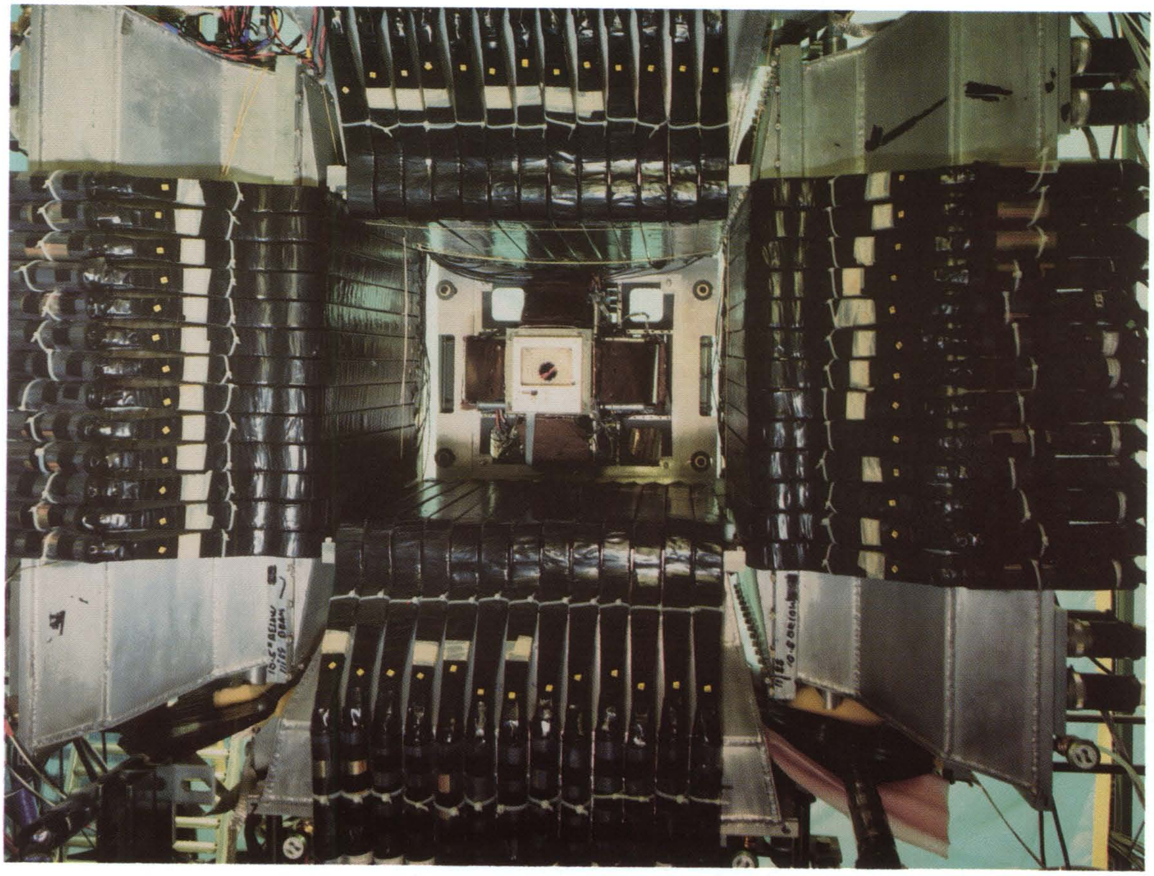

Figure 45: The target calorimeter, scintillator hodoscope and fragment multiplicity detector surrounding the target of a heavy-ion experiment at the AGS. The view is along the beam direction toward a forward multiplicity detector consisting of 1024 elements on two chips of silicon mounted in the square visible at the center.

neutrinos. It also allows a determination of the direction from which the neutrinos arrive. Careful attention has had to be paid in the selection of all materials to reduce the natural radioactive content to extremely low levels as the final sensitivity of the detector depends critically on these. Another exciting new detector concept has been developed by nuclear structure physicists. This new detector (Gammasphere) will combine 110 large germanium detectors with bismuth germanate scintillators to cover fully the surface of a sphere. It will allow the study of nuclear structure at high spin with unprecedented accuracy. The large number of elements allows the simultaneous measurement, with high efficiency, of the energies of up to five time-coincident γ rays. This enhanced multiplicity, together with the greatly improved resolution of each detector, results in improvements of about a factor of 8000 in overall efficiency for identification of the highest spin states in excited nuclei. Both SNO and Gammasphere have been recommended for construction by NSAC, and could come into operation within the period of this LRP.

A special version of a 4π particle detector shrunk in size to fit inside one of the multi-element γ detectors such as the spin spectrometer at Oak Ridge or the proposed Gammasphere is the Dwarf Ball, developed at Washington University in St. Louis and shown in Fig. 46.

Most of these new detector concepts require highly sophisticated computer and electronics systems to record and sort the acquired data. The technology of modular, high-density read-out electronics connected to on-line computers via high-speed data busses, such as the FASTBUS system, has become the basis for very large and powerful data acquisition systems. The development of fast parallel processors is a continuing trend that

Figure 46: The "Dwarf Ball" charged-particle detector developed at Washington University. It is shrunk in size to fit inside a $4\pi\gamma$-detector array such as shown in the left part of the figure. The "ball" consists of 104 elements of scintillator sandwiches and can measure the charge number and energy of reaction products up to $Z = 20$ with single-charge resolution. The fine segmentation allows detection of a large number of simultaneously emitted fragments and determination of their distribution in space.

promises rapid growth in the capability of such systems. Every effort needs to be made to strengthen the manpower in this area, where software development now accounts for more than half of the work necessary to bring a new system into operation.

Computers

Computer Hardware and Software

The explosive development of computer technology in the past 10 years has had a profound impact on nuclear physics. On the experimental side, it has permitted the accumulation and manipulation of large bodies of complex data at a high rate. On the theoretical side, it has enabled extensive calculations and model building, both analytical and numerical, that would have been otherwise impossible.

The enormous increase in event complexity that will accompany nuclear physics experiments in the 1990s will require substantial advances in both hardware and software capabilities for data analysis. Partly as a result of important breakthroughs in hardware design, software has now become the rate-limiting step in analyzing the results of most experiments.

Especially in the area of data analysis, most programming is being done today by physicists and students. There are real needs for professional assistance that are not being met. In addition to specialized programming that must be developed for nuclear physics, considerable resources can be saved by purchasing "off-the-shelf" software for such generic purposes as graphics and database manipulation. Total software purchase and development costs are likely to exceed the hardware costs over the life of a typical data analysis system within the next five years. Funding agencies need to allow for this.

On the theoretical side, a number of hardware developments are having a major impact. Extremely large calculations are now possible using class 6 and 7 supercomputers, and highly parallel systems such as the hypercube and special-purpose computers hold out much promise for continued expansion. The availability of supercomputing has allowed theorists to approach exciting computational projects that used to be impractical:

- Simulations of complex heavy-ion collisions are now possible, and Monte Carlo approaches to the many-body problem have begun to produce complete calculations of the binding energies of finite nuclei with realistic forces.
- Lattice-gauge computations and quantum transport theory in three dimensions are among the areas where major progress can be expected.
- Fully dynamical calculations of few-body systems with relativistic and non-nucleonic degrees of freedom should become possible with the expansion of computer power.

Supercomputers are now available and being heavily used by nuclear theorists at the NSF Supercomputer Centers, at DOE supercomputers at Florida State University and the national laboratories, and at supercomputers at individual institutions. Use of these machines by nuclear physicists has tripled in the past two years, and demand continues to far outstrip supply. NSF-supported nuclear theorists used time on these machines worth about $1M during 1988. During the same year, the DOE nuclear science program used supercomputer time worth about $5M (75% for theory) corresponding to about 10,000 hours of supercomputer time; over 25,000 hours were requested.

In addition, the price/performance ratio of workstations has improved dramatically. Computational power superior to that found in the dominant minicomputers of the 1980s, the Vax 700 series, can now be put on a desktop at a cost of under $5000.

These two pieces of hardware, the supercomputer and the workstation, are not independent. Ideally, they are integrated so that each is used in optimal ways. In particular, the graphics capability of the workstation allows analysis of supercomputer calculations in a much more effective and efficient way. In addition to powerful and easy-to-use graphics tools, symbolic manipulators show promise of becoming a standard theoretical tool. Analytic calculations that would have taken weeks and hundreds of pages can be done by symbolic manipulators in hours. To exploit these opportunities for nuclear theorists over the next five years, it will be necessary to make these tools more widely available.

Software availability is a concern for theory as well as for experiment. Although good use is often made of existing software libraries, the special-purpose programs needed for nuclear physics are rarely developed to the point where they can be shared. Few physicists take the time needed to make a research-level code sufficiently reliable so that it can be used by others, or to provide high-quality documentation. In some cases, good use could be made of off-the-shelf software, but the cost of high-quality commercial programs for graphics, symbolic manipulation, and so on, is often high.

Computer Networks

The use of wide-area computer network services is a relatively new phenomenon for nuclear physics research, but one that is rapidly expanding. All major nuclear facilities have outside user groups, and the number of nuclear physicists who participate in this mode of research is increasing as the research facilities become larger and the experiments more complex. Furthermore, nuclear theorists are making increasing use of distant supercomputing facilities, and computer networks are the primary means of access to these machines. The construction of the new accelerator facility, CEBAF, and, potentially, of RHIC, adds further pressure for access to wide-area networks (WANs).

Reduction in the cost of computing has allowed the research scientist to explore domains previously beyond his reach. The proliferation of workstations means that most of the CPU power is distributed among members of a research collaboration rather than at a central mainframe computer, and data handling and network capacity are the bottlenecks.

Computer networking for the research scientist has rapidly evolved as access to geographically dispersed research facilities and more powerful computing resources became a requirement for the conduct of research. The modern researcher in nuclear physics has a compelling need to exchange data and messages between members of a widely dispersed collaboration, to access experimental data at research facilities where the experiment was performed, and to have interactive access to supercomputing.

The extensive use of BITNET for rapid communication has grown into an essential tool for nuclear researchers throughout the world for a wide variety of collaborative efforts (including the preparation of this report). This will undoubtedly continue to grow and will have a large impact on the amount and style of interaction between scientists.

V. SCIENTISTS AND RESOURCES IN NUCLEAR PHYSICS

Trends since the 1983 Long Range Plan

Introduction

Nuclear physics is a broad scientific discipline whose health depends on a continuing flow of new ideas and challenges, the fiscal and technical resources to address these challenges, and most critically, the community of dedicated, self-motivated scientists who drive the field. Long range planning for a field whose success often requires following new and unexpected directions is difficult, but critical, in the light of limited resources and the large magnitudes of many of the new initiatives.

It is also clear, as is documented in the many technical sections of this report, that nuclear physics occupies a pivotal position in the overall scientific effort because its programs touch so many other basic and applied scientific disciplines. Strong ties to High Energy Physics, Astrophysics, Medical Physics, Condensed Matter Physics, Nuclear Technology, Accelerator Technology and other areas form the basis for the intellectual and technological transfer that is critical for our field and the rest of the U.S. scientific programs. A healthy Nuclear Physics program is important to the overall health of the U.S. scientific endeavor and, thereby, to the vitally important technological stance of the U.S. in coming generations.

In the 1983 Long Range Plan, a serious adverse trend then threatening the health of Nuclear Science, as well as many other scientific disciplines, was highlighted. Quoting directly from the introduction to the Manpower and Training section of that report:

"The crucial element of any science, more important than facilities, instrumentation or funding, is the people who pursue it. Reflecting a combination of circumstances, historical, economic and sociological, there has been a substantial decline in the rate at which scientists, physicists and nuclear physicists, in particular, are being trained in the United States. Yet the continued need for nuclear scientists is considerable, with people trained in this discipline carrying out a variety of tasks in nuclear medicine, energy research, in many industrial research tasks and in government service, in addition to providing the basic resource for continued research in the discipline."

In the six-year period since then, 1983-89, serious efforts have been undertaken by the nuclear physics community, supported and aided by the funding agencies, to reverse this trend. Both statistical and anecdotal evidence suggests that significant progress has been made in reversing the negative trend identified in 1983, although manpower trends in such a diverse field are difficult to quantify and natural time scales are of the order of ten years. This progress has been achieved in spite of serious budgetary limits to growth, inherent in the NSF and DOE funding pattern for nuclear science since 1983, in particular the very serious Gramm-Rudman-Hollings cut in 1986. Continuing revitalization of the field requires, at the very least, modest growth in funding above inflation.

In the following sections we describe the trends, current status and projections into the 1990's with regard to human resources, foreign cooperation and budgets. We also address the balance between universities and large national facilities.

Human Resources.

A primary scientific discipline prospers if it offers exciting, realizable challenges which attract the best young people into the field. In order to influence career choices, it is equally critical that the field and the funding sources project a credible image of stable long term opportunities.

The past decade of nuclear physics has seen the beginnings of attacks on major new scientific questions, including the role of quarks in nuclei, the study of nuclear matter in hitherto inaccessible regions of temperature and pressure, and many other opportunities in the broad base program which have been presented by the development of sophisticated new instrumentation. These new challenges are documented in the preceding scientific sections. Recent manpower statistics suggest that they are inspiring an increasing number of bright young people to pursue nuclear physics as a career.

A special NSF initiative to attract new young faculty members to universities, the Presidential Young Investigator Program, led to fifteen awards to nuclear scientists, over the six years of its existence. However, nuclear science must also accept its responsibility to help build a manpower base from a lower level. At the undergraduate level, nuclear physicists have become more deeply involved in the NSF sponsored program, "Research Experiences for Undergraduates" (REU). Over the past several years, REU site programs with significant nuclear science components have been held at Caltech, Duke, Colorado, Florida State, MSU, Indiana University, University of Virginia, and William and Mary. Supplements have also been made to about 40 nuclear physics research grants to support undergraduates during the summers. In the DOE, many of the national laboratories maintain vigorous, varied programs for the science education and research involvement of undergraduate students, particularly during the summer.

Estimates from DOE/NSF sources of the number of PhD level personnel funded in basic nuclear science research, summed over theory and experiment, are shown in Fig. 47. The number has remained approximately constant at about 1400, over the last six years. It is important to note that approximately 360 of these are faculty members at universities. The fraction of theorists (permanent and nonpermanent) is 22%. When Ph.D. students are added, the total scientific effort comes to about 2200. The approximately constant personnel level parallels the relatively constant federal funding over the past decade and is, therefore, not surprising. The number of graduate students does, however, appear to have increased from about 600 in 1982 to about 800 in 1988. There is also a parallel increase in the number of PhD's, from about 80 to about 100 awarded in nuclear physics per year, over the same period of time. The number of graduate students per faculty member varies from 0.5 for NSF supported nuclear theorists to about 3 for some of the dedicated university accelerator laboratories. There is room to increase these numbers if additional support is available. This is particularly true for theory students, in view of the perceived serious shortage of young nuclear theorists.

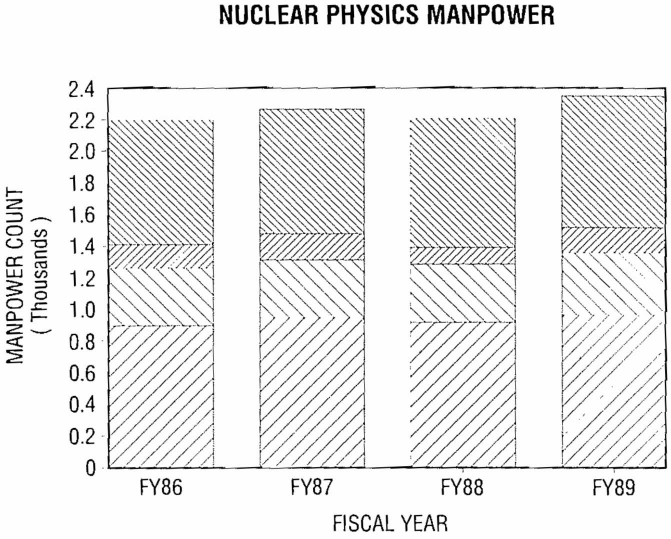

Figure 47: Total nuclear physics scientific manpower, supported by NSF and DOE, from 1986 to 1989. The categories are defined as follows:

(1) From the bottom of the figure: Permanent staff consisting of senior research staff at national laboratories and faculty at universities; (2) next higher category: temporary staff consisting of postdoctoral research associates and visitors; (3) third category: Ph.D. level staff supported by other programs; (4) top segment: graduate students.

During this period of relatively flat overall manpower in nuclear physics, there have been major redirections in effort, in response to the new challenges. These shifts can be best documented with a few specific examples. (1) The opportunities presented by CEBAF have brought new vitality to the study of nuclear properties with electron probes. Since the establishment of this project, there have been 25 new faculty appointed at 14 southeastern universities associated with this project. There are currently 233 users from 58 university groups involved in preparing the initial experiments for this facility; complementary programs at lower energy (MIT) have been strengthened, and potential new opportunities at higher energy (SLAC and HERA) are being considered. (2) The relativistic heavy ion program at the BNL AGS facility was not being seriously considered for funding before the 1983 LRP. It is now entering its third year of operation, has an active user community of about 200 physicists, including about 35 graduate students pursuing theses, and participation from research groups representing 30 universities from the U.S. and abroad. Similar growth has taken place in the heavy ion program at CERN (approximately 300 active users with significant participation from the U.S.) and FNAL (approximately 40 users on the $p/\bar{p}$ fragmentation experiment). In response to the challenges presented by this new field, nuclear physics programs have been strengthened or redirected at several major northeastern universities including Columbia, MIT, McGill, Pittsburgh, SUNY Stony Brook, and Yale. This activity has been generated to a large extent by the expectation of new opportunities and challenges centered around RHIC and the possibility that its construction will begin in the very near future.

Obviously, these new efforts necessitate operation in a user mode, and co-operation in larger groups, to a much higher degree than was typical before in nuclear physics. The user mode is also becoming more common even in the ongoing programs where, by combining resources and utilizing the most appropriate state-of-the-art detector and accelerator facilities, one is able to pursue new opportunities. We pick just two examples of this trend. One is the MEGA project, a major new detector to search for rare muon decay channels at LAMPF. This experiment involves about 30 scientists from 11 different institutions, including 14 new graduate students. The other is Gammasphere, a multi-element γ detector recently recommended for funding by NSAC. This proposal was generated by a collaboration of about 60 people from 20 institutions. It will provide the capability to do forefront research in nuclear structure to a broad, primarily university based community of about 150 to 200 users.

From these and other examples we detect a trend toward an increasingly mobile mode of operation where research groups make use of several different facilities. It is becoming common for groups from a large number of universities and laboratories to combine resources to attack a particularly difficult problem, and after completion to move on, with a new grouping utilizing a different facility.

Nuclear physics, as with other scientific fields, faces a challenging management problem over the next few years. The demographics of the present manpower pool are such that in 5 to 10 years there should be significant numbers of open career positions available in both universities and national laboratories, as the "boom" in career hiring of the mid-1960's passes into retirement. Creative approaches are needed to ensure that an adequate number of young scientists will be available for careers in nuclear physics at that time.

Manpower Projections

We now address the important question of the manpower level that is required to exploit the major scientific opportunities outlined in this report. As in the past, future manpower levels will be closely coupled to funding levels, which are determined on a year-by-year basis. However, for planning purposes we have generated a conservative scenario that is consistent with the major physics goals and the budget projections that are outlined in this report. This scenario involves a growth over the next decade in the number of theorists to about 25% of total manpower, coupled with an approximately constant number of experimentalists. This scenario will require difficult choices and will not allow us to pursue all of the challenges offered by the field. Nevertheless, we believe that this manpower pool will be adequate to pursue effectively the most exciting new opportunities that will present themselves between now and the late 1990s. We emphasize that this scenario is a conservative one. We expect that the recent trend of increasing numbers of students attracted into our field will be further enhanced due to the new scientific initiatives. A prerequisite is the strong university base of nuclear physics. We also strongly believe that nuclear physics should be in an excellent position to compete within the broader scientific enterprise of the United States for a moderate level of growth.

Assuming a steady, timely implementation of this LRP, experimental nuclear physics in the U.S. will look very different at the end of the coming decade. We expect the CEBAF experimental program to begin in 1994. RHIC could be available in 1997. The course of KAON is more uncertain, but one might project a research program beginning in the late 1990's. Thus the 1990's promise a changing environment in nuclear physics. The challenge will be to come through this period maintaining a healthy mixture of strong research at existing facilities, while at the same time planning and constructing experiments for the new accelerators.

A reasonable expectation for nuclear physics at the end of the 1990's would be a roughly equal split between research at the new facilities and pursuit of the most promising initiatives at the lower energy range. As the field moves inexorably toward the user mode, these decisions will be made increasingly by the mobile research groups themselves.

To examine the expected demographics for the next decade, it is useful to divide the field into its traditional subfields: medium energy, heavy ions, and low energy. An accurate census for these subareas is not available, but a qualitative estimate of the distribution is obtained from the assumption that the manpower effort scales like the DOE funding in the three areas (see Fig. 50). Of the 1800 experimentalists (including students), 900 are then in medium energy, 700 in heavy ions and 200 in low energy nuclear physics. We expect that each category would shift primarily between facilities in its own area, although some cross-overs will also occur. We should also expect some influx from high-energy physics to the new facilities.

Current activities in medium energy physics are centered at LAMPF, Bates and IUCF. These facilities will continue to provide the major research capabilities during the next five years. Redirection of effort toward experiments at CEBAF is already evident and should increase. If the KAON project is successful, it will have a major impact on the scientific effort of the medium energy manpower in the later 1990's.

The heavy-ion community represents a broad spectrum of activities that should remain strong throughout the 1990's. The currently expanding effort in relativistic heavy ion physics at the Bevalac, AGS and CERN should provide an adequate base for the research program at RHIC. In addition, we expect that RHIC will attract substantial foreign involvement in its experimental program, if it comes on line in a timely fashion. Roughly half of the community will probably continue to be involved in extensions of the programs at MSU, TAMU and at lower energies, which currently includes the ATLAS, Holifield and LBL 88" facilities. Major new detector initiatives already in the pipeline will provide exciting research opportunities for that domain for the foreseeable future.

The low-energy community is primarily served by the university facilities, many of which have been upgraded in recent years. The increasing effort toward modernization of their instrumentation should ensure a continuation of forefront research efforts in that arena.

The groups that pursue fundamental interactions and symmetries utilize a broad range of facilities and detectors. Hence, for the purpose of this estimate, they are included within the medium-energy and the low-energy categories.

The Role of the Universities

The vital role of the universities for the well-being of nuclear physics cannot be overemphasized. Their educational and research roles are equally important. Nuclear Physics as a field has been fortunate in that the historical tradition of a distributed research base, with universities hosting smaller accelerators, and national laboratories operating the large user facilities, has been maintained to this day. The evolution of the university-based facilities has followed the field toward higher energies,and thus today several medium size facilities, like the Indiana Cooler Ring, the Bates electron accelerator and stretcher ring, and the superconducting cyclotrons at MSU and TAMU, operate on University campuses, complemented by a set of modern, diverse small accelerators which are attracting large numbers of students into the field.

Equally important, the universities are indispensable as staging areas for the experiments at the large facilities. About 360 experimental faculty members and a total 680 Ph.D. physicists are based at Universities, about 50% of the total scientific manpower. When students are added, the total increases to 1,370 or fully 62% of the entire scientific effort. Without the university base as users, none of the new accelerators could flourish. Fortunately, this vital role is recognized by both NSF and DOE, each of which spend about $40 Million per year on nuclear research programs at universities. The shared role of both agencies in this support has been most fortunate and effective. The NSF has an explicit mission, and a long and distinguished tradition, in the education and training of scientists. It is gratifying to note the recent new emphasis expressed by DOE on the training of scientists. This augurs well for the continuing recognition of the role of universities.

Budgets

The funding for basic nuclear science research in the United States comes primarily from the federal government through the Department of Energy and the National Science Foundation. However, substantial contributions are also made by the universities through faculty and graduate student support, matching funds for equipment, special buildings, etc. In order to provide some perspective for recent trends in funding, we show in Fig. 48 the historical DOE/NSF budgets for the fiscal years 1977-1990 where a conversion has been made into 1990 dollars using the DOE-NP cost index deflators. The total funding level (indexed for inflation) shows a minimum in the early 1980's. A recovery starting in FY84 was stopped by the Gramm-Rudman-Hollings dip in FY86. Recent increases have been primarily for CEBAF construction. This is more apparent in Fig. 49 where the construction budgets are explicitly shown. Note that capital equipment, a line item for DOE, has been included in the budgets for operations and research.

The DOE provides about 80% of the total federal funding for nuclear science. The university component, however, is split about 50-50 between DOE and NSF. In 1989 the university support was about $41M for DOE and $46M for NSF.

As a rough estimate of the relative efforts in major subareas at the times of the 1979, 1983, and this LRP, Fig. 50 shows the distribution of funding levels between various program categories, for the two agencies. It should be noted that the delineations between subareas are somewhat flexible and change with time. For NSF the NP category includes all of heavy ion physics. An extrapolation of the funding needs for nuclear physics for the next decade will be given in the following chapter.

Support for theoretical nuclear physics has remained about 6% of the total. The 1988 NSAC Report on Nuclear Theory recommended an increase to about 10% of the nuclear science funds for operations and research. NSAC has also recently recommended an increase in the relative funding for capital equipment to exploit some of the many equipment intensive opportunities under consideration. For comparison, the FY88 DOE nuclear physics budget allocated 9.5% ($17.7M) to capital equipment as compared to a 19% allocation ($76.7M) for the DOE high energy physics program in the same period.

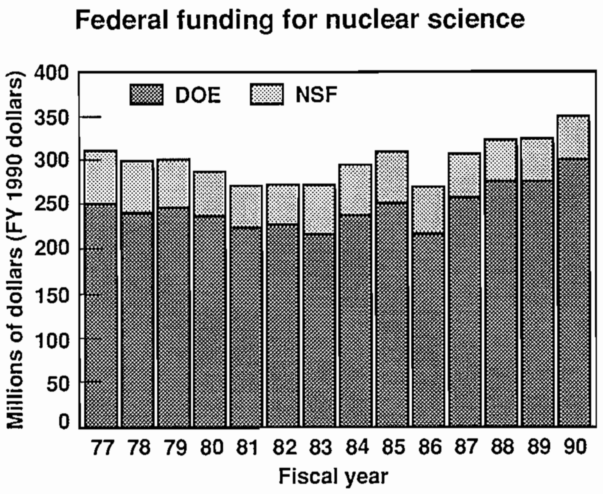

Figure 48: Total nuclear science budgets for DOE and NSF from 1977 to 1990, expressed in FY90 Dollars.

We estimate the minimum budget which would allow for a vibrant and efficient exploitation of the opportunities described in this report, in the final chapter.

Foreign Cooperations.

The past six years have seen an increase in the nuclear physics activity at international facilities. In general, these are facilities that contain unique characteristics (accelerators, detectors) that are too expensive to duplicate cost-effectively and must be shared on a regional or worldwide basis. Typically, these facilities allocate their resources competitively on the basis of scientific priorities to experimental groups who may have participants from many nations. Quite often the individual countries represented in the group contribute to the experimental programs through equipment built or supplied by the individual research groups, and sometimes facilities are developed with formal international collaboration on a worldwide or regional basis. This model is familiar to the high energy physics community, and is now being introduced into nuclear physics. A list of such facilities in Europe and Japan is presented in Table 1. Equivalent U.S. facilities are described in section IV.1 of this report.

Ideally, the advance of nuclear physics as a discipline would be best served by individual research groups making decisions on where to compete with-

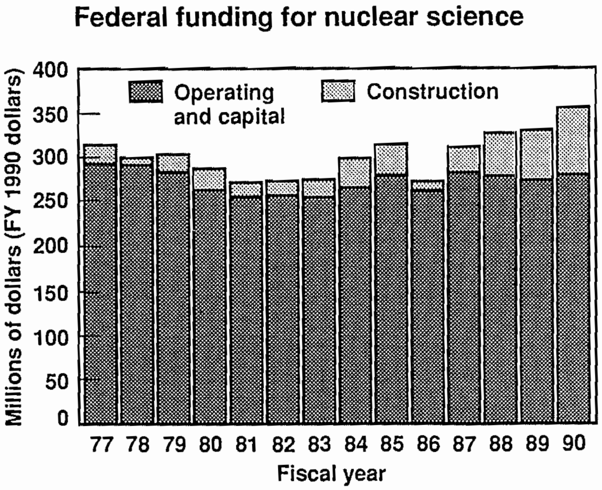

Figure 49: Operating and construction funding for nuclear science from DOE and NSF, in FY90 Dollars.

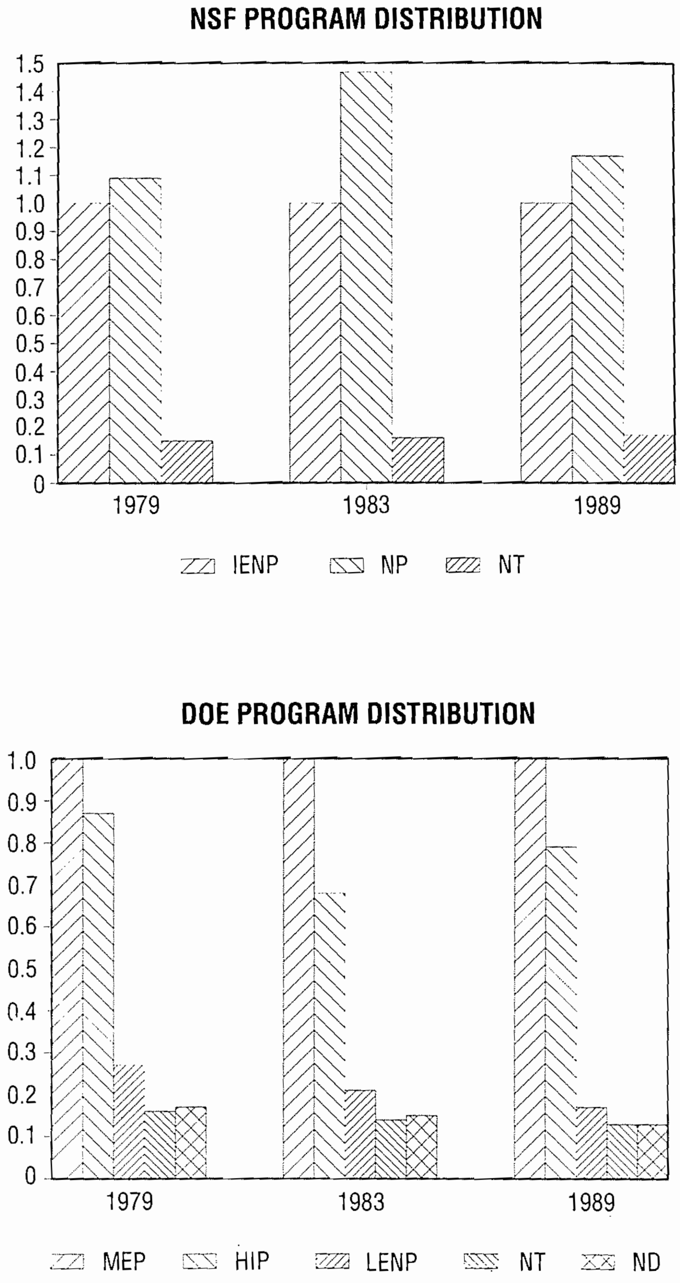

Figure 50: Relative distribution of funds among major categories, arbitrarily normalized to the medium-energy effort level, at the time of the three LRP reports.
(A) Bottom: DOE with MEP = Medium energy physics; HIP = Heavy Ion Physics; LENP = Low energy nuclear physics; ND = Nuclear data; NT = Nuclear theory.
(B) Top: NSF with IENP = Intermediate energy physics; NP = Nuclear physics; NT = Nuclear theory.

Name	Location	Country	Description
Facilities Currently in Operation			
TRIUMF	Vancouver	Canada	500 MeV protons, secondary beams
U. Saskatchewan	Saskatoon	Canada	300 MeV electron stretcher ring
TASSC	Chalk River	Canada	10 MeV/A heavy ions
NSF	Daresbury	England	7 MeV/A heavy ions
GANIL	Caen	France	100 MeV/A heavy ions
Saturne	Saclay	France	1 GeV/A polarized light ions/ heavy ions
ALS	Saclay	France	700 MeV electrons
KEK-PS	Tsukuba	Japan	12 GeV protons, secondary beams
NIKHEF	Amsterdam	Netherlands	500 MeV electrons
PSI (SIN)	Zurich	Switzerland	600 MeV protons
GSI (Unilac)	Darmstadt	W.Germany	20 MeV/A heavy ions
HERA	Hamburg	W.Germany	30 GeV polarized electrons
SPS	CERN	Pan European	200 GeV/A heavy ions
LEAR	CERN	Pan European	Antiproton Storage Ring
VEPP-3	Novosibirsk	USSR	2 GeV Electron Storage Ring
Facilities under Construction			
GSI	Darmstadt	W.Germany	2 GeV/A heavy ions
COSY	Julich	W.Germany	1 GeV Proton Storage Ring
MAMI	Mainz	W.Germany	800 MeV electrons
AGOR-KVI	Groningen	Netherlands	60 MeV/A light and heavy ions
Major Facilities under Consideration for Construction in the Early 1990s			
KAON	Vancouver	Canada	30 GeV protons, secondary beams
JHP	Tsukuba	Japan	1 GeV protons, secondary beams

Table 1: Major Foreign Facilities with Multinational User Programs in Nuclear Physics

out undue emphasis on the national or regional location of the facility to be used. This is in fact close to current practice in our field. The increasing importance of this mode of research places new demands for long-range multinational commitments. The major factors dictating the need for coordinated planning are:
(1) new facilities may depend on the international community for use, support and justification;
(2) new facility construction requires a believable schedule from the host country in order to attract, and hold, foreign participation;
(3) duplication of effort in the largest facilities is not economically viable.

Effective international utilization of the large, unique facilities requires realistic forward planning by the individual nations in addition to cooperation on research and facility development. Examples of this forward planning are the NSAC 1983 Long Range Plan which projected the construction of CEBAF followed by RHIC which has been steadily implemented. In Europe, a recent West German Long Range Plan has recommended concentration on the unique German facilities at GSI (Darmstadt) for heavy ion research,and the electron facilities at Darmstadt, Mainz and Bonn, while supporting major efforts outside Germany at CERN (heavy ions and antiprotons) and in Canada at KAON (hadrons), if this facility goes ahead. In France, recent long range planning recommended operating the unique programs in heavy ion physics at GANIL, Strasbourg and Saturne until the end of the century, while supporting collaboration of French groups at CERN and GSI. In electron physics, the ALS accelerator at Saclay will probably be superceded by the new facilities in the U.S. and West Germany, and development of a new electron facility with an energy of 10 to 20 GeV is being recommended. KAON is the major Canadian initiative under consideration, and its success clearly requires substantial user involvement from the U.S., Europe and Japan. The Japanese Nuclear Physics Committee recently decided on an upgrade of KEK plus support for KAON in the longer term. At CERN a future program with Pb beams in the SPS accelerator is under serious consideration. All of these planning activities are strongly influenced by current US activities and capabilities, and also by the perception of long range directions in the U.S.

In addition to international cooperation on larger facilities, it is increasingly common for multinational collaborations on nonaccelerator based experiments. These are usually multi-year, few 10's of Million$ projects such as the Canadian/US/UK and US/USSR joint efforts in solar neutrino studies.

Finally, there are the large numbers of short and long term exchanges of scientists between the U.S., Europe, and Japan which underline the truly international character of nuclear physics. These exchanges have always had a major role in the vitality of the field. They are becoming even more important for the U.S. effort in the current situation where we can no longer hope to dominate all major subfields.

Foreign Comparisons

In the international nuclear physics community the United States has historically played a very important role. Among the countries sampled to create the data in Tables 2 and Table 3, the U.S. effort is about 1/3 of the total, and if extrapolated to encompass the entire world effort (excluding USSR, East Bloc and China where data are difficult to compare on similar terms), we represent about 1/4. These data suggest a worldwide nuclear physics effort funded at the level of about a billion dollars per year, and involving a community of perhaps 5000 professional scientists at the PhD level. These numbers show clearly why the trend toward new large facilities with construction costs of hundreds of millions of dollars have demanded increased international cooperation for their construction and exploitation. This trend toward international facilities and multinational collaboration is, in fact, leading nuclear physics toward an even more coherent international community than was true previously.

The comparative data presented in Table 3 gives estimates of the total funding in representative countries from sources similar to the U.S. DOE and NSF. Because of the differences in funding procedures, it is not possible to make exact comparisons. Attempts have been made to adjust available foreign funding data for differences in accounting systems, particularly in the way that salaries of university personnel are treated. The nuclear physics budgets presented include both operating and facility construction. The data show rather similar support per physicist in most countries, but large variations in the emphasis given to nuclear physics as measured by the ratio to Gross Domestic Product (GDP).

	Nuclear Physicists	Budget (M$)
U.S.	1290	287
U.S./Total	0.34	0.33
Foreign*	2530	585
Foreign/Total	0.66	0.67
Total	3820	872

* Countries included –
Canada, France, Japan, Switzerland, West Germany

Table 2: U.S. Nuclear Physics in Relation to the International Effort for FY88.

Country	PhD Nuclear Physicists	Total Population (Millions)	Nuclear Physicists Per Capita (Per Million)	Nuclear Physics Budget (M$)	Gross Domestic Product (B$)	Dollars/ Nuclear Physicist (K$)	NP Budget per GDP (per Million)
Canada	180	25	7	37	480	180	78
France	600	56	11	88	945	150	93
Japan	600	122	5	151	2840	250	53
Switzerland	150	7	23	34	183	230	186
United States	1290	244	5	287	4800	220	60
West Germany	1000	61	16	275	1207	280	232
Great Britain	200	55	4	13	734	64	18

Table 3: Foreign Budget Comparisons–Nuclear Physics Program in the U.S. and Selected Foreign Countries (Data are for FY88).

VI. OPPORTUNITIES, RECOMMENDATIONS, IMPLICATIONS

The substantive discussions of the LRP issues took place in a meeting at Boulder, Colorado, from August 6 to 11, 1989. At that meeting, our vision of the next decade in nuclear physics and the most exciting new opportunities were defined, the major recommendations emerged, and the implications for manpower and funding were worked out.

The field as a whole was represented by the Long Range Plan Working Group (listed in the appendix), a group of 54 nuclear physicists, including the 18 NSAC members, who were selected to be representative of all facets of nuclear science. Thirty-seven came from universities, 17 from national laboratories. Seven representatives from the funding agencies, DOE and NSF, attended the meeting. The meeting was open to the public. A number of physicists and administrators attended as observers and were, on occasion, recognized for comments. The agenda of the meeting is listed in the appendix. The results from that meeting are spread throughout this report, and constitute the main body of the executive summary. This chapter serves to compile the priorities and recommendations, and outlines briefly the fiscal implications.

The most exciting new scientific opportunities for the next decade are these:

- The exploration of the quark degrees of freedom and of the underlying theory of the strong interaction, QCD, in the nuclear medium. This includes the decisive attack on the meson degrees of freedom using the superior experimental power of the new CW high-energy electron beams.

- Study of the nuclear equation of state up to very high temperatures and nuclear densities, and of the quark-gluon plasma.

- Study of nuclear structure at the limits of temperature, angular momentum, and neutron-to-proton ratios. This includes opportunities of astrophysical significance.

- The use of the nuclear medium for precision studies of fundamental aspects of the strong and electroweak interactions. This includes the study of neutrinos of astrophysical and solar significance.

These opportunities were the basis for the following recommendations adopted by the LRPWG with the wording given below. The recommendations first address issues of the new major facilities and of new construction, and then address other major aspects. The order of listing does not represent an ordering in priority, unless it is stated in the text.

(1) The highest priority in U.S. nuclear science at this time is the timely completion of the Continuous Electron Beam Accelerator Facility (CEBAF) and the beginning of its important research program.

(2) We strongly reaffirm the very high scientific importance of the Relativistic Heavy Ion Collider (RHIC). Since the last LRP, theoretical progress has strengthened the case for the existence of a quark-gluon plasma, and recent experiments demonstrate the likelihood that conditions favorable to its formation will be attained. RHIC will provide unprecedented opportunities to produce and study ultradense matter. Therefore, we strongly endorse the recommendation of the 1983 LRP and subsequent NSAC deliberations that RHIC has the highest priority for new construction in the nuclear physics program. We urge a swift beginning of this important project.

(3) NSAC recently endorsed the fundamental and exciting scientific opportunities that will become available with a high-intensity, multi-GeV hadron facility.These opportunities will extend our knowledge both of the strong force, which determines the nuclear dynamics based on quarks and gluons, and of the electroweak force, which provides stringent tests of the basic laws governing subatomic phenomena. The Canadian invitation for U.S. participation in the construction of an international research facility, KAON, with Canada providing full support for the operation of the facility, pro-

vides an exceptionally cost-effective way for the U.S. nuclear science community to address this important physics in a timely fashion. We recommend with very high priority that the U.S. enter into negotiations with Canada to participate in the construction and use of KAON.

(4) Crucial elements of nuclear physics are not addressed by the major new facilities of recommendation 1-3. Opportunities range across almost all subject areas discussed in this report. Indeed, the wide range of nuclear phenomena and the unity of the underlying understanding, from the phenomenology of nuclei through collective, nucleon and meson degrees of freedom, and finally to quarks and gluons, is an essential feature of modern nuclear science. Exploration of these frontiers requires a vigorous program using existing facilities that provide electron, hadron, and heavy ion beams across a wide energy range. The distribution of funds between ongoing programs and new initiatives should provide for a broadly based and balanced advance.

(5) Precision tests of fundamental interactions probe physics at mass scales beyond the reach of any planned accelerator and beyond the Standard Model. Nuclear Astrophysics provides both tests of nuclear physics in new regimes and perspectives on the evolution of the universe. Experiments at very high energies allow us to probe the quark structure of nuclei at very small distance scales. These activities are important to our field. Experiments in these areas employ a range of facilities from non-accelerator instruments through reactors and small accelerators, to the largest machines. We recommend effective exploitation of these topics by strong and timely support for the specialized instrumentation needs in this field, and the cost-effective use of the world's high-energy facilities.

(6) As nuclear science explores new frontiers, a strong theory program becomes increasingly essential. We therefore reaffirm the recommendations of the 1988 NSAC Report on Nuclear Theory and the statements of previous LRPs calling for an expansion of the nuclear theory effort. We recommend that the agencies continue the recent trend of increased support for theory.

(7) Nuclear Physics is moving into many new experimental domains that require novel concepts and/or increasing complexity in detectors, targets, or other instrumentation. To realize the most promising new ideas and projects in this area requires an increase in capital funds over the present level, and increasing attention to the technological support structure at university laboratories.

Nuclear Physics is fortunate in having a well-balanced distribution between scientific efforts based at universities and at national laboratories. The several small, but modern, accelerators at universities and the three major facilities BATES, IUCF and MSU, which are operated by university groups, as well as large coordinated user groups at universities tie our field directly to the student base. We emphasize the need to maintain strong support for nuclear physics research at universities. The recent increase in the number of graduate students attracted to nuclear physics is evidence that the next generation of scientists is excited by the challenges and opportunities presented today by nuclear science.

The LRPWG considered carefully what scientific manpower would be required to implement the recommendations given above. The manpower base is discussed in more detail in this report. At this time it consists of about 1400 Ph.D. scientists and about 800 graduate students, and this level of effort has been stable for several years (as has been the funding level). Clearly, the major new machines, such as CEBAF, RHIC and, perhaps, KAON, will lead to some adiabatic redirection of scientific effort, in particular after the mid-90s. In addition, the proposed machines will be each unique in the world and should thus attract strong international programs. Thus we believe that even the present manpower would be sufficient to exploit the most exciting opportunities in each of the areas listed above.

It is clear that new opportunities will arise in the time frame of this LRP, and the LRPWG listened to presentations on a number of projects that are now under preliminary study. We list these projects here, without making specific recommendations. However, the LRP assumes that at least one of these projects, or another of comparable size (judged to be in the $50M range, which does not apply to all the projects listed below), will be developed in more detail and presented for funding consideration in the time frame of this plan. The following facilities were presented:

a. A radioactive-beam facility;
b. A 10-20 GeV cooler ring for polarized light ions;
c. An energy doubler stage and energetic pion facility for LAMPF;
d. An 0.5-1 GeV/A high-resolution heavy ion machine;
e. The potential of a high-flux source of cold and ultracold neutrons;
f. An advanced hadron facility with an energy above 60 GeV.

An advanced hadron facility satisfying f. would be a major undertaking and overlap strongly with the high-energy physics domain. The need for, and the requirements placed on such a facility could be a subject for discussion and exploration during the 1990s.

The budget implications of the priorities and their related programs that we project in this LRP were worked out by a subgroup of the LRPWG and presented at the Boulder meeting. For its deliberations the subgroup received input from all the laboratories operating nuclear facilities. Considerable information was also provided by the agencies on outyear projections. These projections included completion of funding for CEBAF construction in 1993 and a 5-year construction schedule for RHIC (1991-1995).

Our extrapolation of the needs for nuclear science begins with the recognition that the 1983 LRP recommended with highest priority a $20M increase in the base program. This recommendation was not followed at that time.

A budget scenario which allows, at the minimum level, for a viable and broad research program to proceed, while CEBAF and RHIC are being constructed, is given in Fig. 51. It is expressed in FY91 Dollars for the period from FY90 to FY97. The final year was chosen because both CEBAF and RHIC should be completed by that time. We estimate that a program based on the recommendations 1 through 8 (with the exception of the KAON recommendation which we address separately) requires about $340 Million in FY91 for the DOE part of the program and $50 Million for the effort presently supported by NSF. The extrapolation from FY91 to FY97 takes the construction costs for CEBAF and RHIC as they are presently assumed. Similarly, the extrapolation of operating funds is based on present programmatic extrapolations, but recognizes the urgent need to increase funding for operation at some facilities, to increase funds for equipment and for support for university-based user groups, and for nuclear theory, as stipulated in the above recommendations. These increments should increase the DOE base budget (outside of construction) by at least $40 Million between FY91 and FY97. For the NSF part of the program the necessary increase is estimated as $12.5 Million. Thus we estimate for the endpoint of our extrapolation, in 1997, a need for a DOE base budget of $340 (after completion of RHIC), and $62 Million for the NSF program, for a total base of about $402 Million (in FY91 Dollars). We note that this budget estimate is completely consistent with the projections of the 1983 LRP for the needs of nuclear science *after* the completion of CEBAF and RHIC.

U.S. participation in the construction of KAON is a high-priority recommendation of this report and, earlier, of NSAC. The funds required for the presently estimated U.S. part of construction ($75 Million over 5 years) are not included in the above numbers, and are indicated separately in Fig. 51. As stated in our recommendation 3, it is expected that the full operating costs will be borne by Canada. We recommend a strong effort to find additional funding for the KAON project, once it is approved by the Canadian Government, and note that the project could be assigned to either agency.

The LRPWG felt strongly that at least one new facility or upgrade would attain high scientific viability over the time span of this LRP, and require construction. The associated additional construction cost, estimated at $20 Million per year later in the decade, is indicated in the budget extrapolation of Fig. 51, without being specifically assigned to either agency.

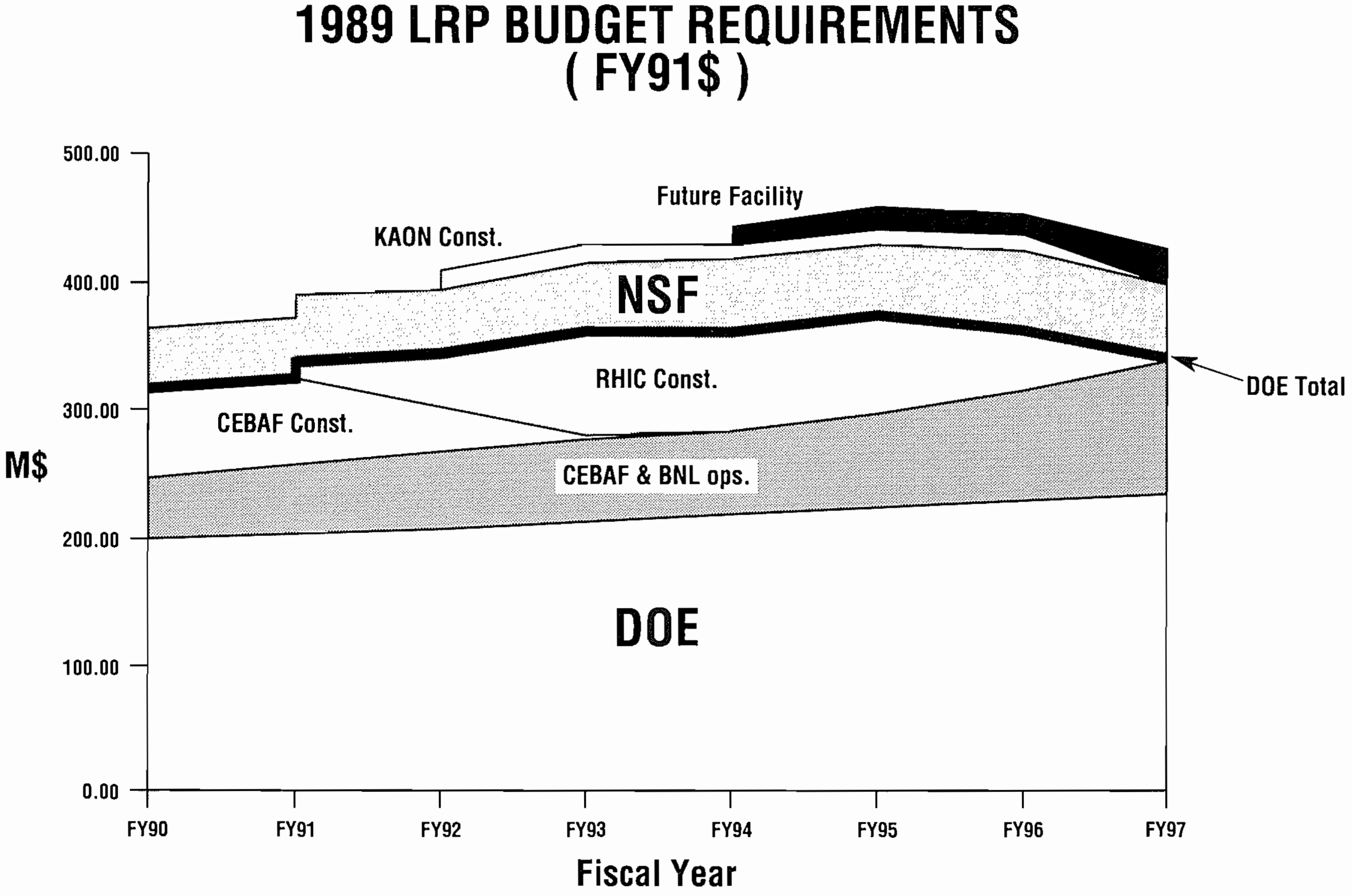

Figure 51: Projected budget needs for the 1989 LRP for U.S. nuclear physics, for the years 1990 to 1997. Amounts are given in FY91 Dollars. The entire area below the solid black line represents the required DOE budget. The cross hatched area above represents the NSF budget needs. Additional needs for KAON and for a future, smaller facility are shown, but not specifically assigned to either agency.

APPENDICES

Charge from DOE/NSF to NSAC

Members of the Long Range Plan Working Group

Agenda of the Boulder Workshop

Topical Working Groups

Town Meetings sponsored by APS/DNP

Meeting at Indiana University

NATIONAL SCIENCE FOUNDATION
1800 G STREET, N.W.
WASHINGTON, D.C. 20550

June 13, 1989

Dr. Peter Paul, Chairman
DOE/NSF Nuclear Science Advisory Committee
Physics Department
SUNY at Stony Brook
Stony Brook, NY

Dear Peter:

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee (NSAC) conduct a new study of scientific opportunities and priorities in U.S. basic nuclear physics research and that NSAC recommend a long range plan which will provide a framework for coordinated advancement of the Nation's basic nuclear research programs over the next decade. The NSAC 1979 and 1983 Long Range Plans are appropriate and important reference documents for this new long range plan you will be formulating. It is a consequence of those earlier long range plans that the nuclear science community has a high-energy CW electron accelerator, CEBAF, now under construction and the relativistic heavy ion collider, RHIC, in an advanced stage of planning. These high priorities recommendations of the previous two NSAC Long Range Plans should provide the starting point of your new plan, which must first and foremost attempt to identify the most important nuclear physics questions to be attacked in the next decade. Please submit your report to the National Science Foundation and the Department of Energy by December 1, 1989.

Nuclear science has moved rapidly ahead since the 1983 Long Range Plan was submitted to the agencies. Major new facilities (ATLAS, the IUCF Cooler/Accelerator, the MSU K-1200 Superconducting Cyclotron Laboratory, the Nuclear Physics Injector at SLAC, the Tandem/AGS Heavy Ion Facility, the Texas A&M superconducting cyclotron, and upgrades to university accelerator laboratories at Florida State University, University of Pennsylvania, University of Rochester, SUNY Stony Brook, University of Washington, and Yale University) are providing exciting new data. Construction of the MIT/Bates South Hall Ring is underway.

The new NSAC plan should identify the most important scientific opportunities that can be attacked with the tools that now are (or soon will be) available and should address the question of what new tools will be needed in the years ahead. In this context it is essential to take into consideration the accelerator facilities expected to be available in Western Europe, Canada, Japan and other nations. The new NSAC plan should again assess the directions needed to maintain the U.S. position of leadership as well as point out opportunities for cooperation with other countries on projects of mutual interest.

After formulating a new long range plan, it is essential that NSAC advise the funding agencies of the resources needed for its implementation. In addition to accelerator facilities and research instrumentation, NSAC should identify the necessary human resources. The role of the universities must be carefully considered.

We appreciate very much your undertaking this important task. The effort will be considerable, but the importance of this work to basic nuclear research in the United States will also be considerable.

Sincerely yours,

Marcel Bardon

Marcel Bardon
National Science Foundation

Wilmot N Hess

Wilmot N. Hess
U. S. Department of Energy

Long Range Plan Working Group

E. Arnold	American University
S. Austin	Michigan State University
D. Balamuth	University of Pennsylvania
P. Barnes	Carnegie-Mellon University
G. Bertsch	Michigan State University
R. Betts	Argonne National Laboratory
P. Braun-Munzinger*	SUNY, Stony Brook
H.C. Britt*	Lawrence Livermore Laboratory
J. Cameron*	Indiana University
R. Casten	Brookhaven National Laboratory
J. Domingo	CEBAF
C. Dover*	Brookhaven National Laboratory
R. Eisenstein*	University of Illinois
J. Garrett	Oak Ridge National Laboratory
G. Garvey	Los Alamos National Laboratory
D. Geesaman*	Argonne National Laboratory
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W. Haxton	University of Washington
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J. McCarthy*	University of Virginia
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J. McClelland*	Los Alamos National Laboratory
A. Mignerey*	University of Maryland
E. Moniz*	Bates/MIT
A. Mueller*	Columbia University
S. Nagamiya	Columbia University
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P. Siemens	Oregon State University
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S. Vigdor	Indiana University
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H. Weller	TUNL/Duke University
G. Young*	Oak Ridge National Laboratory
K. Erb**	National Science Foundation
D. Hendrie**	Department of Energy

*NSAC Members

**Agency Representatives

LONG RANGE PLAN FOR NUCLEAR SCIENCE, BOULDER WORKSHOP

August 6–11, 1989
University of Colorado, Boulder, Colorado
Room CR1-42, Engineering Complex

Sunday, August 6

Afternoon, 4p.m.

Workshop meets from 4–5 p.m. for discussion of agenda

Monday, August 7

Morning 9:00–12:30

9:00–9:15	Discussion of procedures
9:15–10:00	Report of WG1: Symmetries and Elementary Excitations (Glashausser)
10:30–11:15	Report of WG2: The Nucleus Under Extreme Conditions (Garrett, Casten)
11:15–12:00	Report of WG10: Tools of Nuclear Science: Accelerators, Detectors, Targets, Computation (Cameron)

Afternoon 1:30–5:00

1:30–2:15	Report of WG3: Dynamics and Thermodynamics of Colliding Nuclei (Mignerey)
2:15–3:00	Report of WG4: Hadrons in the Nuclear Medium (Jackson)
3:30–4:30	Report by Agencies and Costing Committee: Funding Projections (Agencies, Garvey)
4:00–5:30	Working groups meet

Evening 7:30–open

7:30–8:30	The case for a radioactive beam machine (Stephens)
8:30–9:30	The case for a medium-energy heavy-ion machine (Gelbke)

Tuesday, August 8

Morning 8:30–noon

8:30–9:15	Report of WG5: Strangeness and Flavors in Nuclei (Dover)
9:15–10:00	Report of WG6: QCD Description of Hadrons and Nuclei
10:30–11:15	Report of WG8: Fundamental Symmetries, Conservation, Laws, Electroweak Interaction, and the Standard Model (Robertson)
11:15–noon	Report of WG9: Nuclear Physics of the Universe (Parker)

Afternoon 2:00–5:00

1:30–2:15	Report of WG7: Confined and Deconfined Phases of Nuclear Matter (Gyulassy)
2:15–3:00	The case for RHIC (Satz)
3:30–4:30	Discussion of RHIC

Evening 7:30–open

7:30–9:00	The case for KAON, discussion of KAON (Barnes)

Wednesday, August 9

Morning 8:30–12:00

8:30–9:30	The case for a LAMPF upgrade, discussions (McClelland)
9:30–10:15	The case for LISS (Cameron)
10:45–11:30	The case for an advanced hadron facility, discussions (Garvey)
11:30–12:15	Experiments at high-energy facilities (Geesaman)

Afternoon 1:30–5:00

1:30–2:15	Report by WG12: Nuclear Science Facts and Trends, foreign comparisons (Britt)
2:15–3:00	Balance between equipment and operating funds (Braun-Munzinger)
3:30–4:15	Opportunities in nonaccelerator-based Nuclear Science (McDonald *et al.*)
4:15–5:00	Discussion

Evening 7:30–9:00

7:30–9:00	Discussion of priorities and balance

Thursday, August 10

Morning 8:30–12:00

8:30–9:00	The needs of Nuclear Theory (Redish, Henley)
9:00–10:00	The role of the universities (Haxton)
10:30–11:15	Report by WG11: Applications of Nuclear Physics (Peelle)
11:15–noon	Discussion of revised WG reports

Afternoon 1:30–5:00

1:30–3:00	Further discussion of priorities: implications, funding needs
3:30–5:00	Work on LRP Report

Evening 7:00–open

Final Discussion of priorities and LRP items

Friday, August 11

Morning 9:00–11:00

Final revisions of LRP documents

11:00	Workshop ends

FINAL WORKING GROUPS FOR BOULDER MEETING

June 29, 1989

1. Basic Structure of the Nucleus: Symmetries and Elementary Excitations;
Convenors: S. Vigdor, C. Glashausser, W. Turchinetz
Participants: Austin, Bertsch, Casten, Koonin, Moniz, Serot, Weller

2. The Nucleus under Extreme Conditions;
Convenors: R. Casten, J. Garrett
Participants: Balamuth, Bertsch, Hamilton, Paul, Stephens

3. The Dynamics and Thermodynamics of Colliding Nuclei;
Convenors: A. Mignerey, K. Gelbke
Participants: Betts, Britt, Bertsch, Sobotka, Siemens

4. Hadrons in the Nuclear Medium;
Convenors: J. McClelland, H. Jackson
Participants: Cameron, Moniz, Glashausser, Domingo, Peterson, Redish, Redwine, Walecka

5. Strangeness and Flavors in Nuclei;
Convenors: C. Dover, P. Barnes
Participants: Eisenstein, McClelland, Henley, McKeown, Garvey

6. QCD Description of Hadrons and Nuclei;
Convenors: D. Geesaman, R. McKeown
Participants: Arnold, McCarthy, Moniz, Domingo, Barnes, Henley, Mueller,
Garvey, Walecka

7. Confined and Deconfined Phases of Nuclear Matter;
Convenors: M. Gyulassy, G. Young
Participants: Baym, Bertsch, Braun-Munzinger, Britt, Gelbke, Ludlam, Nagamiya, Schroeder,
Siemens

8. Fundamental Symmetries, Conservation Laws and the Electroweak Interaction;
Convenors: H. Robertson, R. Tribble
Participants: Adelberger, Dover, Garvey, Haxton, McDonald, Henley, Marciano

9. Nuclear Physics of the Universe;
Convenors: P. Parker, W. Haxton
Participants: Adelberger, Austin, Baym, McDonald, Robertson

10. The Tools of Nuclear Science; Accelerators, Detectors, Targets, Computation;
Convenors: J. Cameron, P. Braun-Munzinger
Participants: Domingo, Schroeder, Jackson, Geesaman, Stephens, Redish

11. Applications of Results and Methods of Nuclear Physics;
Convenors: R. Peelle, P. Paul, (D. Lawson)
Participants from outside

12. Facts and Data on Nuclear Physics, Foreign Programs;
Convenors: C. Britt, H. Willard
Participants: Nagamiya, Gregoire (outside), Paul, Kovar

Long Range Plan Town Meetings (Sponsored by the APS Division of Nuclear Physics)

1. Electromagnetic Probes:

Keywords: studies of the strong and weak interactions with photon, electron and muon probes; nucleon and nuclear structure and currents; electromagnetic scattering studies of the weak interaction.

April 11-12 at BATES
Convened by D. Geesaman and J. McCarthy
June 5–6 at CEBAF
Convened by J. McCarthy and D. Geesaman

2. Light Hadronic Probes:

Keywords: protons, pions, kaons, and p-bars with energy > 100 MeV; Advanced Hadron Facility/KAON; glueballs; hadron data needed for CEBAF, RHIC; strange dibaryons; nuclear medium effects; baryon-baryon interaction; a new few-GeV facility.

April 23–24 at Indiana U.
Convened by C. Glashausser and R. Eisenstein
May 22–23 at Santa Fe
Convened by R. Eisenstein and C. Glashausser

3. Low-Energy Nuclear Physics:

Keywords: heavy-ion related fusion-fission, incomplete fusion, quasi-fission; high-spin, Coulomb excitation; deep inelastic collision; quasi-elastic and transfer reactions; nuclei far from stability; anomalous positron lines; light-ion related-reaction mechanisms; polarized probes; mean-field potentials; shell-model, collective models; symmetries and chaos in nuclear spectra; nuclear data centers.

April 17–18 at ANL
Convened by A. Mignerey and J. Garrett

4. High-Energy Heavy Ion Physics:

Keywords: ultra-dense matter; QCD confinement and deconfinement; signatures of quark-gluon plasma; equilibrium/non-equilibrium effects; stopping vs. scaling regime; equation of state, pion/kaon condensation; collective flow and pion dispersion; gas-liquid phase transition, multifragmentation; strangelets, H-dibaryon, Higgs production; giant resonances; radioactive beams.

April 24–25 at ORNL
Convened by G. Young and M. Gyulassy

5. Theory:

Keywords: computational needs and facilities; relativistic many-body theory; QCD; sub-nucleon models; equation of state; collective modes; chaos in nuclear physics; structure and reaction theories; non-linear field-theoretic models; phase transitions at high densities and temperatures.

April 25 at MSU
Convened by E. Redish and A. Mueller

6. Electro-Weak Interaction and Astrophysics:

Keywords: Symmetries and conservation laws, CP nonconservation, conservation of lepton and baryon numbers, tests of C,P, and T; precision tests of the standard model, measurements of weak mixing angle, rho parameter, deviations from V-A, higher order effects; particle properties, neutrinos, searches for new particles; strong interaction effects, weak for factors of hadrons, non-leptonic weak interaction; anomalous phenomena, fifth force, second-class currents; particle aspects of astrophysics, solar and supernovae neutrinos, dark matter.

April 17–18 at Santa Fe
Convened by A. McDonald and C. Dover

Long Range Plan Workshops

1. Nuclei Far From Stability:

Keywords: exotic decays; masses; structure, intruder states, magic regions, deformations and collectivity, p-n interactions, shell model tests; astrophysics-related studies; radioactive beams.

April 9–10 at Argonne National Laboratory

2. Very Light Nuclei:

Keywords: light nuclei, spin, nuclear astrophysics, hypernuclei, NN interaction, hadron and electromagnetic probes of NN dynamics, spin structure using polarized hadrons and leptons, 3-body forces, low-energy reactions for astrophysics, isobar and hyperon components.

April 15–16 at TUNL

Draft Agenda for NSAC MEETING
INDIANA UNIVERSITY CYCLOTRON FACILITY
Monday–Tuesday, June 26/27, 1989

Monday, June 26, 1989

Main Conference Room Indiana University Cyclotron Facility

8:30am-	9:00am	Charge by DOE/NSF for Long Range Plan
9:00-	12:15	Presentations by major Users Facilities: 15 minute presentations, 10 minutes questions
	9:00 - 9:25	BATES
	9:25 - 9:50	CEBAF
	9:50 - 10:15	LAMPF
	10:15 - 10:40	BNL
	10:40 - 11:00	Coffee break
	11:00 - 11:25	IUCF
	11:25 - 11:50	MSU
	11:50 - 12:15	LBL
12:15pm-	1:30pm	Lunch
1:30-	2:30	Continuation of reports on Users Facilities
	1:30 - 1:55	ANL
	1:55 - 2:20	ORNL
	2:20 - 2:30	NPAS
2:30pm-	3:30pm	Discussion of University Laboratory programs
3:30-	4:00	Coffee break
4:00-	6:30	Discussion of LRP input and procedures
	4:00 - 4:30	Program schedule for Boulder Meeting
	4:30 - 5:30	Issues for LRP and how to resolve them
	5:30 - 6:30	Outline of LRP Report
7:00pm		Catered Dinner

Tuesday, June 27, Main Conference Room IUCF

8:30am-	9:15am	Agencies reports on status of programs
9:15	9:45	Response to Instrumentation report
9:45-	10:15	Discussion of Working Groups: Final assignments, scope of reports as input for Boulder
10:15am-	10:45am	Coffee break
10:45-	12:00	Status report from working groups: Working groups 1 – 5
12:00	1:30pm	Lunch
1:30-	3:00	Further status reports on working groups: groups 6 – 12
3:00-	3:30	Final discussions of LRP input and procedures
3:30-	4:00	Other business and public comments
4:00pm		Adjourn

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