A LONG RANGE PLAN FOR NUCLEAR SCIENCE

A Report by the
DOE/NSF Nuclear Science Advisory Committee

DECEMBER 1983

U. S. DEPARTMENT OF ENERGY
OFFICE OF ENERGY RESEARCH
DIVISION OF NUCLEAR PHYSICS

AND

NATIONAL SCIENCE FOUNDATION
DIVISION OF PHYSICS
NUCLEAR SCIENCE SECTION

DOE/NSF NUCLEAR SCIENCE ADVISORY COMMITTEE

PREFACE

The DOE/NSF Nuclear Science Advisory Committee of the Department of Energy and the National Science Foundation is charged with providing advice on a continuing basis regarding the scientific priorities within the field of basic nuclear research to the Department of Energy and the National Science Foundation. It is in this sense that the Committee was asked (Appendix A) to develop a long range plan for the field, a plan that will serve as a framework for coordinated advancement of the research program over the next decade. This long range plan is the second one since the Committee's establishment in 1977; the 1979 Long Range Plan has guided the priorities of the field over the past several years, and has had a substantial impact on new directions and initiatives.

The Committee started discussing the 1983 Long Range Plan at its meetings in January, February, and April 1983 (Appendix B). The major issues were outlined, and the framework for formulating the Plan were established in April. The detailed substance of the Plan emerged from a week-long workshop in Aurora, N.Y. during the week of July 10 (Appendix C). In this Workshop, the scientific questions confronting nuclear science and the relevant technical issues were thoroughly discussed and drafts of sections of the report were formulated. This workshop involved a larger number of participants (about 30 in addition to the Committee) to ensure a broad representation of expertise and of opinions.

The writing and editing of the Long Range Plan document were carried out during August-October of 1983 and, at the meeting of the Committee on the 15th and 16th of October, the final details were discussed and the Plan was endorsed. Copies of the final draft were mailed to the Committee and to external readers, consisting of G. E. Brown, J. Cerny, H. Feshbach, E. M. Henley, and H. J. Jackson for their comments.

The Committee is indebted to a number of individuals for their help in connection with this task, the names of scientists who participated in the workshop and helped in other ways are listed in Appendix C. The chairman would like to express his particular appreciation to Karen Thayer, whose help during the workshop and in the typing of successive drafts has been invaluable.

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SUMMARY

In response to the request by the Department of Energy and the National Science Foundation for a Long Range Plan for Nuclear Science, the DOE/NSF Nuclear Science Advisory Committee (NSAC) held a number of meetings and a workshop during 1983 to prepare such a plan. From these discussions and studies, we reaffirm our earlier recommendation for the earliest possible start on the construction of a national electron accelerator laboratory and we make the following recommendations for the future:

1) **The research program in nuclear physics, with the facilities in existence or under construction, faces many challenges and opportunities *now*. To address those opportunities, central to the vitality of our field, it is essential that the $20 million incremental adjustment in operating and equipment funds for the ongoing research program that we recommended earlier this year be forthcoming.**

2) **We identify a relativistic heavy ion collider as the highest priority for the next major facility to be constructed, with the potential of addressing a new scientific frontier of fundamental importance.**

3) **To effectively utilize the national electron accelerator, the relativistic heavy ion collider and the other vital facilities of the nuclear research program, we recommend a level of funding rising to $270 million per year (FY 1983 dollars) by the time the above two major construction projects have been completed.**

The nucleus continues to be a rich source of new and often surprising phenomena. Exploration of many of these lies within the scope of existing accelerators and instrumentation. Nuclear physics both in the U. S. and abroad is in the midst of a renaissance of interest, excitement and optimism. The purpose of this Long Range Plan is to provide the United States with a strong role in the leadership of nuclear physics during the coming decade in which this renaissance is developing.

The major questions facing nuclear physics point to a number of important scientific opportunities beyond the reach of the facilities in existence or under construction. Many of these opportunities may be attained by a variety of possible upgrades and additions to the capabilities of present facilities. Among these are the capability for high resolution continuous (CW) electron operation below 1 GeV, substantially enhanced kaon beams, improved medium energy neutrino capability, antiproton beams, improved proton beams of variable energy between 200 and 800 MeV, and also above 800 MeV, intense neutron sources with energies up to a few hundred MeV, capabilities for accelerating very heavy ions with easily varied energy between 3 and 20 MeV per nucleon, a high intensity pulsed muon facility, and a number of other options. We estimate that a reasonable fraction of these opportunities can be realized within the currently envisioned base program. Decisions on relative priorities should be made at a later time and with more specific proposals in hand.

A high intensity 10-30 GeV proton accelerator (kaon factory), capable of producing intense beams of kaons, neutrinos, and other particles would provide substantial opportunities for physics, in areas that are clearly fundamental and exciting. Given our commitment to the national electron accelerator laboratory and the heavy ion collider discussed above, the financial assumptions of this report preclude a major additional facility. But as circumstances change, we want to keep this important option readily available.

There are fundamental issues in nuclear symmetries, in nuclear excitations, and nuclear dynamics for which the facilities, the instrumentation, the techniques and the theoretical framework are just beginning to come into existence. These major questions facing our science are discussed in the body of the report. We note that in addition to the wide variety of studies of nuclear structure and interactions at lower energies, there is an increasing interest in exploring the nuclear implications of quantum

chromodynamics (QCD), the theory of strong interactions that has emerged from particle physics. Not only are the implications of QCD for nuclear physics profound, but nuclear physics may provide fundamental new information on crucial aspects of QCD, such as quark confinement, by studying the elementary constituents of nucleons within nuclear matter. The 4-GeV electron accelerator of the national electron accelerator laboratory recently recommended by NSAC, will be an ideal instrument for exploring this crucial area and it is eagerly awaited by the nuclear physics community.

Our increasing understanding of the underlying structure of nuclei and of the strong interaction between hadrons has developed into a new scientific opportunity of fundamental importance—the chance to find and to explore an entirely new phase of nuclear matter. In the interaction of very energetic colliding beams of heavy atomic nuclei, extreme conditions of energy density will occur, conditions which hitherto have prevailed only in the very early instants of the creation of the universe. We expect many qualitatively new phenomena under these conditions; for example a spectacular transition to a new phase of matter, a quark-gluon plasma, may occur. Observation and study of this new form of strongly interacting matter would clearly have a major impact, not only on nuclear physics, but also on astrophysics, high-energy physics, and on the broader community of science. The facility necessary to achieve this scientific breakthrough is now technically feasible and within our grasp; it is an accelerator that can provide colliding beams of very heavy nuclei with energies of about 30 GeV per nucleon. Its cost can be estimated at this time only very roughly as about 250 million dollars. ***It is the opinion of this Committee that the United States should proceed with the planning for the construction of this relativistic heavy ion collider facility expeditiously, and we see it as the highest priority new scientific opportunity within the purview of our science***. The tasks of specifying the detailed characteristics of the accelerator, identifying technical issues, and planning for the necessary instrumentation will have to be taken up by workshops and NSAC subcommittees as soon as is appropriate and practical.

The tools, techniques and concepts of nuclear physics have found wide application in our sister sciences—as indeed we have benefited from advances in other sciences. Many applications have been made to the betterment of society and the nation. Radioisotopes and nuclear detectors, for example, have provided both research and clinical medicine with probes of unprecedented specificity and sensitivity. Nuclear medicine is the most rapidly growing subfield of medicine at the present time. The ion beam technologies developed for nuclear physics have revolutionized many aspects of surface and materials science and of technology. And fundamental concepts such as pairing have been passed back and forth between nuclear and condensed matter physics to the enrichment of both. All these are only isolated examples of the unusually broad impact that nuclear science has had and continues to have on other basic sciences, on technology and on society at large.

The budgetary implications of the Long Range Plan are stated. Comparison to other advanced countries indicates that the relative U. S. investment in nuclear physics is presently substantially lower (by a factor of two to three). In order to respond to the major new opportunities confronting the field with the present facilities we point out the need for the 10% ($20 million) incremental adjustment in operating and equipment funds recommended by our Committee on April 29, 1983.

We see this increment as helping alleviate some of the most urgent needs of the field: (a) supporting long-term developmental work on accelerators and instrumentation; (b) fuller utilization of existing facilities that are funded at subcritical levels of operation, far below their potential to produce outstanding research; (c) support of technical manpower for user groups; (d) support of young investigators; and (e) many opportunities in research where a relatively small investment would have significant impact. Looking further into the future, the budgetary implications of the major new facilities are considered as leading to a total annual budget of about $270 million (FY 1983 dollars) after the completion of the relativistic heavy ion collider.

The opportunities for new research confronting us now are highly promising, a number of them involve changing perspectives and close interactions with other fields of science. Our progress towards meeting the challenges ahead of us is only limited by the resources at hand. Within the framework of this Long Range Plan one can anticipate a decade in which nuclear science will confront key scientific questions and in which the United States will play a leading role.

I. INTRODUCTION

The world in which we live is made mostly of nuclear matter. Though some of the important features of our universe, such as chemical and biological properties, are determined by the fragile shell of atomic electrons surrounding the nucleus, others, such as our sources of energy, are predominantly nuclear in origin. The nuclear fusion reactor that is our sun provides the energy for all life in the biosphere, and this solar energy, as stored in wood, coal and oil, has been the basis for the development of civilization on this Earth. It is also nuclear fission and fusion energy that our society has been attempting to tame during the last four decades as the energy sources for future generations.

The drive to study, understand, and control our environment has been the unique distinguishing characteristic of the human race. This must have been true for many millenia, and has been a crucial element in our evolutionary success. But this pursuit of knowledge based on observation and measurement has been institutionalized by our society only in the very recent past, in the form of systematic support of science.

It is clear that the enormous advances mankind has achieved in the last century in controlling the environment and improving the quality of human life are directly related to prior investments made in very basic, then apparently "useless," science. The pursuit of basic knowledge and of the understanding of our world, this very uniquely human curiosity, pays off in the most unexpected ways, and is the soundest investment our society and our country can make in its future.

We view this Long Range Plan for the future of nuclear science in this spirit. Our perspective is to observe, characterize, and attempt to understand the properties of the atomic nuclei which are the overwhelmingly dominant component of the universe in which we live. Many applications have already sprung from this pursuit of knowledge and understanding—some as techniques, perspectives or insights into other basic sciences—others as direct tools to be used to satisfy the needs of society.

The discovery of the *existence* of atomic nuclei is three quarters of a century old—barely one human lifetime. Our knowledge and characterization of nuclear properties have made enormous advances since that discovery—particularly in the latter part of this century and particularly in the United States

As children are taught now in grade school science classes, the nucleus is made of nucleons: neutrons and protons. There are nuclei with one or two nucleons and nuclei with several hundred. The force that holds nuclei together has been studied and characterized but it is understood only in a very qualitative sense. But the properties of nuclei—simple and isolated many-body systems—show a rich variety of phenomena that are often not sensitively dependent on the details of the nuclear force. Many mathematical techniques of group theory have found their realization in descriptions of the symmetries exhibited by nuclear structure. As it involves the study of a many-body system, nuclear physics shares a common frontier and intellectual overlap with solid-state physics on one hand and atomic physics on the other. In astrophysics, the properties of nuclei and nuclear matter play a crucial and detailed role in stellar evolution and are of critical importance in determining the behavior of supernovae and neutron stars.

The characterization of the symmetries and of the simple excitations and simple modes of motion of nuclei is by no means finished. The interplay between these and the limits where the symmetries change or break down needs to be explored systematically, and there are important lessons to be learned not only for our understanding of nuclei, but also for the applicability of mathematical techniques to the properties of (finite) many-body systems. The limits of nuclear structure symmetries and what lies beyond them are explored in a number of directions: with heavy-ion beams, allowing more and more nucleons within the nucleus to become stirred up from their normally quiescent and relatively inert states; with simpler probes, which can add more energy and momentum to nuclear excitations; and with more precision, exploring the quantitative limits of our understanding of the nucleus.

A currently very lively frontier of nuclear physics is the one it shares with its younger and precocious sister field—particle physics. The quark-gluon theory of elementary particles that has evolved over the past two decades has been enormously successful in describing the properties of these particles. Since protons and neutrons consist of three quarks each, and the mesons, which are the carriers of the nuclear force, are quark-antiquark pairs, the implications of these new ideas about the structure of nucleons on our understanding of the nucleus must be explored.

The fundamental forces governing the physics of nuclei and all subatomic phenomena have recently been embedded in a consistent theoretical framework involving the basic building blocks—quarks and leptons—and their interactions. It is of paramount importance to determine whether this theory is correct or is in need of modification or extension. This requires experiments at high energies in elementary particle physics and precision experiments at low and intermediate energies using nuclei and the tools of nuclear physics. Nuclear physics has provided a testing ground for many implications of the structure of matter and of the basic forces of nature. Some recent examples are limits on the existence of stable free quarks, of light particles such as axions or light Higgs bosons, of neutrino oscillations and neutrino masses, to name only a few.

The expansion of our horizons and knowledge in nuclear physics has had a unique impact on society. The influence of nuclear fission on the modern age is universally known, as is the continuing search for a major new energy source in the form of nuclear fusion. But the applications of nuclear techniques are much more widespread. Nuclear medicine is the fastest growing subfield in medicine, nuclear accelerators find widespread use in fields beyond medicine, ranging from food preservation to the fabrication of integrated circuits and the measurement of the ages of paleolithic artifacts. Nuclear systems measure environmental contaminants with unprecedented accuracy, and nuclear techniques have given life scientists exquisitely sensitive and selective probes. Most important of all, a good fraction of each generation of U. S. nuclear scientists serve society in industry and government, by applying their skills and training in the techniques of the field to further help solve societal problems. For this contribution to continue, and for the continued scientific vitality of the whole field, it is important that the training of young nuclear scientists receive the high priority that it deserves.

The field of nuclear physics is on the threshold of a new phase in its development. A number of new techniques are in the process of being applied to the investigation of areas of the science where our knowledge is at best fragmentary. The next decade is certain to uncover new results, better understanding and improved insights into this major area of our physical universe.

In 1979 the DOE/NSF Nuclear Science Advisory Committee proposed its first Long Range Plan. It is gratifying to see the extent to which the overall recommendations of that Plan have been and are being implemented, even though the *level* of funding has been severely constrained and some difficult priority decisions have had to be made in order to allow the research programs to continue productively within the available, very limited, resources. The severe lag in accelerator construction of the mid 1970's has been partially corrected and several modest but important construction projects are either underway or just completed. These new capabilities open fresh areas for investigation and should provide us with a new harvest of knowledge over the coming decade.

Especially encouraging is the prospect of a 4 GeV CW electron accelerator which has been a gleam in the eyes of the nuclear physics community for a decade and which was the key goal of the 1979 Long Range Plan. Since 1979, that goal has evolved into specific facility proposals and, in 1983, into the specific recommendation of this Committee for the national electron accelerator laboratory. This facility will play a crucial role in extending the frontiers of nuclear physics to encompass studies of the nuclear dynamics based upon quark degrees of freedom on the interface between nuclear and high-energy physics.

II. THE SCIENCE

In this chapter we formulate some of the basic questions facing nuclear physics today. These questions span a broad range, including both strong and electroweak interactions and the properties of the physical world from the scale of nuclear forces to the large-scale structure of the universe. Nuclear science deals with the many-body aspects of the strong interactions. It also deals with tests of fundamental theories and symmetries. In particular, the limits of the electroweak theory must be explored and nuclear science has important contributions to make to this effort, as it does also in connection with the role of nuclei and nuclear processes in determining stellar structure and in constraining cosmological models.

Our understanding of nuclear structure and nuclear dynamics continues to evolve. Under the impact of improved facilities, new techniques in instrumentation and computing, and fresh ideas we have made substantial progress in the last five years. New simple modes of excitation have emerged, new symmetries are appearing and some completely unexpected new phenomena have been discovered. We may expect this trend to continue in the next decade as new facilities with qualitatively new capabilities will become available for use by nuclear scientists. The identification and characterization of simple modes is a difficult challenge requiring a multiplicity of experimental techniques. But as our knowledge of these modes increases and becomes more complete, it can confirm or alter our understanding of the structure of the atomic nucleus very profoundly. The study of the symmetries inherent in the nucleus has been very rewarding and the insights gained of the nature and the limits of the symmetries have considerable overlap with the study of symmetries in other branches of science. There are many aspects of nuclear symmetries that require further work and hold promise of qualitatively new results, particularly outstanding among these is the pursuit of nuclear structure symmetries in very rapidly rotating nuclei.

Our microscopic approach to a multiparticle system seeks to identify its constituents, to discover and study its elementary modes of excitation, and to describe the elementary excitations in terms of the constituent nucleons and, to some extent, the other hadrons. But as experimental evidence accumulates to confirm quantum chromodynamics (QCD) as the correct theoretical framework for hadronic phenomena, it becomes clear that the basic degrees of freedom in multihadron systems are those of the constituent quarks. The theoretical description of the nucleus in terms of quark dynamics is not yet tractable. Nor is it the whole story. Many-body problems can only be solved approximately and in building such approximate solutions qualitative physical insight is as important to our understanding as numerical prediction. In studying a given mode of excitation, the preferred description reproduces the essential physics in the simplest most readily-visualized way and the selection of the proper degrees of freedom contains a crucial element of qualitative judgment.

In most low-energy nuclear phenomena, the quark dynamics appear to be well approximated in terms of three-quark nucleonic clusters with meson exchanges. The validity of this approximation resides in the fact that in the center of nuclei the typical internucleon separations seem to be substantially larger than the diameters of the nucleon "bags" within which the quarks are confined. The appropriate description here is then in terms of nucleons and the effective interactions between them. This nucleons-only regime is well known and far reaching; the remarkable success of "conventional" nuclear models in correlating nuclear phenomena has profound importance for QCD-based dynamics. The richness and beauty of the excitations and phenomena it encompasses are central to nuclear physics; the pursuit of the detailed characterization and understanding of these nucleonic excitations will remain of crucial importance even as we dig deeper towards the underlying quark structure.

At somewhat higher energies and for high-precision treatment of electroweak and hadron-induced processes, the description in terms of inert, structureless nucleons breaks down, and a level of description intermediate between that based on structureless nucleons and that based on quarks becomes valuable. At this level, the nucleons (bound states of three quarks) can exist *and* propagate in their ground and excited states, and their effective interactions are described in terms of the exchange of mesons (bound states of quark-antiquark pairs). This intermediate level of description has had impressive successes, but its place in many-particle strong-interaction physics is still imprecisely defined, although a deeper level of understanding appears to be tantalizingly close. At still higher energies, as the substructures of baryons and mesons become important, so also does the quark content of nuclei, and the basic features of QCD should begin to emerge. It will certainly be of considerable interest to understand such distinctions more precisely as more experimental results emerge.

One of the greatest challenges facing nuclear physics today is to find and follow the implications of quarks and of QCD in nuclei. This challenge is experimental and theoretical in equal measure. We must design experiments that will reveal the relevant degrees of freedom as clearly and unambiguously as possible; we must attempt to find experimental signatures for modes of excitation in which the quark degrees of freedom participate individually, not merely as the underlying structure of nucleons and mesons. The 4-GeV CW electron accelerator recently recommended for funding will play a crucial part in beginning this endeavor.

The more macroscopic approach to nuclei views them as aggregates of nuclear, hadronic or quark matter. Experimental studies focus on the flow of matter and energy in collisions between such aggregates. What matter densities are achieved in such collisions? How much energy can be deposited in regions of high density and over how large a volume is this energy distributed? As answers to those questions are found, it becomes possible to study the nuclear equation of state over a wide range of density and temperature. We may look for phase transitions in which new forms of hadronic matter are produced and the many-body aspects of QCD are realized as they were in the early Universe, new forms in which quarks are no longer confined into individual nucleons and mesons. In this report we identify this physics as presenting a major new opportunity of fundamental significance.

Another interface area with elementary particle physics stems from the fact that nuclear physics can provide tests of the theory of the electroweak interactions which together with QCD forms the "Standard Model." The electroweak theory has been enormously successful. Its prediction and its limits of validity must be explored and understood, and nuclear physics and the tools of nuclear physics can provide some of the crucial experiments for this purpose.

The questions in the subsections of this chapter of our report represent the major current issues in nuclear science. There are certainly other interesting issues that deserve attention, but in this report we have identified these ten questions as being central to future progress in nuclear science.

With the facilities in existence, those under construction, and those recommended previously, the field of nuclear science faces a decade in which our horizons have expanded dramatically and in which we may expect major qualitative progress both in the understanding of nuclear structure and nuclear dynamics and in the elucidation of the foundations of nuclear matter in terms of the basic interactions of nature.

II.1 ELEMENTARY EXCITATIONS

What are the simple modes of nuclear motion? What information do they provide about the properties of the nuclear many-body system, and what constraints do they place on fundamental theories of the nucleus?

A nucleus is a quantal system, built from a number of strongly interacting particles, mainly nucleons, but with important admixtures of pions, other mesons, as well as excited states of the nucleons such as the delta isobar. A consequence is the coexistence and interplay in nuclei of an astonishingly rich spectrum of motions, some involving one or a few nucleons, some involving the coherent motion of many nucleons, and still others involving simultaneously pions, deltas and nucleons. But there is considerable order within this complexity. Studies with a variety of projectiles, targets and energies have led to remarkably successful models of nuclear structure. Two aspects of the nuclear many-body system have made this possible. First, there are simple modes of motion of the nucleus which serve as the elementary degrees of freedom for describing more complex motions; and second, reaction probes are available which selectively excite the simple modes. In the past decade many new elementary excitations have been discovered and their properties characterized. The behavior of these excitations, as a function of mass, proton-neutron ratio, angular momentum and energy provides a controlled laboratory in which to test and develop models of nuclear structure.

The Mean Field

Perhaps the most fundamental and conceptually simple of the elementary modes is the motion of a single nucleon in a nucleus. To a good approximation each nucleon moves almost independently in a mean field created by its average interaction with all other nucleons. The goodness of this approximation is the basis of the shell-model description of nuclear phenomena. Self-consistent Hartree-Fock calculations have now put this picture on a firm theoretical foundation and predict nucleon densities in nuclei that are extremely accurate, deviating significantly from experiment only deep in the nuclear interior.

A similar picture should describe the interaction of a nucleon scattering from a nucleus, but the mean field, or optical model potential, must now contain an imaginary part to account for absorption of the projectile by the nucleus. Accurate measurements of elastic proton scattering cross sections and spin analyzing powers for energies up to 800 MeV have now been made for many nuclei. New experimental techniques yield similar data for neutrons and permit estimates of the difference in the mean field for neutrons and protons, a difference that affects many nuclear phenomena. These data span a broad range of energy and momentum transfer to provide stringent tests for theories of the mean field.

Progress in the derivation of the mean field from a fundamental theory has been made at three levels: in terms of neutrons and protons alone; in a relativistic theory involving implicitly not only the nucleons but also mesons; and finally at the most fundamental level, in terms of the quarks and gluons of QCD.

It is certainly an oversimplification of the nuclear system to consider only nucleon coordinates. Mesons play a central role for the nuclear force; a more complete theory of the nuclear many-body system must explicitly include them and also include relativistic effects. Many-body and multiple scattering theories based on the relativistic Dirac equation are being considered; they have already provided a simple and accurate description of some nuclear properties and scattering. The spin-orbit interaction, crucial to the success of the nuclear shell model, arises naturally from the relativistic treatment, as it does in atoms.

The detailed implementation of relativistic effects in mean field theories awaits future developments. It will be necessary to understand the status of a relativistic field theory based on composite objects rather than on the presumably fundamental quarks; the origin of certain of the mesonic degrees of freedom in the theory; and the meaning of the implied large decrease in nucleon mass in the relativistic nuclear field. Studies of nuclear structure and reactions within this framework will form a major task for the future.

Single Particle and Collective Excitations

In its simplest form, the shell model describes nucleons moving independently, it is not well suited to the description of more coherent modes. Allowing for a residual pairwise interaction between valence nucleons yields an interacting shell model with greatly increased predictive power. It provides a remarkably accurate description of low-lying nuclear energy spectra in light nuclei and near closed shells where detailed calculations are practical and its predictions have a general validity even for nuclei far from the valley of stability. A recent measurement of the charge density difference between ^{205}Tl and ^{206}Pb determined the shape of a specific proton orbital in the deep interior of the lead nucleus as shown in figure II.1-A; it was found to be well described by the shell model.

These single particle excitations are the basis for the descriptions of more complex phenomena, and must be understood for nuclear excitations to be described on a fundamental basis. At present the location and width of hole states is reasonably well understood only for the two outermost shells, and little is known about deeper lying states. The coming generation of high duty-cycle electron accelerators will allow one to form these in a particularly clean fashion by electron induced knockout of a nucleon, and may even permit definitive studies of short range pair correlations between nucleons. Proton induced knockout reactions provide complementary information through their sensitivity to neutrons and their control of the spin degree of freedom.

The macroscopic collective model is often used to describe phenomena in which large numbers of nucleons move coherently. In this model, the nucleus is treated as a liquid drop, capable of vibrating and rotating. The structure of low lying collective states in most nuclei is dominated by the prolate spheroidal shape. Coulomb excitation is a selective probe for this mode, exciting states with probabilities directly related to this quadrupole deformation. New experimental and analysis techniques involving comparisons of Coulomb excitation with light and heavy projectiles allow an essentially complete determination of the quadrupole structure of nuclei. Other studies have found independent-particle and collective excitations coexisting at low excitation in many nuclei.

New technical developments in gamma-ray spectroscopy involving germanium detectors with anti-Compton shields and many-detector arrays, the so-called "crystal ball" multiplicity filters, should allow extension of these studies to still higher spin and excitation. Unusual new collective modes may be discovered in these unexplored regions. Already there may be some indication of octupole, or pear-shaped deformations for nuclei with mass numbers between 220 and 230. In general one hopes to delineate better the interplay of single particle and collective degrees of freedom, and to determine the limits of the macroscopic collective model.

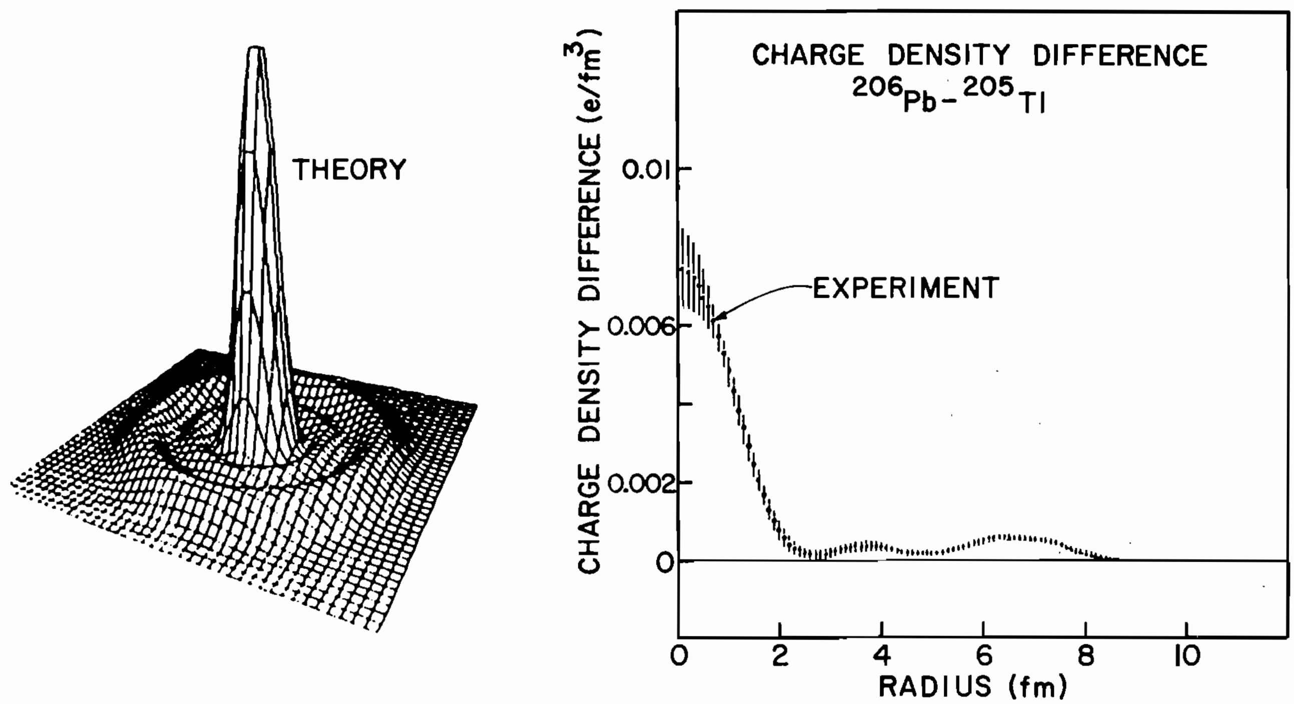

Fig. II.1-A. The density distribution of the least bound proton in ^{206}Pb. The shell model predicts that the last ($3s_{1/2}$) proton in ^{206}Pb should have a distribution with a sharp maximum at the center as shown on the left. Even though there had been considerable skepticism about the validity of the shell model deep inside a heavy nucleus, recent experimental results shown on the right confirm this expectation.

Giant Resonances and Selective Probes

Over the past few years our knowledge of giant resonances has increased dramatically. These resonances are states of the nucleus in which all available nucleons participate coherently. One classifies them into multipoles by the angular momentum L characterizing their vibration (L = 0, monopole; L = 1, dipole; L = 2, quadrupole; etc.). Since the nucleus has four components, protons and neutrons with spin up or down, each multipole vibration can be of four types, neutrons and protons with particular spin orientations moving in or out of phase. These are classified as isoscalar (neutrons and protons in phase), isovector (neutrons and protons out of phase), electric (no spin coherence), and magnetic (spins parallel).

Because these resonances are expected to be broad and often overlapping, it is imperative to use probes which selectively excite the specific modes. The history of the discovery of the giant resonances — the isovector dipole in the mid 1940's, the isoscalar quadrupole in the early 1970's and many others in the past six years — reflects our success in developing such selective probes. Systematic data on the location, width and strength of the electric giant resonances now exist for the isoscalar monopole, quadrupole and octupole and for the isovector monopole, dipole and (possibly) quadrupole. Similar data exist for the spin excitation or magnetic monopole (Gamow-Teller transition) and higher magnetic multipoles. In addition, a variety of data clearly show that the giant dipole resonance exists even when built upon excited states of the nucleus or states with very high spin. The location, width, strength, and systematic variation with nucleus of these simple giant resonance vibrations provide an excellent testing ground for the unification of macroscopic models based on the bulk properties of the nucleus and microscopic descriptions based on the shell model. The location of the isoscalar electric monopole states, in which only radial or breathing motion occurs, provides by far the best measurement of the resistance of nuclear material to compression. This compressibility is important for testing nuclear matter calculations, for understanding shock wave phenomena in heavy-ion collisions and supernova explosions, and for establishing bounds on the sizes of neutron stars.

An important discovery followed from a property of the nucleon-nucleon force around 200 MeV. When a 200-MeV proton projectile knocks a neutron out of a nucleus in a charge exchange (p,n) reaction, it almost always transfers a unit of spin to the nucleus. This process is then a uniquely selective probe for the spin structure of nuclei. A striking application of this probe is the discovery of the giant spin-vibration or Gamow-Teller resonance in many heavy nuclei as shown in figure II.1-B. The distribution of such spin strength is closely related to the distribution of beta decay strength and is important in a variety of applications in astrophysics (supernova explosions and the rapid-neutron-capture process in the synthesis of the heavy elements) and in the calculation of average fission fragment beta decay spectra in reactors. But perhaps the most important feature of these spin excitations is that their strength is quenched, having only about half the expected value. Evidence is accumulating for a similar quenching in other spin excitations, suggesting that perhaps all spin-dependent phenomena are quenched by about a factor of two. A simple and elegant explanation of this quenching has been proposed in terms of the role of chiral symmetry and the underlying QCD structure in the nucleus. A related simple mechanism is the polarization of the nucleon by the nuclear medium leading to admixtures in the nuclear states of high-lying delta-hole states. However, other phenomena can also affect the transition strength, so that the quantitative importance of this quenching is one of the most interesting open questions involving giant resonances. Further studies of spin excitations offer perhaps the best opportunity for establishing the importance of new degrees of freedom in nuclei. Inelastic scattering and charge-exchange reactions such as (n,p) and (p,n) should play an important role in these studies; new accelerators providing intense beams of polarized protons and neutrons up to a few-hundred MeV will be crucial for such work.

Recent studies of elementary excitations have greatly increased our understanding of a number of the core problems in nuclear physics: the fundamental basis of the nuclear mean field; the importance of relativistic effects on nuclear structure; the interplay of single-particle and collective degrees of freedom in the nucleus and the importance of non-nucleonic degrees of freedom in giant resonance excitations. One expects that further study will further enrich this understanding.

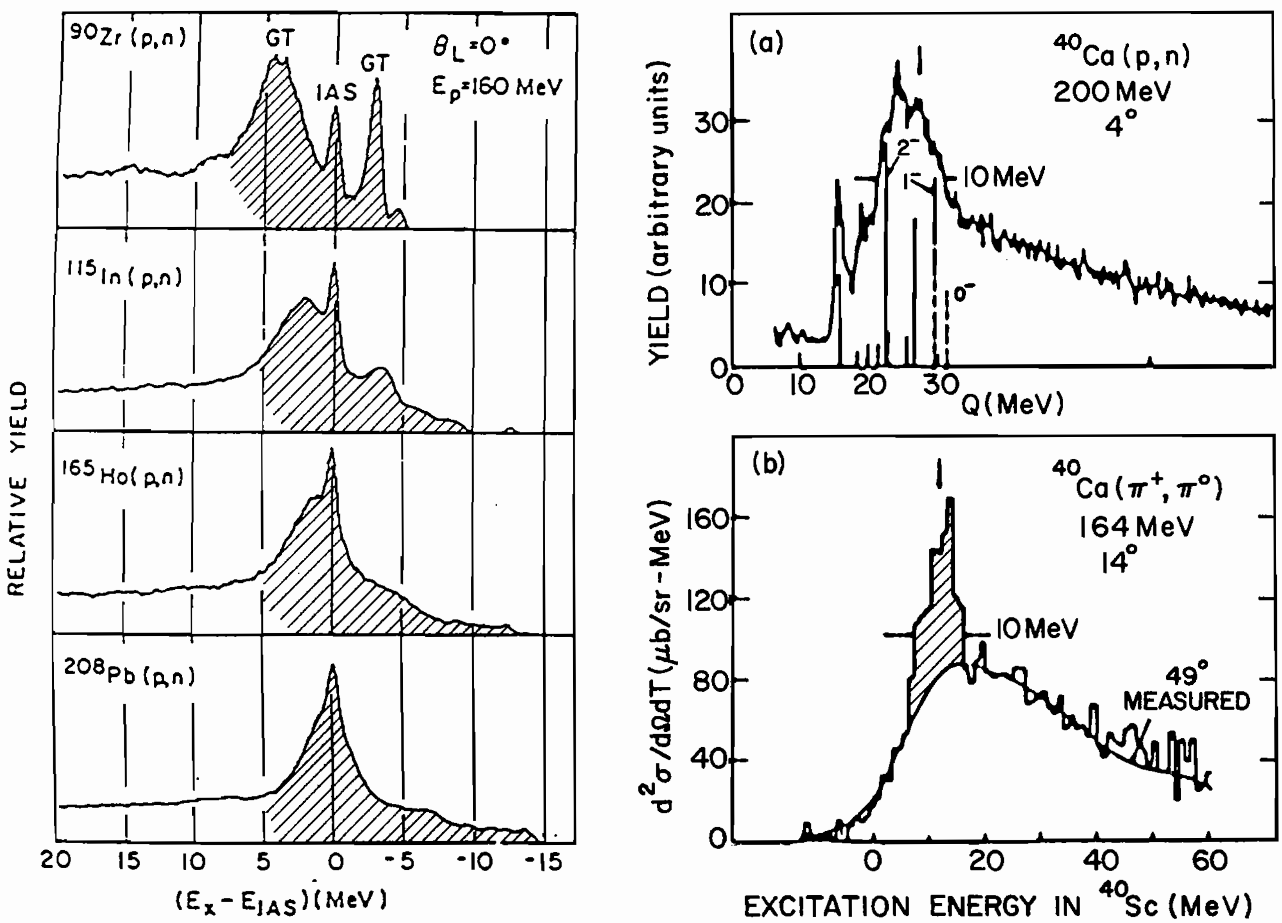

Fig. II.1-B. New giant resonances: evidence for the Gamow-Teller (GT) giant resonance in (p,n) spin flip reactions are shown on the left; on the right recent data from pion charge exchange show evidence for an isovector charge-exchange dipole giant resonance in ^{40}Sc based on ^{40}Ca.

II.2 NUCLEAR SYMMETRIES

How extensively can symmetry considerations be used to describe nuclear properties?

"Symmetry, as wide or as narrow as you may define its meaning, is one idea by which man through the ages has tried to comprehend and create order, beauty and perfection" (H. Weyl). The first serious use of symmetry considerations in physics was in the classification of the shapes of molecules and crystals; the symmetries here are *geometrical*. Later it was realized that the lack of preferred orientations in space-time places severe restrictions on the form and content of physical theories; these are *space-time* symmetries. A third class of symmetry, *dynamic* in character, was first discovered and applied in atomic and nuclear physics around 1930; dynamic symmetries express general properties of the interactions between the constituents of many-body systems (involving the symmetrical interchange of neutrons and protons—isospin invariance—to name but one). Symmetry considerations enable us to identify properties of complex physical systems that transcend the details of their structure and interactions. We concentrate in this section on *dynamic* symmetries. Some milestones in nuclear symmetries are shown in figure II.2-A.

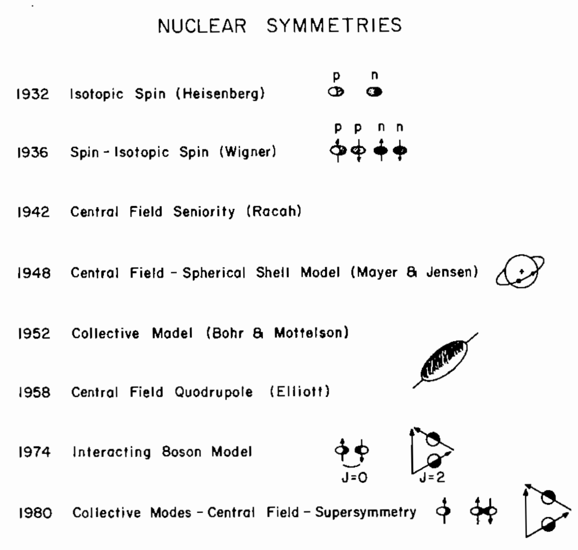

Fig. II.2-A. Milestones in the development of nuclear symmetries.

Isospin

The symmetry represented by charge independence, expressed by the isospin quantum number, has the mathematical group-theoretic structure of SU(2) and has long been an important tool in the study of nuclear properties. It is now understood in terms of the underlying symmetries in QCD. It relates families of states and giant resonances in nuclei with the same mass number. The energy relations between members of these isobaric multiplets provide exacting tests of our understanding and raise as yet unanswered questions about small charge-dependent components in the nuclear interaction. The relative strengths with which the different multiplet-members are excited in reactions and decays yield precise information about the neutron and proton content of nuclear orbitals.

Isospin considerations have been a fertile source of information about nuclear structure but their application to date has been confined to a restricted class of excitation and to nuclei close to the line of stability. The opportunity now exists to study the isospin properties of new types of nuclear excitation and to push isospin considerations far beyond the line of stability. Detailed study of isobaric multiplets involving low-lying collective excitations may shed light on the elusive relation between the neutron and proton deformations of deformed nuclei.

Isospin symmetry is the simplest of dynamic symmetries; it expresses the fact that nuclear interactions are invariant under interchange of neutrons and protons (charge independence). Spin and isospin symmetries were combined by Wigner in 1936 to fashion a much richer symmetry—supermultiplet [SU(4)] symmetry. The direct impact of supermultiplet symmetry on nuclear physics has been slight; it has been applied only to light nuclei and even there it is strongly broken. There are some prospects for new applications, however. The recently-discovered Gamow-Teller giant resonance involves the simultaneous reversal of the spin and isospin of a single nucleon and it is possible that the supermultiplet symmetry may play a significant role in describing its properties.

Indirectly, of course, supermultiplet symmetry has played a fundamental role in the development of modern physics. A generalization of the symmetry represented by the isospin group [SU(2)] and that of supermultiplet symmetry by [SU(4)] led to the introduction of the Gell-Mann—Ne'eman quark model based on the group [SU(3)]. Indeed, many applications of symmetry considerations in elementary particle physics trace their origins to Wigner's work on supermultiplet theory.

Shell-Model Symmetries

To a surprising extent, nuclear interactions conspire to produce a mean field in which the nucleons move freely. The possibility arises that some of the symmetries of the interactions may achieve simple expression in symmetries of the mean field. Exploitation of this idea started with

Elliott in 1958. He noted first that the mean nuclear potential is quite similar in shape to a deformed harmonic-oscillator potential, second that this oscillator potential has a dynamical symmetry described by the group SU(3). Systems of nucleons moving almost independently in the mean nuclear potential thus have an approximate SU(3) symmetry. This discovery opened the first fruitful avenue to a microscopic interpretation of nuclear collective properties.

Although Elliott's work is almost 30 years old, much remains to be done before its full implications in nuclear many-body physics become clear. Elliott's early work concerned low-lying modes of excitation, in which valence nucleons populate the levels of the lowest accessible oscillator shells. Consideration of excitations into higher oscillator shells involves enlarging the symmetry group from SU(3) to Sp(6,R). The implications of this group in nuclear physics remains to be explored. Is the symmetry that it carries sufficiently weakly broken to be useful? Can it identify new excitations or families of levels that are of physical interest and are accessible to experimental study? Another interesting property of the harmonic-oscillator potential is that it permits a natural description of another fundamental mode of excitation of nuclei: clustering. The Elliott SU(3) scheme has been extended to describe alpha-particle clustering in nuclei. How accurate is this description?

Pairing and Seniority

The interaction between nucleons in nuclei is particularly strong and attractive between pairs of identical nucleons (neutron pairs and proton pairs) coupled to total angular momentum zero. This pairing property of the interaction between identical nucleons plays a fundamental role in the systematics of both spherical and strongly-deformed nuclei. It is of central importance in studying the effects of rapid rotation on the interaction between nucleons. Nuclear pairing is at bottom a dynamic symmetry of nuclei, the corresponding symmetry label having acquired the name "seniority." Applications of seniority or pairing symmetry to the study of nuclear spectra have been widespread. The main unfinished task, the choice of a physically-motivated generalization to systems involving both valence neutrons and valence protons, has recently come to be viewed from a fresh and promising perspective suggested by work on dynamic symmetries of the collective modes of nuclei.

Collective Models and Symmetry Breaking

The deformation of the mean potential field in a large class of nuclei is an example of a very general phenomenon called spontaneous symmetry breaking. It was applied early in the development of physics to the discussion of ferromagnetism and is now an essential ingredient of modern particle theory. The restoration of symmetry under rotations produces the rotational band, and a new quantum number arises because these nuclei are still axially symmetric. Many nuclear properties can be viewed as a manifestation of this partially broken symmetry of the underlying many-body interactions.

Symmetries of the collective modes can be considered not only from the many-body viewpoint, but also in terms of a phenomenological collective model whose exploration was started by Bohr and Mottelson in the early 1950's and pursued actively since that time. This model possesses three distinct dynamic symmetries, corresponding to special shapes of nuclei: the spherical, the axially deformed, and the axially asymmetric.

Examples of these symmetries abound in the structure of medium and heavy nuclei, although in most cases they are significantly broken. Many important questions remain in the study of this type of symmetry. For example, what are the patterns of symmetry breaking? What is the relation between the dynamic symmetries of the collective modes and the symmetries of the central field? In other words, what is the microscopic origin of the dynamic symmetries of the collective modes?

Interacting Boson Model

Dynamical symmetries of the collective modes have been discovered within the context of a model in which collective features arise because protons and neutrons pair together to form quasi-stable objects (interacting bosons). We have here, on the one hand, the generalization of pairing symmetry alluded to above and, on the other, an opportunity to study from a new viewpoint the microscopic basis of the Bohr-Mottelson collective model. Many open questions remain. In this context, three major threads of nuclear physics meet—the shell-model, the Bohr-Mottelson collective model and new collective dynamic symmetries based on the interacting-boson Hamiltonian. Work in this interface area, with the collective symmetries, and the rich structure of the Bohr-Mottelson model to provide guidance, is bound to yield new insights into the physics of the nucleus.

The Search for Supersymmetries

The concept of symmetry has been further extended in recent years to include a more complex type. Such supersymmetries were originally examined for applications to elementary-particle physics. They apply to mixed systems of bosons and fermions and bring together both bosonic and fermionic states in the same multiplet. Although the search for supersymmetry has focused on elementary-particle physics, indications of supersymmetry have recently been found in nuclear spectra. The supersymmetry here links the bosonic collective degrees of freedom and the fermionic single-particle degrees of freedom. Numerous interesting questions arise. Can enough convincing examples of supersymmetries be found in nuclei to establish systematic patterns? What is the microscopic origin of supersymmetries in nuclei? What properties of the basic interactions do they express? Since the bosonic degrees of freedom in nuclei are composite, the supersymmetries observed are effective supersymmetries. Is this a general property of all supersymmetries and what implication does it have for supersymmetry searches in elementary particle physics?

Statistical Aspects

In addition to predicting properties of individual levels and excitations, symmetries also affect the statistical properties of physical systems. The relation between statistical properties and symmetries has been systematically investigated in recent years. Techniques have been developed to assess the goodness of symmetries from averaged properties of nuclear spectra. These techniques are being applied to the study of collective symmetries. A problem of great current interest in several branches of physics is the transition between ordered and chaotic behavior, the interplay between statistical properties and those associated with a few selected degrees of freedom. The characterization of this interplay is a profound problem in many-body quantum physics. The nucleus has certain obvious advantages as an arena for such a study. First, the nucleus has an unparalleled richness of dynamic symmetries, stemming from the fact that three levels of fundamental interaction—strong, electromagnetic and weak—play essential parts in determining its structure. Second, the nucleus is a system of precisely the right size ($\sim$100 nucleons)—large enough for statistical properties to manifest themselves, not so large that all signs of privileged degrees of freedom are washed out. It will be important to study the interplay between statistical and nonstatistical behavior in nuclei and the role of symmetry considerations in this interplay.

Remarkable though it may seem, the exploitation of dynamical symmetry in nuclei is still, if not in its infancy, not far beyond adolescence. This is due in part to the fact that symmetry considerations, by their very nature, relate data over wide ranges of nuclei and nuclear excitation; data of sufficient quality over sufficient ranges are only now becoming available. The prospects of finding new dynamic symmetries and of finding new uses for those already known, are major challenges for nuclear physics.

II.3 HIGH SPIN AND EXOTIC NUCLEI

How does the nucleus rearrange its shape and structural symmetries under increasingly rapid rotation? What happens to nuclei at the limits of stability?

Nuclei at High Spin

In recent years it has become possible to study nuclei at very high angular momentum under enormous, rotation-induced Coriolis and centrifugal forces. Under these conditions important changes occur in nuclear structure which may still be essentially simple—as long as all the internal energy is concentrated into two macroscopic degrees of freedom, that of collective rotation, and that of particle alignment along the rotation axis.

Changes in pairing and deformation occur as nuclei are subjected to these increasingly strong forces. Do nuclei continue to show both single-particle and collective properties and behavior? When both the temperature and angular momentum are raised, shell effects and pairing effects should disappear; do the nuclei then behave like classical rotating liquid drops, or do new forms of quantal collective motion appear?

The limit to the amount of angular momentum that can be added to a nucleus is provided by the centrifugal force which, in the liquid drop model, is expected to eventually deform the nucleus into a (prolate) triaxial shape before fissioning it into two fragments. The liquid-drop model is based on Coulombic, centrifugal, and nuclear (surface tension) forces, and provides a surprisingly good estimate of the gross limiting angular momentum for fission as a function of neutron and proton number, giving a maximum value of spin of $\sim$70 units for stable nuclei around mass 130. It predicts smaller maximum spin values both for heavier nuclei (due to increasing Coulomb repulsion) and for lighter nuclei (due to the rapid increase in the centrifugal force).

The nucleus carries angular momentum in two ways: by the alignment of the orbital motion of individual nucleons along the rotation axis and, if deformed, by the rotation of the nucleus as a whole. The nucleon alignments tend to destabilize the collective rotation, whereas the centrifugal stretching tends to stabilize the collectivity. Rather extreme examples of these two modes are shown in figure II.3-A. On the right, the levels of ^{212}Rn illustrate particle alignment; the level sequence is quite irregular, with a variety of electromagnetic transitions. On the left, the yrast sequence (lowest energy for each spin) of ^{238}U exhibits features characteristic of a spheroidal rotor, that is, regularly spaced levels connected by

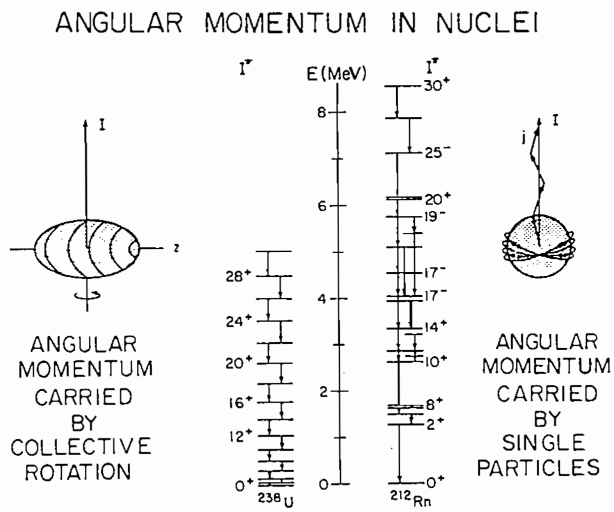

Fig. II.3-A. The sequence of angular momenta in two nuclei. On the left we see the regular level scheme of a nucleus that is a good rotor: ^{238}U. On the right is an example of the irregular pattern that arises as angular momentum increase is being accommodated by the successive alignment of nucleons in single-particle orbitals, in the levels of ^{212}Rn.

enhanced photon emissions. Most nuclei, however, combine both types of motion, and it is this interplay between collective and single-particle motion that makes the behavior of cold nuclei with changing angular momentum so fascinating and so rich in variety.

The nuclear pairing correlations play an important role for spins up to about 30 units. The nucleon orbitals in a static deformed potential can each accommodate two nucleons, corresponding to the two time reversed states. Thus every orbital, whose nucleons have individual angular momenta j, can give rise to a pair of nucleons with total spin zero. The nucleons in a just-filled orbital can scatter as *a pair* into a nearby empty orbital, and the coherent scattering pattern that develops comprises the nuclear pairing correlations. These correlations affect the ability of the nucleus to generate angular momentum and the magnitude of the nuclear moment of inertia.

With high-resolution gamma-ray spectroscopy, we can investigate the changes caused by increased angular momentum as evidenced in the alignments, shapes, and pairing correlations for discrete states up to 20-30 units of spin. These studies have led to an understanding of why the nucleus does not show the nuclear analog of the dramatic phase transition that is seen in superconducting solids where similar pairing correlations occur—the Meissner effect. With increasing angular momentum, the nucleus undergoes a gradual phase transition from the paired to a normal state. Nuclear phase transitions, with only ~100 particles, are less sharp than those in an effectively infinite solid. Because the several pairs of nucleons in the paired phase are made of nucleons with very different j-values and because the Coriolis interaction is stronger the greater the value of j, large irregularities in the nuclear level spacings can occur due to the sudden alignment along the rotation axis of one high-j pair of particles, with all the other (lower-j) nucleons essentially retaining their pairing correlations. An example of the crossing of two bands, the paired and the 2-quasi-particle band, is shown in figure II.3-B. The spectroscopic study of these alignments, or band crossings, is a new endeavor of the last few years and has contributed greatly to our knowledge of the pairing correlations, but has also left unexplained, as yet, a number of changes in behavior at the band crossing. An example of the degree of understanding achieved is illustrated by the fact that the change in the band-crossing frequency (one-half the transition energy) for the first $i_{13/2}$ neutron band-crossing in several odd-mass rare-earth nuclei appears to be well correlated with the deformation (quadrupole moment) of the odd neutron orbital occupied. The blocking effect of the odd neutron on the pairing correlations depends on its configuration; not all orbitals participate equally in the pairing state, as given by the model based on the simplest

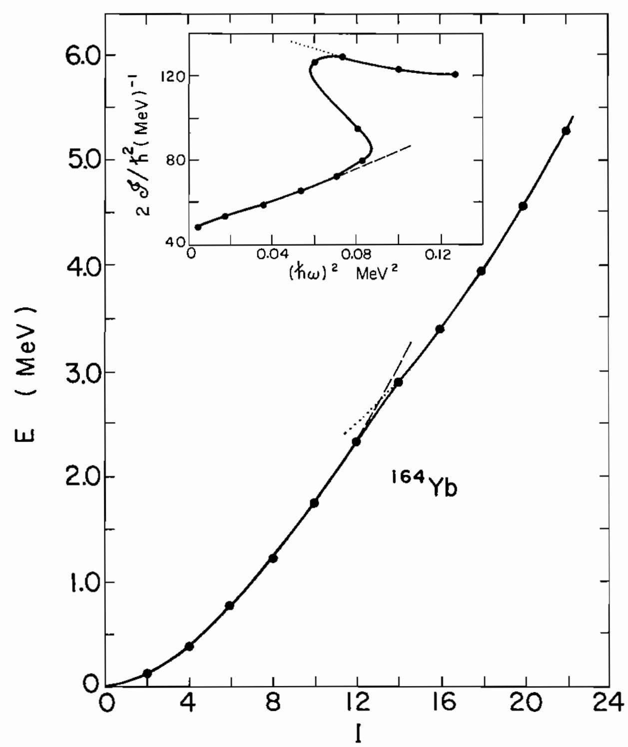

Fig. II.3-B. Plot of excitation energy (E) against spin (I) for the lowest-lying (yrast) levels of ^{164}Yb. The insert shows the same data in a typical backbending plot of the moment of inertia ($2\mathcal{J}/\hbar^2$) against the rate of rotation $(\hbar\omega)^2$ deduced from these energies. The dotted and dashed lines show the extensions of the ground and two-quasi-neutron bands that cross to form the backbend.

Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. There are other interesting and detailed results from measuring the changes in other nuclear properties (such as lifetime and branching ratios) through the first "backbend" discontinuity in the sequence of highest spin states; some of these can be explained, but others are not yet understood.

Discrete-state γ-ray studies may be pushed to spins as high as 40-50 units using newly developed multidetector arrays: "crystal balls" and Compton suppression techniques. But in the foreseeable future, there probably will remain a region of highest spin (up to 60-70 in the rare-earth nuclei), where the discrete transitions become too weak to be observed, and that region can thus only be studied through its continuum γ-ray spectra. Such studies of necessity yield only average properties over a distribution of states. But they still show significant changes with angular momentum, and at these high spins nuclei along the yrast line may still be as individualistic as they are in the ground state. The goal of such studies is not only to determine the persistence of shell effects, but also the role of particle alignments and the importance of collective motion on the properties of nuclei up to the highest spins before fission. Very interesting first steps have been made, both in experimental measurements and in theoretical calculations, to define and measure "kinematic" and "dynamic" moments of inertia. The latter are very sensitive to the local configuration, that is, to changes in alignment and deformation, but have only been available and understood from experiments performed during the past year. In addition, first experiments are being made to measure average lifetimes and magnetic moments in the continuum, and angular distribution measurements have provided evidence in some transitional nuclei of electromagnetic transitions of dipole character, suggesting possible changes in shape at high spin.

Angular momentum may be carried by nuclei in still another, very special way, in the orbital motion of two, almost distinct, nuclear fragments rotating around each other in a transient, molecule-like configuration. Examples of such behavior seem to appear throughout the range of available nuclear systems, but particularly striking examples occur in light nuclei at excitation energies of several tens of MeV above the nuclear ground state. This is a domain where relatively unstructured many-body features of nuclear systems were thought to predominate, but imbedded in this chaotic region are found structures involving simple coherent patterns of motion that have many features in common with atomic molecules, have relatively long lifetimes, and appear in the form of sharp resonances in the yields of heavy-ion reactions. Measurements have shown that in some cases these structures reflect a reorganization of the host nucleus into two massive clusters undergoing an as yet imperfectly understood form of dinuclear molecular motion.

The study of these quasi-molecular and resonance phenomena at high excitation has progressed in step with advances in the ion source, accelerator, and detection apparatus technologies, and has broadened from its original focus on a few nuclei (^{24}Mg and ^{28}Si) to encompass the entire periodic chart. It is clear that the narrowness of these resonances implies a stability that is remarkable at such high excitation energies. We would very much like to know what physical processes underlie this stability.

Molecule-like configurations are also thought to be crucial to understanding the narrow peaks observed in the positron spectra from U + U collisions at around 6 MeV/amu. The positrons reflect spontaneous decay of the e^-e^+ vacuum in the supercritical electromagnetic field of two uranium nuclei in close proximity; the 70-80 keV observed width of the peaks implies the formation of a long-lived giant system in which two uranium nuclei maintain a quasi-stable fixed separation for an extended period of time. The implications of such simple structures at high excitation in the 500 nucleon system are very exciting and have not been fully absorbed.

Future Opportunities

There are many as yet unanswered questions in high-spin nuclear physics. Where and how are the pairing correlations finally quenched by the rotation? What is the detailed nuclear shape and how does it vary as a function of spin in going down an average path through several bands connected by crossings (alignments)? What are the changes in shape induced by excitation above the yrast line holding the spin fixed? Do particle alignments continue as a source of angular momentum all the way to fission, and are the responsible orbitals those of high j from the next shell or even the one above that? What are the appropriate quantum numbers to describe the system at the highest spins? Are there still shell effects along the yrast line at high spin? This is related to interesting questions connected with "superdeformation" and the shape evolution to fission. If there are very large deformations, with the pole-to-pole distance twice that of the diameter at the nuclear equator, what part is played by shell effects and what part by the predicted stretching of a liquid drop before fission? Over a broad range of masses the angular momentum we can study is limited mainly by fission, so it is clear we can reach situations where the centrifugal force produces major changes. How these are influenced by new shell effects or other aspects of the single-particle motion will be fascinating to study. In addition, we still have the problem of the molecule-like resonances to understand. To accomplish this, experiments must be done with good energy resolution and with highly efficient special-purpose detection apparatus capable of probing specifically the molecular degrees of freedom. Very few theorists have possessed the means of carrying out even remotely realistic calculations and thus the full ramifications of the two-center shell model, the double and multi-resonance coupled channels models, the time-dependent Hartree-Fock approach, and other promising avenues remain largely unexplored. The situation is changing, however, and continued emphasis on modernizing our computing facilities should pay dividends in unlocking the secrets of these quasi-stable configurations found at high excitation energies.

Exotic Nuclei

An important dimension in nuclear structure is that represented by changes in the number of neutrons vs. protons; this clearly yields marked changes in nuclear shapes, structure, and properties. In regions of a great excess of neutrons or of protons, the question arises whether this imbalance affects the relative importance of the effective nn, pp, and particularly the np interactions. This would be reflected in changes in the masses, in different shell closures, and thus in different shapes. Near the proton and neutron drip lines (zero particle binding energy) one has observed in the last few years exotic forms of radioactivity, such as ground-state proton decay, β-delayed two-neutron and two-proton emission, and β-delayed fission.

The production of very heavy elements and the attempts to reach a possible "island of stability" formed by the still heavier "superheavy elements" were pursued in the past by irradiating the heaviest targets with the lowest-Z projectiles that could make the desired nucleus. This method was employed to produce new elements up through 106 at Berkeley, but with decreasing yields. Scientists at Dubna pioneered a new method for making element 106, involving less excitation energy in the compound nucleus, using a closed-shell nucleus, ^{208}Pb or ^{209}Bi, as the target for appropriate heavy-ion projectiles. This technique, coupled with the use of an excellent velocity filter to separate the few product nuclei from the beam particles, enabled the group at G.S.I. to observe ^{262}107 last year and possibly a single atom of ^{266}109 this year. The tentative decay chains of these nuclides are shown in figure II.3-C. Since the single atom of element 109 was produced in 12 days of bombardment, it does not seem likely that one will be able to follow this path to much heavier elements.

Neutron-deficient nuclei far from stability are most frequently studied by using a heavy-ion compound-nucleus reaction (although high-energy proton spallation is also used) and then selecting the desired nucleus with an

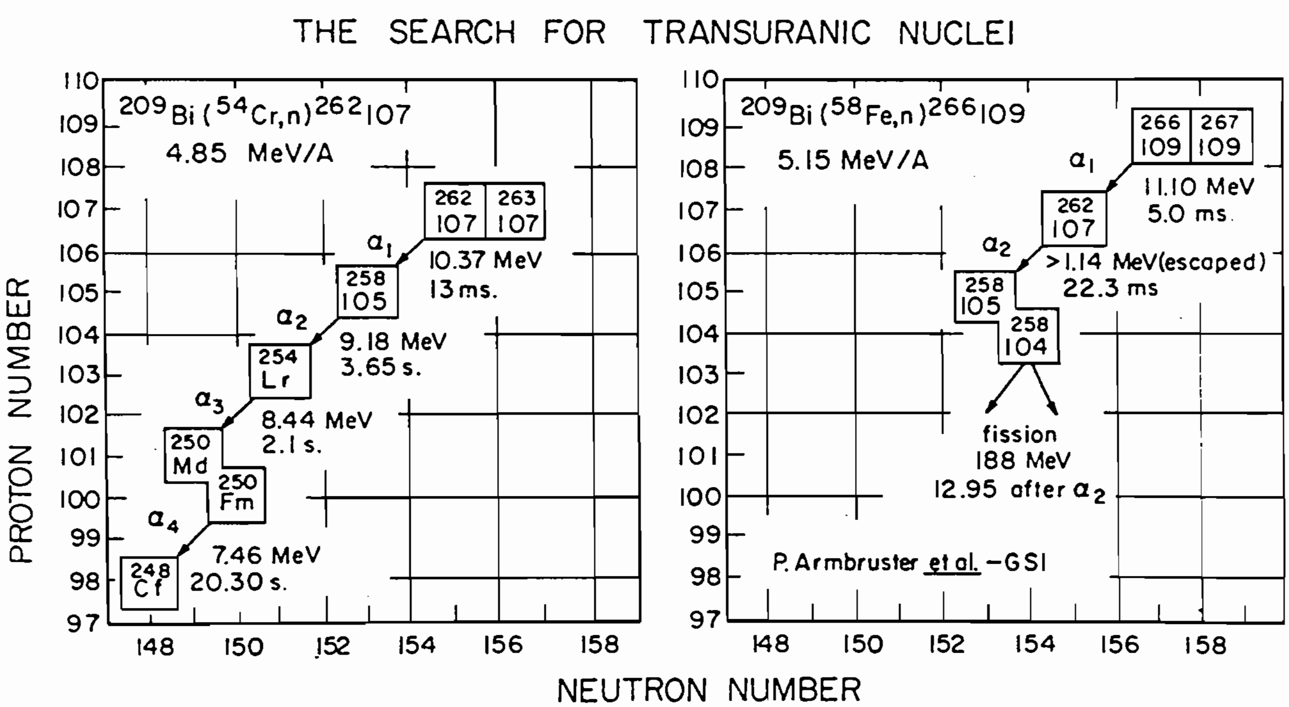

Fig. II.3-C. Evidence for new heavy elements. On the left is the decay scheme for an isotope of element 107 of which several atoms have been identified. On the right is the level scheme suggested for the one atom of element 109 that has been tentatively identified so far, with a lifetime of 5 msec.

isotope separator. Nuclei with a neutron excess are studied by coupling a similar isotope separator to a fissionable target in a reactor or again looking at the products of high-energy spallation or projectile fragmentation. By these methods the systematics of the energy levels of a wide range of isotopes have been obtained in a few cases, and, in still fewer cases, some transition probabilities have been determined. A significant new development has been the increased use of atomic-beam and laser techniques for the determination of nuclear spins, moments, and changes in the mean-square-charge radius. In favorable elements properties can be measured for long sequences of isotopes.

The systematics of energy levels and moments obtained so far show that shell closures depend on the number of the other type of nucleon present; that is, shells are a dynamic variable of the nucleonic makeup and depend on the neutron-proton interactions. Pragmatic tests of various mass formulae can be made by Q-value determinations from transfer reactions or from α decay or from β-decay endpoints. Far from stability β decay may go to highly excited levels; the near continuum of excited states in the daughter nucleus leads to the description of the β-decay rate in terms of an energy-dependent strength function which is crucial to the calculation of stellar production of heavy elements in supernovae. Direct proton radioactivity is also possible in neutron-deficient nuclei and is most likely at the very limits of particle stability. This decay mode was originally observed in a high spin isomer of a nuclide closer to beta stability, but recently was also seen in two rare-earth isotopes, most likely to be ground state decays.

Such radioactivities should become more common as studies extend to the limits of particle stability and even new radioactivities such as direct two-proton emission, should be discovered. The limits of particle stability have been reached only in very light nuclei: future research should greatly increase our knowledge of these exotic decay modes.

II.4 NUCLEONS AND OTHER HADRONS IN NUCLEI

What are the limits for describing the nucleus in terms of nucleons? How do the non-nucleonic, hadronic degrees of freedom manifest themselves? What is the nature of the strong interactions between the hadrons, and how are these interactions modified inside a nucleus?

For most low-energy phenomena, the simplest and therefore the most appropriate description is that in terms of nucleons and the effective interactions between them. As was discussed in Sec. II.1, the main role of the interactions between nucleons inside a nucleus is to establish a smooth mean field in which the nucleons move almost freely. The interaction between nucleons imbedded in nuclear matter is referred to as the *effective* interaction in the nuclear medium. It is qualitatively different from the interaction between free nucleons. In particular, it is not strongly repulsive at short distances; it depends, furthermore, not only on the distance between interacting nucleons but on the ambient matter density of their nuclear environment.

Not all properties of nuclei can be described in terms of protons and neutrons alone. This is not at all surprising since the baryons (of which the proton and neutron are the lightest and most stable) have structure and excitations of their own. These hadronic degrees of freedom are manifest in the spectrum of free baryons and of the mesons which couple them, and reflect the elementary quark composition of strongly interacting particles. These degrees of freedom are at the interface between nuclear and particle physics, with the associated questions spanning the range from hadron dynamics to nuclear structure. The physics of the intermediate and short-range nuclear force clearly involves baryonic excitations, with the role of explicit quark and gluon degrees of freedom still an open question. The propagation of hadronic resonances through the nuclear medium, including modifications arising from multi-nucleon interactions, promises new insights into nuclear forces. The nuclear electromagnetic and weak currents are altered from their "classical" values by the flow of charged mesons and by excitation of nucleon isobars. Even at low energy, spin-isospin modes can couple strongly to modes generated by nucleon excitation. The study of all of these phenomena has begun vigorously in the last few years, with the horizon of "nuclear degrees of freedom" irrevocably enlarged beyond the limited view of nucleons only. The understanding of these phenomena, extrapolation into new regimes such as high density, and the search for qualitatively new nuclear modes based upon the internal degrees of freedom of the nucleon comprise a central program in nuclear science.

The delta (Δ) plays a special role in these considerations. It is the lowest excitation of the nucleon and appears as an isolated resonance dominating the landscape of pion- and photon-nucleon interactions. In quark language, the Δ is a "static" spin-isospin excitation of the nucleon, accounting for its importance in low-energy phenomena. A focus on Δ-nuclear systems will be a unifying element in much of the discussion to follow.

The Two-Baryon System

The most basic arena in which to study the interplay of nuclear and nucleon degrees of freedom is the two-baryon system. Careful investigation of such systems is of crucial importance for the understanding of hadronic effects in nuclei. There has been enormous effort recently in examining the coupled two-nucleon, nucleon-delta, and pion-two nucleon systems at intermediate energy, measuring spin observables in particular. An example of data is shown in figure II.4-A. A major motivation for this program, in addition to refining understanding of the nuclear force, is the search for possible dibaryons associated with the color degree of freedom "hidden" in the study of baryon spectroscopy. Despite considerable theoretical effort, the data have not been reproduced in a unified way with hadronic degrees of freedom alone. Progress in experimental determinations of two-baryon spin amplitudes will provide important further clues.

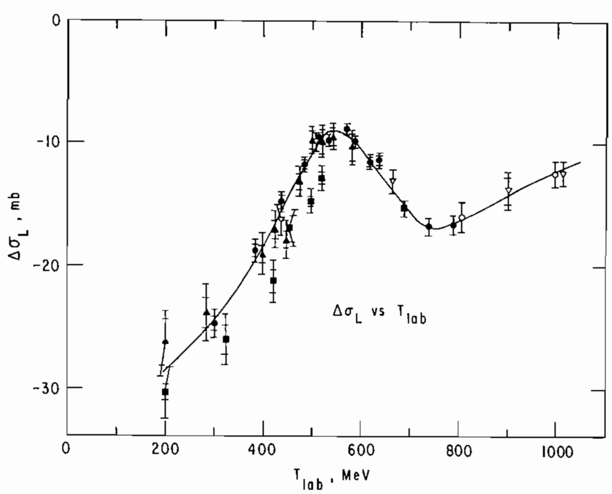

Fig. II.4-A. Compilation of measurements of the polarization parameter $\Delta\sigma_L$ in proton-proton scattering from a number of laboratories. There has been speculation that the sharp energy dependence may be a reflection of exotic 6-quark states.

Studies of antinucleon-nucleon collisions may uniquely complement nucleon-nucleon experiments by highlighting the difference between quark-quark and quark-antiquark interactions. Medium- and long-range meson-exchange contributions to the nucleon-antinucleon force are simply related to the nucleon-nucleon force, but the annihilation of nucleons by antinucleons introduces entirely new features. Some calculations suggest that since the force between a nucleon and an antinucleon is much more attractive than the NN force it may support a number of bound states and resonances, some of which may couple to narrow diquark-antidiquark states.

The nuclear electromagnetic current has been probed to distances small compared with the inter-nucleon separation. The interplay between nucleon and nuclear degrees of freedom is seen clearly here: though the current is a rather simple one-body operator at the quark level, it is decidedly *not* a one-nucleon operator, and the structure of the operator is a measure of the strong-interaction dynamics of the nuclear system. The two-nucleon electromagnetic current recently seen in photodissociation of the deuteron and illustrated in figure II.4-B clearly demonstrates the spectacular failure of using the "classical" one-nucleon current alone and probes a region where the simple exchange currents, based upon the one-pion-exchange potential and charge conservation, must be supplemented by heavier meson and isobar contributions. A key problem of intermediate energy nuclear physics is to develop a quantitative understanding of this question in an underlying QCD description.

Nuclear Matter

It is found that, although individual nuclei may be very different in their low-energy properties, the nature of the nuclear substance in the interior is the same for all but the lightest nuclei. The idea of nuclear matter arose in the attempt to study the material deep inside nuclei free from complications connected with finite size and special "surface" properties. Normal nuclear matter is an idealized infinite system abstracted to allow calculation of properties of the material at the heart of a heavy nucleus.

The crucial problem of calculating the binding energy per nucleon and the density of nuclear matter from a given two-body free-nucleon interaction has been solved. It is now understood why nuclear matter has roughly its observed binding energy and density. A significant residual discrepancy, larger than the errors in the calculation, remains between the observed properties of nuclear matter and those predicted on the basis of the best nucleon-nucleon interaction potentials. At the correct density, nuclear matter is more tightly bound by about 1 MeV per nucleon than the best theoretical estimates. Attempts are now being made to account for the discrepancy in terms of three-body interactions between nucleons or equivalently by explicit reference to the internal structure of nucleons.

Few Body Systems and Forces

The improvement of our microscopic understanding of the three-nucleon systems is a crucial step in the development of a quantitative microscopic theory of nuclear structure. The experimental data to consider for the bound states include binding energies, the ^3H-^3He mass difference, radial distributions of charge and magnetization, and the interaction and absorption of pions by these

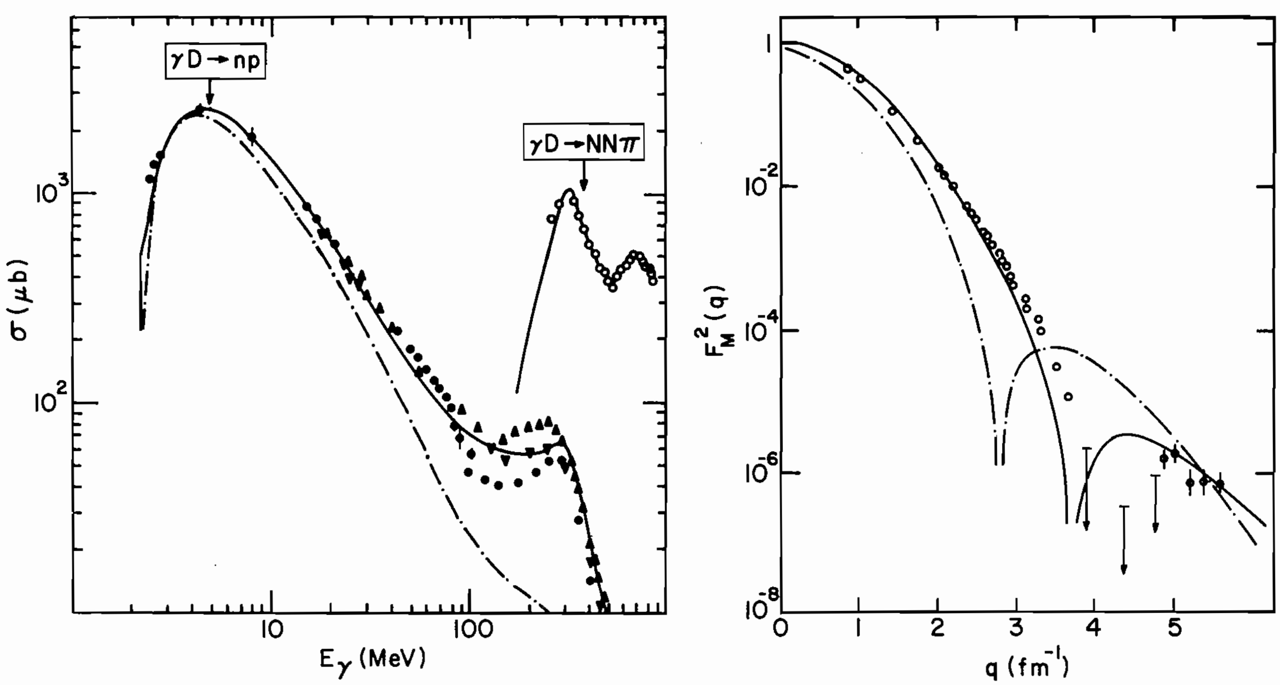

Fig. II.4-B. On the left are data on the photodisintegration of the deuteron and on the right the magnetic form factor for the ^{3}He nucleus. These data demonstrate the limitations of the "nucleons only" description of nuclei. The dashed line represents a calculation with only nucleons included, while the solid line includes mesonic effects and fits the data reasonably.

nuclei. Given a nucleon-nucleon interaction potential fitted to two-nucleon data, it is now possible to calculate the binding energies of three-body nuclei to an estimated accuracy of better than 1%. A significant discrepancy remains between the observed binding energies and those computed from the best two-nucleon interactions; the calculated binding energies are too small by about 1 MeV. This underbinding is consistent with what is found in nuclear-matter studies and presumably is of similar origin.

Three-body nuclei offer the simplest bound system for studying the isospin structure of electromagnetic exchange currents. The ^{3}He magnetic form factor data were shown in figure II.4-B together with the wholly inadequate one-nucleon-current predictions. The analogous data for ^{3}H are awaited eagerly. Our quantitative understanding of exchange currents is still largely restricted to parts of the long-range pion exchange current which are largely independent of dynamical models. For example, the many-body corrections to the nuclear charge operator are bound up with relativistic corrections that must be made in the usual theories of nuclear systems. This problem points to the more general, very important issue of the need for a consistent relativistic theory of nuclei. The pressure for this is provided in many ways, including the probing of nuclei at short-distances with large momentum transfer electron scattering, and the intriguing systematics uncovered in phenomenological relativistic treatments of the nuclear mean field. A substantial theoretical effort is required here.

Great strides have been made recently in our understanding of effective interactions within the nuclear medium. The approximate inclusion in treatments of finite nuclei of the effective interaction resulting from nuclear matter theory has led to a new level of quantitative success and expectations for microscopic many-body calculations of nuclear structure and dynamics. One is now able, for example, to attach significance to systematic small discrepancies between Hartree-Fock calculations and the precise maps of nuclear densities obtained in medium-energy electron- and hadron-scattering experiments. Microscopic analyses of intermediate-energy proton elastic and inelastic scattering data reveal very clearly the role of medium modifications to the internucleon force. Nucleon inelastic scattering and charge exchange transitions initiated at 100-400 MeV have been discovered to provide very useful filters to probe the strength and momentum-dependence of specific terms in the effective interaction. This advance arose from the use of an adequate direct-reaction theory, combined with the selective excitation of states of simple structure (especially involving spin transfer), and with transition densities measured in complementary electromagnetic experiments.

Non-nucleonic Degrees of Freedom in More Complex Systems

In extending these studies to heavier nuclei, it becomes clear that meson contributions play an important role in essentially all large momentum-transfer electromagnetic form factors, particularly for magnetic transitions. Here, the richness of the nuclear spectrum (states of varying angular momentum and isospin transfer and structure) must be utilized to extract systematically the spin, isospin and momentum transfer dependence of the two-body current. The systematics then should lead to the isolation of multi-nucleon contributions to the nuclear current. Such contributions are linked to the fundamental nature of short-range hadron dynamics. The nuclear weak current has been probed far less extensively, partly because of the extreme kinematic restrictions of processes such as muon capture or beta decay.

Spin-isospin modes in nuclei present a particularly good example of possible strong coupling between nucleon and nuclear degrees of freedom at low excitation energy. As indicated above, this possibility arises from the fact that the Δ is a simple spin-isospin excitation of the nucleon. In a series of experiments at Indiana University, the intermediate energy (p,n) reaction proved to be the right tool for locating the nuclear spin-flip response. These experiments, together with electromagnetic studies of transverse magnetic excitations, have systematically found only about half of the expected strength. Qualitatively, some of the strength is expected to be mixed into high-lying Δ-hole excitations with the same quantum numbers. Quantitative resolution of the question will benefit from measurements of the spin-transfer in the continuum region.

Turning to hadron dynamics, the wealth of data from the meson factories has dramatically improved our understanding in the Δ region. The studies at the two-baryon level have been discussed already. Systematic studies of pion reactions with heavier nuclei have included energy and target dependence of pion elastic and inelastic scattering, pion single and double charge exchange, and total pion annihilation. For light nuclei, a rather complete picture of the pion-nucleus reaction, including "competition" between pion scattering and annihilation, has emerged, and is supplemented by electromagnetic data in the corresponding energy region. Much of the data have been described rather concisely in terms of Δ-hole states with a strongly-absorptive, spin and isospin dependent Δ-nucleus interaction. While this theoretical description represents considerable progress, many questions remain open. The Δ reaction processes in heavy nuclei, involving many nucleons, are certainly poorly understood. The important pion annihilation process, which provides a direct link to theories of the strong force, has not been understood microscopically. The role of multi-nucleon absorption processes, analogs of many-body forces at low energy, is an open question, and the rapid fall of the annihilation cross section just above the resonance is not consistent with available models. While we have learned a great deal about the phenomenology of Δ-dynamics in nuclei, fundamental advances in microscopic understanding of the strong short-range force in nuclei remain ahead of us. This progress will depend upon the availability of more data specifically aimed at unraveling the spin-isospin structure and the multibody nature of the Δ-nucleus interaction and the precision nature of the electromagnetic probe must be brought to bear upon these questions more effectively. We note that resonance dominance of meson reaction processes leads in some cases to qualitative tests of nuclear structure. For example, the isospin selection rule implied by Δ dominance leads to a direct measure of isospin mixing in nuclear particle-hole states.

We have focused upon the nuclear interaction of baryon resonances. However, meson interactions not dominated by resonances, such as the low-energy (S-wave) interactions, also pose interesting problems. For example, the origin of the repulsive S-wave pion-nucleus interaction and of the narrow width of deeply-bound pionic atom states has no accepted explanation. These problems are basic to understanding pion propagation in nuclei over a broad range of kinematic conditions and nuclear densities. Experimental reaction studies in this low-energy region have not yet been pushed very far.

The existing key facilities in this area of nuclear physics are LAMPF with its pion, muon and proton beams, and neutrino capabilities, the Bates Laboratory with high-resolution electron scattering, and the Indiana University cyclotron with its proton beams. In the last decade nuclear physics has changed radically under the impact of new research with these intermediate-energy accelerators. The new 4-GeV CW electron accelerator will be an essential forefront facility. However, as was noted in the 1983 Report of our Panel on Electron Accelerator Facilities, CW electron capability up to 1 GeV is likely to play a key role in these areas of nuclear physics. In other areas, upgrading the Indiana cyclotron and its new cooler to higher energies could be an important national program and an improved pion channel deserves serious consideration.

The interpretation of experimental results addressing the fundamental issues of hadron dynamics and large momentum transfer nuclear excitations relies heavily upon theoretical interpretation in terms of strong interaction models and upon assumptions about short-range nuclear structure. Many of the interesting questions are inextricably tied up with the need for the development of a consistent relativistic theoretical treatment of nuclei.

II.5 QUARKS AND QCD IN NUCLEI

How does the nucleus appear in terms of its quark content and how does the nuclear medium affect quark confinement?

We now believe that hadrons and their interactions have an underlying quark structure whose effects extend beyond the known properties of free baryons and mesons. One of the fundamental questions of nuclear physics is the importance of these quark degrees of freedom for our understanding of nuclei. Models of nuclear structure and nuclear matter have not yet dealt explicitly with this problem. Within nuclei, two complementary questions arise. First, does the fact that the nucleon itself is a composite particle have important consequences for the properties of nuclei? And secondly, how can the effect of the nuclear medium on the nucleon lead us to a better understanding of the manner in which quarks are confined?

On the first question we need to understand better how the observed features of hadrons and their interactions fit into the framework of QCD. QCD is not presently soluble, but in describing hadronic physics it leads to useful approximations in two simple limits. At short distances (high momentum transfer), the "colored" quarks (and gluons) are asymptotically free. At longer distances, the quarks and gluons are confined in "colorless" color-singlet clusters (hadrons), which interact via the exchange of other hadrons (mesons), as in the traditional interpretation of the internucleon potentials. Although the transition between these two regimes has not yet been understood quantitatively, it has been incorporated in existing models by the *ad hoc* introduction of a potential, or "bag," to confine the quarks and gluons. These models have already had significant success in accounting for some properties of hadron structure and hadron-hadron forces, but lead to a number of fundamental questions that remain to be addressed by theory and experiment. Is there a sharp transition between the meson- and gluon-exchange regimes, and if so, what are the characteristic dimensions? What are the relative roles of the constituent quarks and of the meson cloud in hadron structure? How are these roles altered when two hadrons interact? How does QCD produce the observed short-range repulsion between two nucleons? Do the quarks and gluons contribute essentially (e.g., via color excitations of the interacting clusters) to the intermediate-range attraction?

The search for QCD effects in nuclei is very new with only a few but extremely significant results in hand. Most striking is the result from deep inelastic scattering of 250 GeV muons from iron and deuterium which has been beautifully verified by the re-analysis of deep inelastic electron scattering data taken a decade ago at SLAC at lower electron energies between 8 and 20 GeV. These deep inelastic scattering reactions result from a single hard collision of the lepton with a quark within the nucleus. Comparison of the yields from iron nuclei, with 56 nucleons, and deuterium with only two, as a function of the variable x, shows, as seen in figure II.5-A, that for small x the yield from iron is relatively larger by 15%. As x increases the ratio first drops, and then increases again as x approaches one. This latter increase is expected, but the unanticipated behavior at $x < 0.6$ indicates that the quarks in a heavy nucleus have lower average momentum than those in the deuteron. The low-momentum effect may possibly be understood in terms of an increase in the relative number of virtual mesons (mostly pions) in Fe relative to deuterium. The *decrease* in the relative yield for $0.3 \leqslant x \leqslant 0.6$ may indicate a depletion of the higher momentum component of the constituent quarks, which

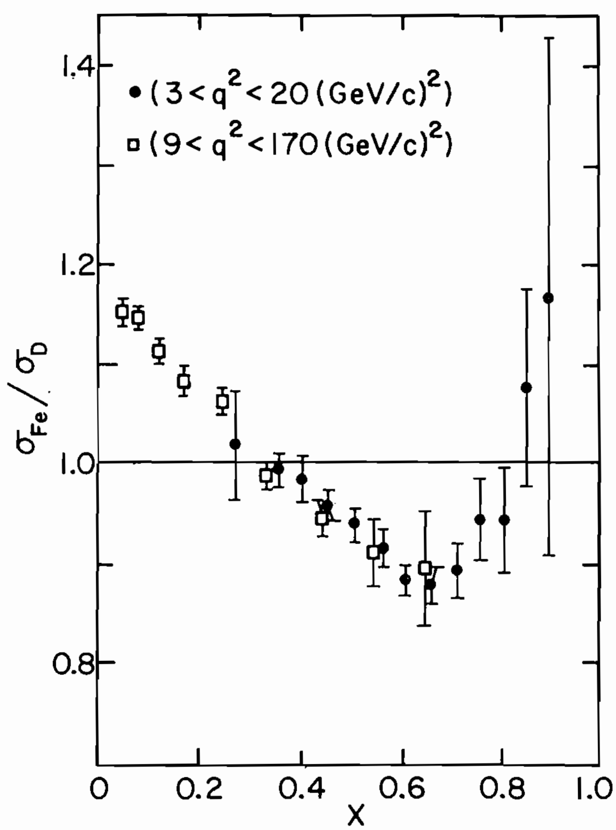

Fig. II.5-A. The observed ratio for the highly inelastic electron scattering cross sections for iron to that for deuterium. The data are a collection of results employing high-energy electrons and muons and are plotted as a function of the scaling variable x ($\equiv q^2/2M_p\nu$). The unexpected increase in the ratio for x below 0.6 indicates relatively more quarks with lower momenta in the heavy nucleus.

could result from their occupying a larger volume, either due to "percolation" or from 6 quarks sharing a larger "bag." The results of these experiments are potentially very important as they could appreciably alter our ideas on what happens to the nucleon in the nucleus.

All inelastic scattering processes involving very high momentum transfer between leptons and hadronic systems are best understood by treating the process as a hard collision with a single quark. This point has been demonstrated in a host of deeply inelastic scattering experiments which qualitatively can be accounted for within the framework of QCD. In the high momentum transfer limit, QCD predicts a power law falloff of the helicity conserving elastic form factors. Figure II.5-B shows this result applied to the deuterium form factor. This prediction appears to work at momentum transfers less than 1 GeV/c. This is viewed as surprising, insofar as one believes that the non-perturbative effects of QCD would be extremely important at values of momentum transfer, q^2, that small. For an understanding of nuclei in terms of their quark substructure, the result presented in figure II.5-B is most tantalizing.

When considering the directions of future research one should realize that up to the present detailed knowledge of hadronic structure has come almost exclusively from the deep inelastic scattering of high energy leptons and e^+e^- collisions producing hadrons. Electrons, the most accessible leptonic probe, have provided the bulk of the information, although potentially there is further information contained in neutrino scattering. The interactions between the hadrons may be investigated by the scattering of high energy leptons from composite systems as well as direct hadron-hadron scattering.

Further measurements of quark distribution functions from inclusive deep inelastic electron scattering are awaited with great interest. Systematic studies of the dependence of the quark momentum distribution on nuclear size can yield information about how the pion and "6-quark bag" content of nuclear matter depends on nuclear density. Further measurements of the momentum transfer dependence are needed to tell at what wavelength electrons can first resolve individual quarks inside nucleons.

Following the above series of experiments with measurements of exclusive inelastic scattering is an extremely exciting prospect. This research is required to explicitly characterize the modification to the free nucleon by the nuclear medium. Over the range of momenta accessible to a 4-GeV electron accelerator, a systematic program of (e,e'X) coincidence experiments (where X is a nucleon, excited nucleon, pion, light nucleus, or quasi-

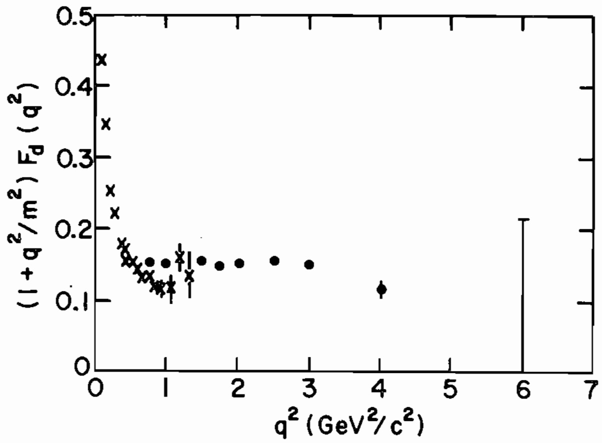

Fig. II.5-B. Product of the deuteron elastic scattering form factor times a kinematic dependence predicted from QCD. The constancy of the results down to $q^2 < 1\ \mathrm{GeV}^2/c^2$, indicates that certain types of scaling may extend to quite low values of momentum transfer.

two-body state) will provide detailed information which will shed light on the nature of short-range correlations and components of nuclear wave functions. Many of these components can be expressed in terms of hadronic degrees of freedom (N,Δ, higher resonances plus mesons), but others are not. In particular, interactions in which two nucleons exchange quarks, or states in nuclei in which 6 quark configurations are important, are phenomena beyond the conventional description. A very high priority is to quantify the effects of these "hidden color" configurations.

Even for the deuteron, where the dominant configuration, at low (1 fm^{-1}) momenta, is that of colorless protons and neutrons, at higher momenta small components acquire some "color" in the 3-quark bags via gluon exchange. These configurations may couple preferentially to (highly) inelastic channels, and so may be detected in (e,e'N*) experiments. Also, these color degrees of freedom could possibly appear as highly excited dibaryon states with unique decay properties. Unable to decay by pion emission they would have narrow widths, and thus be readily detectable. The search for such states is likely best carried out by exclusive (inelastic) electron scattering. A several-GeV CW electron accelerator is ideal for such searches.

In very deep inelastic electron scattering, a single quark receives a great deal of momentum and attempts to escape from the hadron in which it was confined. The strong force of QCD can be viewed as a string that keeps the quark from becoming deconfined. An individual quark that acquires a large momentum in a collision loses energy as its string stretches by radiating gluons and creating many quark-antiquark (meson) pairs. While this phenomenon has been studied for free nucleons, it is quite possible that the properties of the extended "string" and the mechanism for losing energy are modified within the nuclear medium. By studying deep inelastic electron scattering on a nucleon imbedded in a heavy nuclear target and comparing the radiations produced with those obtained from a similar process on a free nucleon, one can explore quark propagation in the nuclear medium and the effect of the medium on the "string." The development of QCD at low momenta is of greatest interest to nuclear physics, and conversely the results from nuclear physics are most likely to impact the low-momentum aspects of QCD. Ultimately, analysis of all experiments for evidence of explicit quark-gluon degrees of freedom will depend heavily on the theoretical interpretation, and this requires not only considerable effort directed toward realistic, usable, QCD-based models, but the development of sophisticated relativistic conventional models which can provide a believable standard of comparison.

While much research in this area of quark degrees of freedom of nuclei will involve leptonic probes as discussed above, the properties of baryon and meson spectra plus searches for "exotic" new states predicted by models of QCD will be carried out using hadronic probes. These searches employ polarized protons, pions, kaons and antiprotons in addition to electrons and muons. Unraveling the explicit role of quarks and gluons in nuclei, the integration of nuclear physics with QCD, is one of the most exciting and challenging problems ever faced by nuclear physicists. Its resolution will mean that we have obtained a more fundamental description of hadronic matter, an issue of great impact on nuclear physics, and on both elementary particle and astrophysics.

II.6 STRANGENESS IN NUCLEI

What happens when "strange" quarks, belonging to a different "family" of quarks, are brought into the nucleus? What are the forces, the appropriate degrees of freedom and symmetries?

Nuclei are made of protons and neutrons, with mesons, and isobars (the delta prominent among them) also present. All of these particles are built of quarks that belong to one "family," that of the "up" and "down" (u and d) quarks. Introducing a new quark, from another family, brings a completely different and new degree of freedom into the nucleus, that can test our understanding of nuclear structure and nuclear interactions at a very basic level and strengthen our understanding of the underlying role of QCD. A single "strange" (s) quark, combined with a u and a d quark, forms a baryon called the lambda (Λ), which is sufficiently stable to form long-lived nuclei; the next heavier strange baryons are the sigma (Σ) and the cascade (Ξ). The Λ and Σ can be produced from interactions of the nucleon with the lightest meson containing a strange quark, the kaon (K).

Nuclei containing a strange particle are called "hypernuclei" and were discovered some thirty years ago in emulsion studies. Kaon beam lines and spectrometers for hypernuclear studies have been developed at CERN and Brookhaven National Laboratory (BNL) in the last decade. Because of the low intensity of these K^- beams, the sparse data are of poor resolution and restricted to light hypernuclear systems. Even so, dramatic results determining the small size of the Λ-nucleus spin-orbit force and the tendency to develop dynamical symmetries in hypernuclei have been obtained. The availability of intense kaon beams at some future "kaon factory" would lead to qualitative new insights within nuclear science.

Consider, for example, the question of whether the baryon-baryon interactions can be described in a unified manner, both at the phenomenological and at the fundamental quark levels. Phenomenologically, one must explore the relationship between nucleon-nucleon, lambda-nucleon, and lambda-lambda effective interactions in the context of QCD, where the various quark flavors (u,d,s, ...) are treated on an equivalent footing, and the spectroscopy of hypernuclei is as fundamental as that of ordinary nuclei.

Lambda Hypernuclei

The information available from the early emulsion studies was used to estimate the Λ central potential well depth (some 30 MeV compared to 50-60 MeV for the nucleon) and to determine loose constraints on the lambda-nucleon interaction. With the advent of magnetic spectrometer systems, production of hypernuclei via the strangeness exchange (K^-,π^-) reaction became possible. At a "magic momentum" of about 530 MeV/c, recoilless production of Λ-hypernuclei, in which the 0° reaction produces a Λ at rest in the nucleus, becomes sizeable. These favorable kinematics were first exploited by the CERN group, and a sampling of their results is shown in figure II.6-A. Under these kinematic conditions, the excitation of "substitutional states," in which a neutron is simply replaced by a Λ in the same shell-model orbital, is emphasized. These data led the CERN group to the surprising conclusion that the spin-orbit potential for a Λ is much weaker than that for the nucleon. This fact has subsequently been explained both in the context of meson exchange and of quark models.

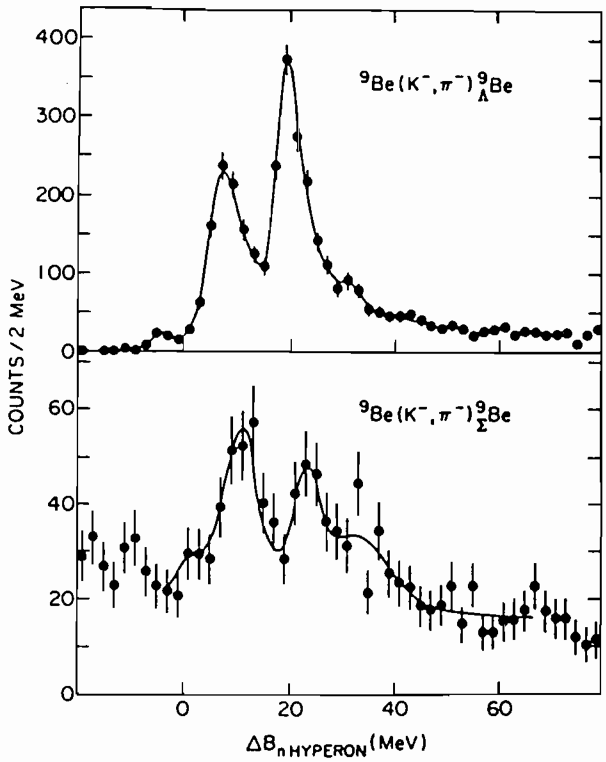

Fig. II.6-A. Evidence for hypernuclei with Λ and Σ hyperons forming $^9_\Lambda$Be and $^9_\Sigma$Be.

The first spectra measured at 0° did not yield quantitative constraints on the residual interaction because of the coarse energy resolution. Subsequently angular distributions were measured with improved energy resolution. Data for ^{13}C at 4° and 15° are shown in figure II.6-B. As the pion angle is varied hypernuclear states of different spin are excited preferentially, relative intensities change, and small but significant energy shifts occur. The data were analyzed in terms of a hypernuclear shell model. The most interesting conclusion is the determination that the spin orbit splitting is an order of magnitude smaller than that for normal nucleons. Despite the weaker central as well as spin orbit interaction, some hypernuclear states show a tendency toward a high degree of spatial symmetry. However, the available energy resolution still does not permit the extraction of quantitative constraints on the ΛN spin-spin and tensor forces. Recently, the feasibility of studying the $(K^-,\pi^-\gamma)$ reaction has been demonstrated at the Brookhaven AGS and electromagnetic transitions between hypernuclear levels were observed. Results for several light nuclei suggest that level splittings due to the spin dependence of the lambda nucleon force are less than 200 keV. Good γ-ray energy resolution permits the precise measurement of energy level differences even when the absolute energies are not accurately known.

Sigma Hypernuclei

The $(K^-,\pi^\pm)$ reactions have also been exploited to produce Σ-hypernuclei. Results for $^9_\Sigma$Be at 0° are included in figure II.6-A and compared with the corresponding excitations in $^9_\Lambda$Be. Figure II.6-C shows similar narrow structure for $^6_\Sigma$H. Presumably, the relatively narrow Σ peaks result again from coherent substitutional transitions. Recently, evidence has also been seen for narrow Σ structure in other light nuclei. There are indications from these data that the Σ central potential is shallower than that of the Λ. The Σ-nucleus spin-orbit potential has not been conclusively determined from the data. In the naive quark model, the Σ-nucleus spin-orbit potential is predicted to be comparable to that of the nucleon, whereas conventional boson exchange models predict it to be about 1/3 as large. Appreciable isospin mixing may occur in contrast to the very small isospin mixings which prevail in normal nuclei. A number of effects have been noted which reduce the Σ widths below simple optical model estimates, but better data are required in order to provide definitive answers.

Future Prospects

The current program should be extended in several directions. High resolution $(K^-,\pi^-\gamma)$ measurements need to be pursued for a variety of targets in order to obtain the systematics necessary for a unique determination of the spin-spin, symmetric and antisymmetric spin-orbit, tensor, and three-body parts of the effective interaction in nuclei. M1 spin-flip transitions between members of the ground-state doublet provide direct information about the Λ-nucleon spin dependence, but their observation requires efficient photon detection below 200 keV. Application of γ-ray methods to heavier hypernuclei is a challenge. One can consider working at higher K^- energy, where the kaon beam intensities are greater and the kaon decay length is longer. Conversely, one could utilize the $(\pi^+,K^+\gamma)$ reaction, which provides access to a wide variety of hypernuclear states with high momentum components. A recent experiment at Brookhaven demonstrated that hypernuclei can be produced in the (π^+,K^+) reaction. The higher pion flux would make possible higher resolution spectrometers for studies of heavier hypernuclei with more complex level schemes. Yet a further opportunity lies in the $(e,e'K^+)$ reaction, which with few GeV electrons from the new 4-GeV electron accelerator will be a very effective tool for producing hypernuclear excitations.

The full exploitation of the structure information available from Λ-hypernuclear spectra clearly requires a considerable improvement in both energy resolution and intensity. Good resolution is particularly important in heavy systems, where level splittings are generally small.

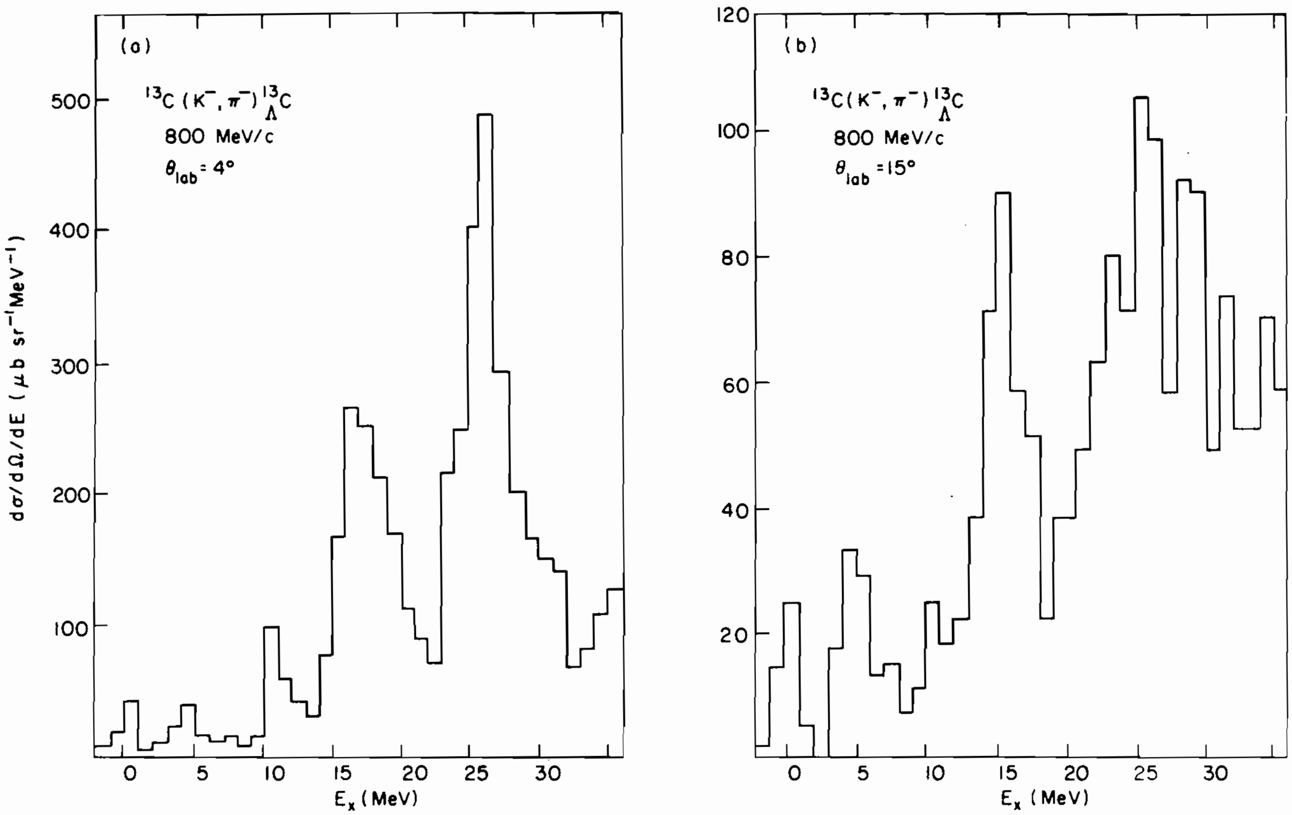

Fig. II.6-B. Production of $^{13}_{\Lambda}$C at two angles. The variation of intensities with angle enables extraction of crucial spectroscopic information.

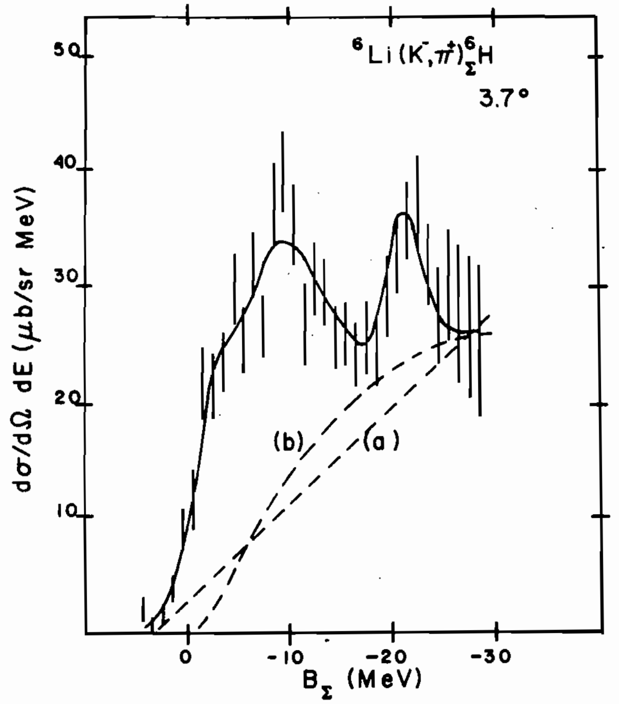

Fig. II.6-C. Evidence for a heavy hydrogen hypernucleus $^{-6}_{\Sigma}$H produced by the (K^-,π^+) reaction on ^{6}Li. The peak near a binding energy (B_Σ) of −22 MeV is probably the ground state.

To observe processes with any but the largest of cross sections requires an improvement in intensity. The degree of collectivity in heavy hypernuclei (do "strangeness analog states" exist?) can only be determined with better facilities. Measurement of spins of excited levels, electric and magnetic multipole moments, lifetimes, and disintegration products must also await these improved facilities.

High-resolution work could exploit the Λ as a relatively weakly coupled probe of properties of conventional nuclei. A Λ coupled to a rotational or vibrational nucleus would alter the moment of inertia or effective phonon spectrum of that nuclear core. In superfluid nuclei, the Λ would influence the energy gap. Through core polarization induced by the Λ, one expects changes in the quadrupole moment of a rotational nucleus, and enhanced isoscalar magnetic transitions in the nuclear core. The change in radius due to the presence of the Λ may shed some light on the question of nuclear compressibility. These and other fascinating possibilities for nuclear structure investigations remain totally unexplored.

The study of elastic and inelastic scattering processes induced by $K^{\pm}$ beams or $K_L \rightarrow K_S$ regeneration experiments on nuclei with neutral kaon beams has not yet been explored in depth. At low momenta, the K^+ has a very long mean free path and is sensitive to neutron as well as proton densities. The K^-, on the other hand, is strongly absorbed and can be considered the strange equivalent of the pion. More intense higher resolution kaon beams with better kaon-pion separation are needed to exploit kaon-induced reactions for these nuclear structure studies. Of course, we must also refine our knowledge of the two-body kaon-nucleon amplitudes, which are only poorly determined at present but which would be critical input for such nuclear structure studies.

The first hypernuclear weak decay experiment was completed recently. More could be done in this particular area with present facilities. Precision measurements of the decay modes of very light hypernuclei, where the nuclear cores are not spin-isospin saturated, are essential in order to unravel the spin and isospin dependence of the $\Lambda N \rightarrow NN$ conversion process. Hypernuclei offer a unique possibility for studying baryon-baryon weak amplitudes. In all but the lightest systems, the weak decay of the Λ hypernuclear ground state proceeds via the $\Lambda N \rightarrow NN$ process which is inaccessible except in the nuclear environment.

The (K^-,π^-) reaction on deuterium or ^3He should be thoroughly explored to investigate possible strange dibaryon resonances in the Λp system. Angular distributions are needed to obtain spin assignments; the lowest-lying six-quark bag states which couple to the Λp system require one unit of angular momentum for their excitation (nonzero angle).

The doubly-strange six-quark dibaryon (the "H") is a dramatic prediction of the MIT bag model. A search for such a state requires intense kaon beams in the 1-2 GeV/c range. The "H" particle plays a special role in multiquark spectroscopy because it is predicted to decay only weakly. Two methods for its production have been proposed: the reaction $^3He(K^-,K^+n)$"H" in which the K^+ and neutron are detected, and the production of a Ξ^- in the reaction $p(K^-,K^+)\Xi^-$ followed by the atomic capture (in say deuterium) leading to the "H" and a neutron, with the monoenergetic neutron being detected.

The study of Σ-hypernuclei would benefit immensely from higher kaon intensity, both for increased counting rate and improved beam purity. A very low-momentum beam (approximately 400 MeV/c is optimum) is required in order to emphasize the production of the narrow substitutional states without large quasi-elastic backgrounds. This is a technically difficult project because of the short decay length and low kaon production cross sections. A basic question is whether narrow states occur only in light nuclei or whether they are representative of a rich, but as yet undiscovered, Σ shell-model spectroscopy of heavier systems.

A subject of much interest in the study of normal nuclei is the role of the Δ resonance in the nucleus. The analogous problem in hypernuclear physics is the production, propagation, and decay of Y* resonances. The narrow Y*(1520), with a width of only 15 MeV, is a particularly interesting quark excitation with one unit of internal orbital angular momentum, and thus its study within the nucleus has important unique aspects. Such study also requires a low-momentum K^- beam (400 MeV/c).

Finally, the $(K^-,K^+$ or $K^-,K^\circ)$ reactions on nuclear targets offer a possible window into the spectroscopy of hypernuclei with two strange quarks, containing a Ξ or two Λ hyperons. Such studies represent a logical next step in the evolution of hypernuclear physics. The spectroscopy of such hypernuclei is potentially rich: narrow Ξ states are likely to exist, just as in the case of Σ's, though their widths will depend on the $\Xi^- p \rightarrow \Lambda\Lambda$ conversion rate as well as other factors, such as the hypernuclear wave function. Cross sections to specific high-spin discrete $\Lambda\Lambda$ states are predicted to be a few nb/sr at 0°, requiring a very intense K^- beam, and providing a formidable challenge to experimenters.

It is remarkable that so much information has already been uncovered from the relatively sparse data now available with strangeness in nuclei. Higher intensity and higher quality kaon beams would help this field toward expanding a more detailed and fascinating new perspective on our understanding of the structure of nuclei.

II.7 THE ELECTROWEAK INTERACTION AND BEYOND

Are there new interactions beyond those of the minimal standard model? Are there new particles of low mass beyond those we know? How can low and intermediate energy nuclear physics contribute to these issues?

The investigation of nuclear processes has always involved to a substantial degree the study of the properties and interactions of elementary particles. Our sister field of particle physics is entirely devoted to this undertaking with its main thrust directed towards the questions which can be probed at higher and higher energy. The study of fundamental interactions has important frontiers in addition to those at high energy. The existence of the weak interaction was one of the early discoveries emerging from the study of nuclei and the existence of neutrinos was inferred from the properties of nuclear decays half a century ago. Later, the discoveries of many of the critical properties of the weak interaction have come from the study of nuclei and nuclear processes: the confirmation of the existence of neutrinos through their interaction with nuclei; in the late 1950's the discovery of dramatic violations of parity conservation in weak processes, essential to our understanding of this interaction; more recently the demonstration of the conserved vector current relations between weak and electromagnetic processes; and currently some of the most important issues in neutrino physics are being addressed within nuclear physics, such as limits on the neutrino mass and on possible neutrino oscillations. Contributions to these fundamental questions have been made by many branches of physics including atomic physics, astrophysics and cosmology as well as nuclear and high energy physics. These have long been recognized and welcomed as a sign of the coherence and the unity of physics.

Many fundamental questions in both strong and weak interaction physics have been and continue to be investigated with the nucleus as a physical arena. We embrace here, within this long range plan for nuclear science, those questions and aspects of elementary particles which can be effectively addressed within nuclear physics. The pursuit of this subfield of nuclear physics has grown in size and importance because of recent startling developments in our understanding of elementary particles and because of their potential impact on the description of atomic nuclei.

The recent unification of electromagnetic and weak forces is one of the most extraordinary developments in modern physics and it may be compared to the unification of the electric and magnetic forces by Maxwell 100 years ago. The discovery earlier this year of the heavy vector bosons, the W and Z particles, whose large mass is related to the relatively "weak" nature of the weak force, beautifully confirms and reinforces the new theory. These new particles, together with the photon, are responsible for the electroweak force. This theoretical model, with its many experimental triumphs, further challenges us to explore its range of validity and to search for new fundamental interactions and particles.

The two fundamental interactions governing the physics of nuclei as well as of elementary particles (the "strong" and the "electroweak") have recently been embedded in a consistent theoretical framework supported by experiment, the so-called ***Minimal Standard Model*** (MSM). The MSM is a gauge theory (akin to the quantum theory of electricity and magnetism, quantum electrodynamics) and is described by the group theoretical symmetry $SU(2)_L \times U(1) \times SU(3)_C$. [Here the electroweak interaction is represented by $SU(2)_L \times U(1)$ while QCD is contained in the group SU(3).] The known fermions (leptons and quarks) are grouped into three "families" or "generations" each containing two types of quarks and two kinds of leptons; the existence of one hitherto unobserved quark (the top quark) and one unobserved neutrino (the tau neutrino) are predicted. The term "minimal" in MSM refers to the fact that the model contains only the minimal number of ingredients necessary to account for the known facts. For example, MSM does not contain right-handed neutrino fields.

The basic theory has massless particles. In order to generate the masses of the W and Z and the masses of the fermions, the symmetry of the theory is broken through the so-called Higgs mechanism and leads to a hitherto unidentified neutral Higgs particle. This Higgs mechanism is a crucial element of the theory as it is now formulated.

A number of important features are embedded within the MSM framework: baryon number is conserved, as is not only the total lepton number, but also lepton number within each "family" separately. Thus electron number, muon number, and tau number are each conserved leading to the prediction, for instance, that the decay of a muon into a photon and electron is forbidden. The charged-current weak interactions have a vector minus axial vector (V-A) structure. The neutral-current weak interactions are determined by a single new parameter, the Weinberg angle θ_W which determines the ratio of the masses of the Z and the W particles. The neutrinos are massless and there are no neutrino oscillations. The theory contains a CP-(charge conjugation-parity) violating interaction which may account for the observed CP-violation in the neutral kaon system, but there are, in first order, no CP (or time reversal T) violating effects in the leptonic and semi-leptonic weak interactions. The weak and electromagnetic interactions of the leptons e, μ and τ are identical (perfect e-μ-τ universality).

Although all the known physics is consistent with the Minimal Standard Model, it is unlikely to be the ultimate theory. For example, it is described by more than one coupling constant; it provides no clues for the replication of fermion families; the fermion masses and various weak mixing angles are not calculable.

The theoretical possibilities for physics beyond the MSM include: theories which unify the electroweak and the strong interactions (grand unified theories), new interactions which distinguish the fermion families, e.g., the electron and the muon (horizontal gauge interactions), theories which do not require elementary Higgs fields but involve a new strong force and further new interactions (technicolor schemes), a symmetry which relates fermions and bosons (theories with supersymmetry), and theories in which the leptons and the quarks are not elementary (composite models). In addition, the electroweak interaction may be described by a group larger than that of MSM (e.g., electroweak theories involving right-handed currents). Also, there may be more than one Higgs particle.

In the presence of any of these possibilities some or all of these quoted features of the MSM will be lost. Thus the major directions of research are, and will likely continue to be: *(a) search for new interactions, and for possible new light particles; (b) further study of the physics of the minimal standard model.* There are important contributions to be made by nuclear physics in both parts of this scientific challenge.

A. ISSUES AND EXPERIMENTAL PROBES RELATING TO PHYSICS BEYOND THE MINIMAL STANDARD MODEL.

Using nuclear processes, or particle beams developed for nuclear physics, a number of issues can be studied which pertain to possible new physics beyond the minimal standard model. Experiments with improved sensitivities may uncover new phenomena, limit proposed theories, or lead to new theoretical possibilities. We shall briefly outline several of these important issues.

CP-Violation. The phenomenon of CP-violation was discovered nearly 20 years ago in the neutral kaon system but, despite considerable effort, its origin is still unknown. It was an unexpected result at the time and to date CP violation has been seen only in this one system. While the data are consistent with the expectation of the MSM, they are also consistent with other possible sources of CP violation that may be present in some of the mentioned extensions of the MSM. The most important experiments to understand the origin of this symmetry violation include: higher precision measurements in the neutral kaon system which require intense kaon beams; searches for CP and T violation outside the neutral kaon system, in particular a sensitive measurement of the electric dipole moment of the neutron, using ultra cold neutrons (the present limit is $D_n < 6 \times 10^{-25}$ e-cm, while 10^{-29}—10^{-32} e-cm is predicted by the MSM); and improved tests of time-reversal invariance in semileptonic kaon decays, muon decay, nuclear beta decay (where present results have sensitivities down to 10^{-3}) and in other leptonic and semileptonic processes.

Conservation of Muon and Electron Number. The relevant processes to study include $\mu \rightarrow e\gamma$, $\mu^- \rightarrow e^-$ conversion in nuclei, and $K_L \rightarrow \mu e$. Meson factories have improved the sensitivity for the branching ratios of the first two processes by two orders of magnitude, to about 10^{-10}. Further improvements are expected from new experiments in progress or proposed on rare kaon decay modes but still higher sensitivity would require better kaon beams. Direct observation of forbidden decays would be of the greatest importance and would signal the existence of new interactions or additional neutrinos. Branching ratios could be just beyond the existing experimental limits. In technicolor schemes, for instance, the branching ratios of $K_L \rightarrow \mu e$ and $\mu^- Z \rightarrow e^- Z$ are expected to be not far from the present limits.

Conservation of Lepton Number. At present the most sensitive test for the conservation of total lepton number is neutrinoless double beta decay, a process that may occur in many nuclei. Another example is neutrino-antineutrino oscillations which also provide tests of lepton number conservation.

Baryon Conservation. Stimulated by predictions of grand unified models the *decay of the proton* is being studied presently with large-scale detectors. One of these experiments has recently set a lower limit for the lifetime of the decay $p \rightarrow \pi^o e^+$ of 10^{32} years, while theoretical estimates based on the simplest grand unified theory give 10^{28} to 10^{31} years. This crucial confrontation between observation and theory needs to be explored further including sensitive measurements of other decay modes. The search for transitions between neutrons and antineutrons, a process violating baryon number conservation by two units and referred to as a *neutron oscillation* is being conducted at nuclear reactors.

Deviations from the (V-A) Nature of Weak Charged Currents. Precision tests of the space-time structure of the charged-current interaction are important because of the possibility that the standard left-handed (V-A) structure is modified slightly by possible contributions from right-handed currents or charged Higgs exchange. A high-precision search for right-handed currents in muon-decay has just been completed at TRIUMF, and is consistent with V-A. Another relevant muon-decay experiment is in progress at LAMPF. Other tests of V-A come from measurements of helicities and asymmetries of beta particles in nuclear beta-decay. Improvements in the sensitivity of these and other tests are possible with the advent of new techniques for measuring positron polarizations.

The Structure of the Neutral Current Interactions. A powerful probe of possible deviations from the standard model is a set of precise measurements of the neutral current parameters $\sin^2\theta_W$ and ϱ ($\varrho = M_W^2/M_Z^2 \cos^2\theta_W$). In the standard model the parameter $\sin^2\theta_W$ is arbitrary and $\varrho = 1$. In some grand unified models $\sin^2\theta_W$ can be predicted rather precisely; the simplest SU(5) theory agrees well with the experimental value of 0.224 ± 0.015. The corresponding value of $\varrho = 0.992 \pm 0.017$ from semileptonic neutral current processes is consistent with 1.0. Information on ϱ and/or $\sin^2\theta_W$ will come from precise determinations of W and Z masses.

One of the important challenges is to also measure, to an accuracy of a few percent, the *purely leptonic* scattering reactions $\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$, such studies are under way at present high energy accelerators. One would also want to improve substantially the results for $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$ and to study $\nu_e e \rightarrow \nu_e e$, which are uniquely sensitive to interference between neutral and charged current interactions, and such improvements are not feasible at high energy accelerators. High-intensity neutrino sources, such as those proposed for kaon factories, would be able to achieve substantial improvement in the measurement of these purely leptonic processes.

The scattering of longitudinally-polarized electrons from nuclei offers a way to study the structure of the neutral current interaction. Scattering of polarized electrons on deuterons at SLAC first showed the existence of a parity violating neutral current. An electron accelerator with energies up to 4 GeV, as recently recommended by NSAC, is ideally suited for these pursuits. Precision nuclear excitation and elastic scattering studies with polarized electrons at available electron accelerators (e.g., Bates), and perhaps with eventual neutrino beams, are also useful for testing the isospin structure of neutral hadronic currents and therefore serve as tests of the electroweak theory. The availability of different nuclear targets and variable electron energies is helpful in this regard.

Neutrino Properties. Besides being an important issue in the present theoretical framework, the question of neutrino mass has profound ramifications in astrophysics, and cosmology. Nonzero masses for the neutrinos are strongly suggested by grand unified theories.

From the experimental point of view there are several approaches to pinpoint the neutrino mass. There are *kinematical tests* using low-energy nuclear beta decays such as tritium, or the decay of the pion into a muon and a neutrino. Present sensitivities for the electron neutrino mass are about 35 eV. Several experiments currently in progress with nuclei are expected to resolve an existing experimental controversy concerning the electron neutrino mass, and should be sensitive to a mass as small as 10 eV within the next 2 years. Similarly, the $\pi \rightarrow \mu\nu$ decay should be studied with the aim of obtaining more stringent limits (or values!) of the ν_μ mass whose present limit is only about 500 keV.

For massive neutrinos one expects in general the phenomenon of *neutrino oscillations*, i.e., transitions from one type of neutrino to another. Searches for such processes are currently being carried out with high energy neutrinos from high-energy accelerators, medium energy neutrinos from meson factories, and low-energy neutrinos from fission reactors. To date no evidence has been found for oscillations, but more sensitive tests may yet uncover them. The most sensitive test for $\bar{\nu}_e$ oscillations has been obtained with low-energy reactor neutrinos, and the limits provided by these experiments are shown in figure II.7-A.

The *solar neutrino problem*, the observation of fewer neutrinos from the Sun than expected from the standard solar model is still an unresolved problem despite years of

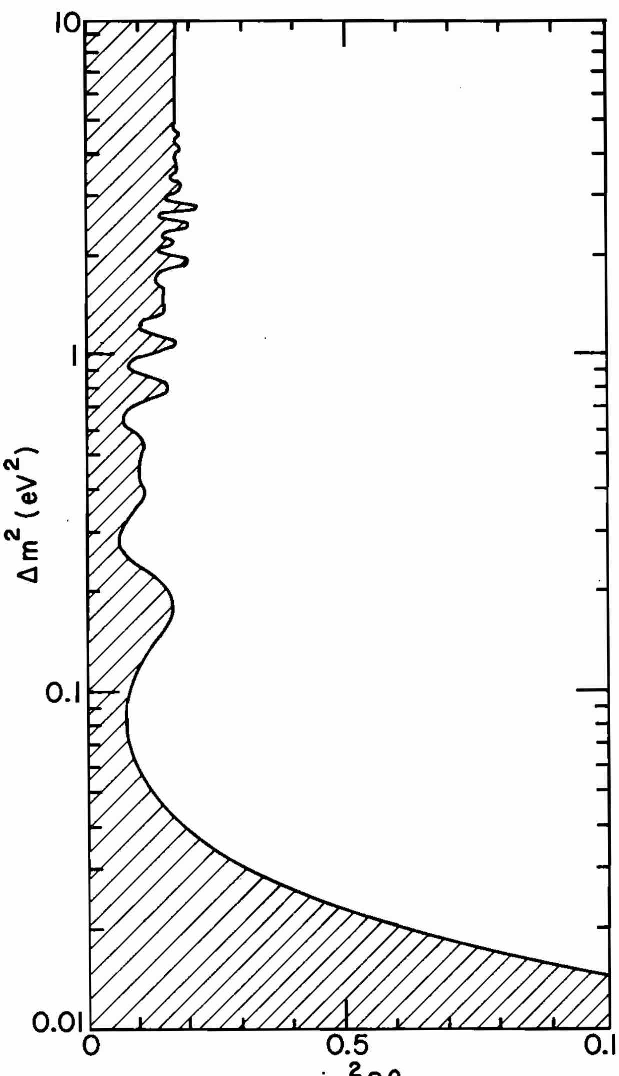

Fig. II.7-A. Present limits on neutrino oscillations. The unshaded region of the plot has been ruled out by reactor experiments. The plot is of the mass difference (between two possible neutrino states) squared, as a function of the phase angle ($\sin^2 2\theta$) that mixes the two states.

studies. This may be related to neutrino oscillations with long oscillation length as discussed in Sec. II.10.

If neutrinos have mass, the question becomes pertinent whether they are *Dirac or Majorana particles*, the latter being particles that are identical to their antiparticle. Neutrinoless double beta decay in nuclei appears to be one of the most sensitive tools to answer this question. Recent studies based on ^{76}Ge set upper limits on the mass parameter of 10-20 eV. New experimental techniques adapted from high-energy physics, such as the time projection chamber, will make these nuclear experiments much more sensitive.

Deviations from e-μ Universality. At present the most sensitive test of e-μ universality in charged current weak interactions is the ratio of the $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu$ rates. This ratio has recently been measured with an accuracy of about 1.5%, and further improvement is possible. A deviation from e-μ universality would suggest the presence of charged Higgs mesons and/or mixing in the leptonic sector.

New Particles. Experiments possible with nuclear transitions and nuclear physics accelerators or reactors are well suited to search for new particles of low mass. Such particles include the axion (conjectured to explain the apparent absence or smallness of CP violation in QCD), light Higgs bosons, massive neutrinos, and some new particles predicted by supersymmetric theories. Among the processes in which such particles might appear are specific nuclear transitions and rare decay modes of kaons. Sensitive experiments to look for possible massive neutrino states are searches for peaks in the charged lepton momentum spectra from the decay of pions and kaons.

Anomalous Phenomena. An example of anomalous phenomena not permitted in renormalizable gauge theories are *"second-class"* currents. Second-class currents are weak currents which have opposite "G parity" quantum number to that of the usual weak quark currents. Existing experiments on correlations in beta decay are all consistent with no second-class currents, but more sensitive experiments are needed. An interesting new technique involves measuring the electron-neutrino correlation in beta decay, since interpretation of the result does not require knowledge of the weak magnetism form factor.

B. OTHER OPEN AREAS OF RESEARCH IN THE PHYSICS OF THE MINIMAL STANDARD MODEL

Besides the above tests there are other issues bearing on the physics of weak interactions within the MSM.

Weak Form Factors of Hadrons. The weak interaction of hadrons cannot, in general, be predicted directly from the weak interactions of the quarks because of the effects of the strong interactions which induce form factors not present for point particles. It is not known yet how to calculate these effects accurately, although conservation principles (CVC and PCAC) provide some useful relations. Understanding the weak structure of hadrons (especially of the nucleon) complements the studies of the electromagnetic and strong interactions of nucleons. Processes of particular interest, beta decay, parity violating studies in electron scattering, and muon capture, address several issues. *CVC* can be tested by way of the weak magnetic form factor. Current experiments test this at the $\sim$10% level. It would be valuable to push this down until isospin breaking becomes important. A precision determination is needed of the *axial-vector coupling constant* in the beta decay of the neutron. Aside from its intrinsic importance, this quantity is needed, for example, to predict the amount of ^{4}He produced in the "big bang." At present there are conflicting results on the neutron half-life, however the axial vector coupling constant g_A can probably be better determined from an angular correlation measurement. *The axial-charge form factors in nuclei* are believed to be strongly enhanced by pion-exchange. There is some evidence for this, but more work remains to be done to clarify the issue. There is also evidence for a *quenching of g_A* in a nuclear medium. Further study is needed to shed light on the nature of this effect. Muon capture is particularly sensitive to g_p, the *induced pseudoscalar* form factor. Present results are consistent with the (PCAC) predictions, but the experimental precision should be improved.

The Nonleptonic Weak Interactions. The only strangeness conserving nonleptonic weak interaction which is presently accessible experimentally is the parity-violating nucleon-nucleon force. Parity violation has been observed in both heavy and light nuclei, and also in polarized proton-proton scattering. These experiments provide valuable input for tests of dynamical calculations: for instance, studies of parity-mixed doublets in light nuclei have set constraints on the isospin structure of the parity violating interaction. Parity violating effects in scattering of polarized protons from protons, and in light nuclei are consistent with quark model calculations in the framework of the MSM. Information on this nonleptonic weak interaction can also be obtained from studies of polarized electron nucleus scattering at low momentum transfer.

Study of Higher Order Effects in the Standard Model. Studies of decays forbidden in first order in the standard model are motivated by the desire to test higher order calculations, to constrain the parameters of the standard model, and to probe for the existence of new interactions. An example is the decay of a charged kaon into a charged pion and neutrino-antineutrino pairs. Calculations lead to the conclusion that a branching ratio significantly above 3×10^{-9} would represent evidence for new physics, while one significantly below 4×10^{-10} would suggest the presence of more than three fermion generations or new interactions. Other examples are precision tests of quantum electrodynamics such as measurements of the anomalous magnetic moment of the muon and the hyperfine splitting in muonium.

Conclusion

In the area of electroweak interactions the lines between particle physics and nuclear physics are especially blurred. Many of the crucial questions in this area can be addressed by nuclear physicists, using nuclei, nuclear processes, or the particle beams developed for nuclear studies. In high energy physics the detailed studies of the decay modes of the W and Z particles as well as many other experiments (searches for the Higgs particle, for evidence of the top quark, for new heavy particles associated with possible extensions of the MSM, etc.) will provide a rich field of study over the coming decade. The combined results of the two scientific communities are likely to lead to a deeper and more thorough understanding in an area of physics which has produced the most quantitative new insights into the nature of matter in the latter half of the twentieth century.

II.8 MACROSCOPIC PHENOMENA

What are the new macroscopic and microscopic phenomena associated with collisions between two nuclei? How and on what time scale is energy absorbed and a new equilibrium established?

Nuclei are many-body systems with many degrees of freedom and with dimensions that are comparable to or often smaller than the mean free paths of their constituents. Exploration of these systems has thus far been limited largely to relatively cold configurations near their quantum ground states. Collisions between nuclei have provided one of the richest sources of information concerning both the microscopic and macroscopic structure and behavior of nuclei; these collisions involving heavier nuclei produce—in controlled fashion—nuclear complexes very different from those encountered in nature and permit study of the phenomena occurring in them under conditions of higher temperature, density, high spin, and high mass-to-charge ratios. Of particular interest are the discovery and understanding of the simple modes of nuclear excitation produced in these damped nuclear collisions, their microscopic foundations, their eventual decay, and the cooperative and relaxation processes responsible for them.

The study of heavy-ion collisions was initiated more than forty years ago by measurements of Alvarez and his collaborators at Berkeley but the full power of heavy-ion studies did not become apparent until the late 1950's with the development of the tandem electrostatic accelerators and the new generation of precision cyclotrons and linacs designed to accelerate all ions in the lower end of the periodic table. This power stemmed from the fact that the heavy-ion collisions, for the first time, gave the experimenter much broader control over collision parameters including charge, angular momentum, linear momentum, number of transferred nucleons, and neutron to proton ratio, than had been possible with more traditional lighter projectiles. Reflecting the very small de Broglie wavelength, these heavy-ion interactions were also amenable to quite simple classical or semiclassical analyses. The early measurements, and indeed, until recently, a very large fraction of *all* studies on the physics of heavy-ion collisions focussed on their macroscopic aspects such as shapes, deformations, and fragment distributions in mass and charge. Only recently has it become possible to focus upon the underlying microscopic behavior of the nucleons responsible for these macroscopic observations; despite this, impressive progress has already been made.

An exception to this rather general rule is the case of Coulomb excitation. These Coulomb-excitation studies were, and remain, one of the most productive sources of information on nuclear collective motion and as such were complementary to light-ion reactions such as deuteron stripping which mapped out much of the single-particle structure of nuclei. The fact that heavy ions could bring large angular momenta into colliding systems, without concomitant energy sufficient to disintegrate them directly, gave access to entire new regimes of hot, high-spin, nuclear configurations and partial answers to the ubiquitous question of how the nuclear many-body system responds to increasing energy and increasing spin. What happened when it was heated?

One of the early discoveries in this field, now thought to be a very general feature of nuclear interactions, was the nuclear molecule—a transient configuration in which the target and projectile retain their identity but are bound together for times long compared to the collision time during which they rotated and vibrated in a fashion familiar from the atomic domain.

Recent discoveries in this field, shown in figure II.8-A, have demonstrated the rather remarkable fact, for example, that at excitations above 70 MeV in the 56 body ^{56}Ni

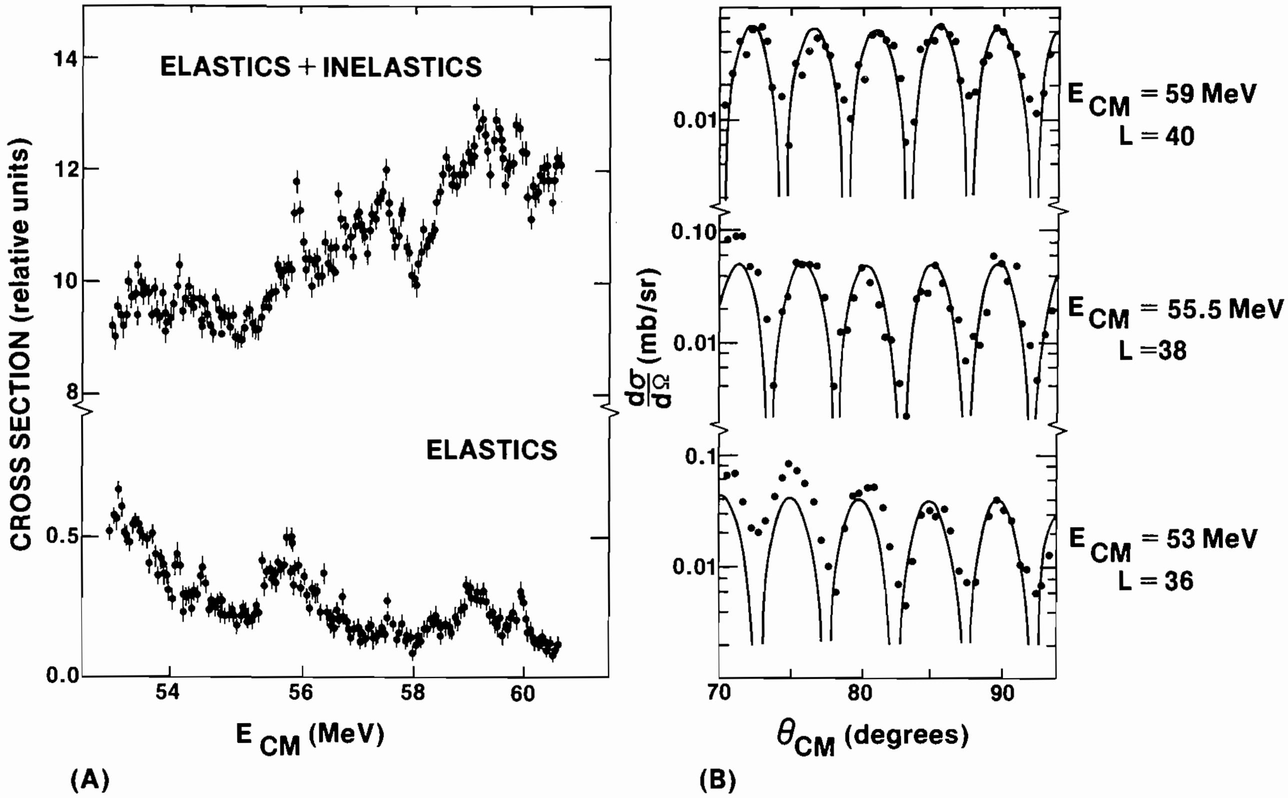

Fig. II.8-A. Scattering of two ^{28}Si nuclei from each other shows sharp energy-dependent structures as seen on the left. On the right are angular distributions of the elastic scattering in this system. These distributions demonstrate that very high angular momenta dominate these "molecular" processes.

system there are sharp states having angular momenta between 40 and 50 units which have very simple structure indeed—two ^{28}Si nuclei bound in a dinuclear molecular configuration.

Damped nuclear collisions are intermediate between the traditional nuclear physics classifications of compound nucleus and direct reactions; they involve the last classical phenomenon to be introduced into the quantum domain—friction; and they show every evidence of presenting entirely new phenomena in nuclear physics. Thus far experimental studies have been extremely limited in scope. Large areas remain unexplored awaiting the availability of new accelerators, new instrumentation and new understanding. Already this class of reactions has provided substantial insight into the behavior of the nuclear many-body quantum system, with some illuminating analogies and connections to other branches of science such as chemical physics and quantum statistics. The possibility of entirely new kinds of nuclear matter—density isomers—of dramatic phase transitions in nuclear matter, and of a wealth of other new phenomena await investigation, as soon as the facilities and instrumentation become available.

It is convenient to divide the energy range into five domains; the critical energies marking their boundaries are roughly 5, 20, 150 and 1000 MeV per nucleon, respectively. The lowest energy is that where Coulomb barrier effects are important; the second is that at which supersonic (i.e., shock wave) effects might first be expected; the third is an effective threshold for mesonic effects and the fourth marks the onset of pronounced relativistic phenomena. We will here discuss the physics near the first three of these boundaries and return to the fourth in Sec. II.9.

Elastic and Inelastic Scattering

Elastic scattering is the simplest interaction between two nuclei dominated, respectively, by electromagnetic and by strong nuclear forces at low and at high energies. The small de Broglie wavelength, comparable to, or smaller than the nuclear size, makes the analogy with optics a very good one and a wide variety of optical phenomena—interference, diffraction, rainbow scattering—are observed dramatically in the nuclear domain.

Passing beyond elastic to inelastic scattering, we have both Coulomb excitation where the electromagnetic interaction is dominant, and the strong nuclear interactions. In both instances, strong coupling to the nuclear collective modes occurs and has been exploited effectively to provide detailed information concerning the static and dynamic shapes of nuclei.

It is important to note that much of what we know about nuclear quantum states relates to excitations within the pairing gap of the ground state—to cold nuclei. We do not know what happens to collective states when they are superimposed on the continuum, how they spread or dissolve. We do not know in any detail how high in excitation we can hope to follow microscopic behavior and whether we will necessarily turn to macroscopic descriptions. We really do not know in any comprehensive manner how the nuclear many-body system will respond to systematically increased energy and/or angular momentum.

The Nuclear Continuum

The nucleus is one of the few examples of a many-body system which both exhibits statistical behavior and can be studied in sufficient detail to resolve individual energy levels. The behavior of nuclei as a function of excitation energy, angular momentum, and other properties varies dramatically from domains of collective motion and elementary excitations to domains of random motion in which the levels show no correlations between observables. The density of levels is the most basic statistical property of the nucleus, and is usually expressed as a temperature—energy relation. Recent heavy-ion reactions show that the nucleus can maintain its identity at least to temperatures up to 3-6 MeV, but with many properties altered by the large energy the nucleus contains. Experimental data on a much more systematic scale are required to test theory beyond its present rather crude level.

Deep Inelastic Scattering

It has been traditional in nuclear physics to separate nuclear interactions into two broad classes, direct and compound, depending upon the characteristic time scale and the number of degrees of freedom involved. Heavy-ion studies have been unique in that they have included a totally new kind of interaction—deep inelastic scattering, characterized by a massive transfer of kinetic energy into internal excitation as well as limited mass and charge flow. A definite correlation has been postulated between the interaction time and the magnitude of the kinetic energy loss.

The exact mechanism whereby this energy transfer is accomplished remains a matter of some debate and models range from those involving stochastic transfer of individual nucleons between the target and projectile to those based upon excitation of surface vibrational modes. The general characteristics of the deep inelastic process are only just beginning to emerge in broad areas of the periodic table.

Fusion

Enormous impetus has been given to fusion studies by the development of new ion sources, high energy electrostatic accelerators and second-generation linacs in recent years. Once thought to be the consequence primarily of simple one-dimensional barrier penetrability, fusion in heavier systems is now suspected to be strongly dependent on dissipation mechanisms, modes of nuclear excitation, on the dynamics of the collision process, and in general on both the microscopic and macroscopic properties of the colliding nuclei.

With the recent availability of adequate computer capacity, time dependent Hartree-Fock (mean field) TDHF fusion calculations can be extended to very heavy nuclear systems; in these it is found that the flow of matter between the interacting nuclei has a very major influence on the dynamics. Macroscopic calculations, using multidimensional potential energy surfaces have also been applied to the fusion process. They have further elucidated the role of nuclear dynamics and have provided an estimate of the excess energy required to fuse massive nuclei over that anticipated on the basis of simple one-dimensional pictures.

There is a growing suspicion that surface dominated reactions such as inelastic scattering and single and multinucleon transfer can have an appreciable effect on the evolution of the nuclear complex, and that dynamical thresholds for fusion must be tied at least in part to nuclear structure properties. What is badly needed to help clarify these connections is a careful study of quasi-elastic yields in reactions between heavy and moderately heavy nuclei. An example of experimental data showing evidence for fusion, quasi-elastic scattering as well as strongly damped scattering is shown in figure II.8-B.

Fission

The large angular momenta involved in heavy-ion reactions have provided a unique opportunity to extend fission studies beyond their traditional domain. The disruptive nature of the centrifugal force can make any nucleus in the mass table unstable toward fission under experimental conditions readily accessible with the new generation of heavy-ion accelerators. Studies of fission barriers of relatively light systems have provided a testing

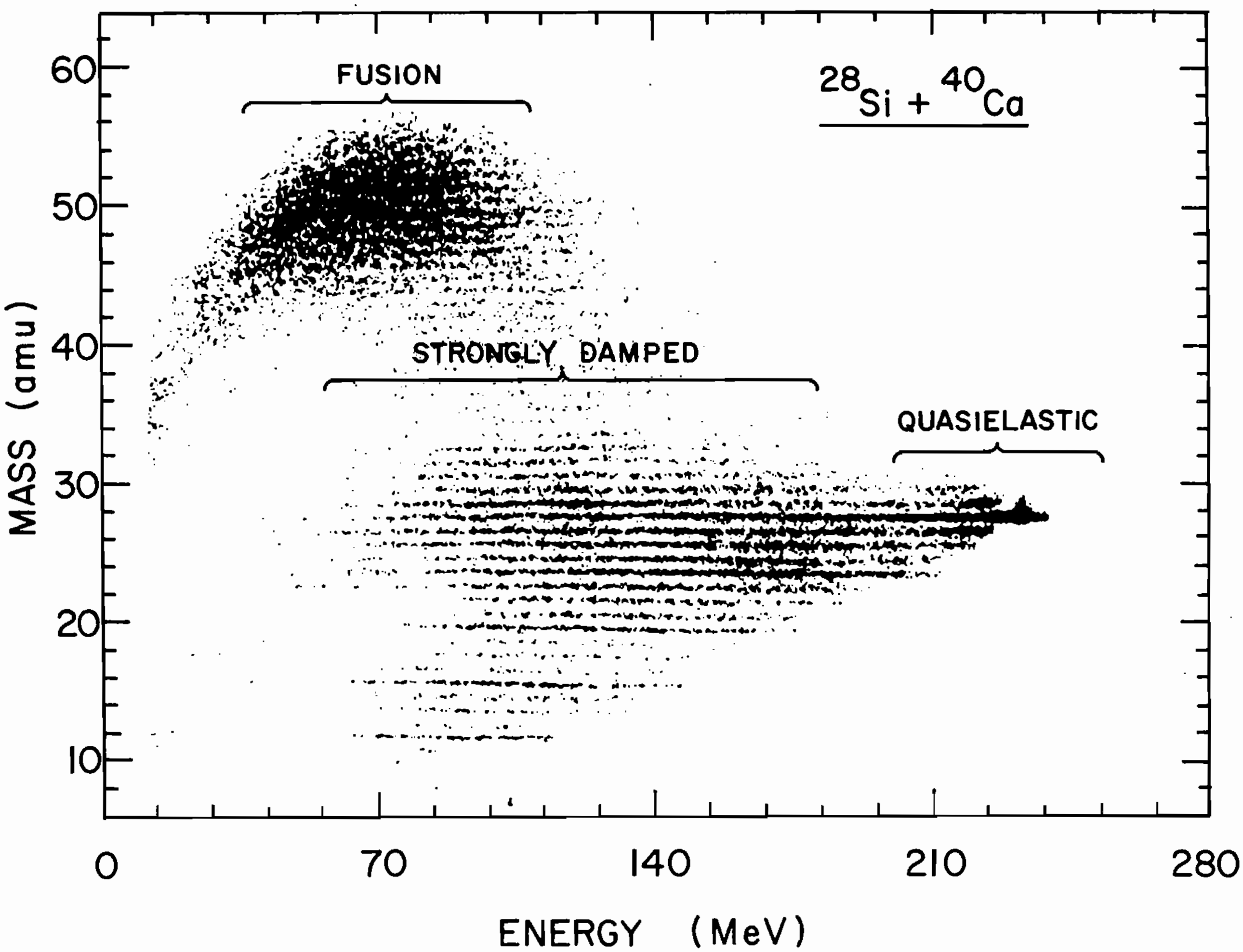

Fig. II.8-B. The particles observed at a forward angle (12°) from the collision between a 250-MeV ^{28}Si nucleus with a ^{40}Ca target. The regions of energies and masses corresponding to three reaction mechanisms discussed in the text are indicated.

ground for the liquid drop model as applied to shapes of extreme deformation. The importance of the diffuseness of the nuclear surface and of the role of the finite range of the nuclear force has been demonstrated, while the effects of shells and other microscopic effects present a challenge for future studies.

In addition to the fission of compound nuclei, a new process, fast-fission, has been identified. The reaction time associated with the process is $\sim 10^{-20}$ sec. Fast fission has been observed under any of the following three conditions: when the energy needed for fusion is just below the threshold; when the compound nucleus is unstable toward fission; and when there is a third body present. While the time involved is intermediate between that of compound nucleus fission and that which characterizes strongly damped reactions, the precise relationship between these processes remains to be explored.

The major challenge here, as yet unanswered, is that of bridging the gap between fission and the fragmentation processes that have been approached via reaction channels.

Collective Phenomena

As we go up in energy can we consider nuclear collisions as just the incoherent sum of a whole range of nucleon-nucleon collisions or rather are there coherent collective phenomena involving all, or a large fraction of, the nucleons present? A number of relatively low energy studies clearly point to such collective effects.

A good example derives from measurements of charged particles emitted in collisions of 400 MeV/nucleon ^{20}Ne beams with heavy targets. The number of protons observed is significantly fewer than predicted and there is evidence for the existence of a slowly moving source in the laboratory system, suggesting that the projectile appears to be stopped inside the target matter.

These findings all are suggestive of large energy deposition in a small volume, and appear to require a cooperative effect involving many nucleons. Recent work on 86 MeV/nucleon $^{12}C + ^{12}C$ collisions at CERN provides additional evidence for strong collective phenomena. Finally, and most revealing, the reaction $^{3}He + ^{3}He \rightarrow ^{6}Li + \pi$ has been observed using slow beams, well below threshold velocity for the pion production in the free nucleon-nucleon interaction while systematic studies with 35-MeV/nucleon ^{14}N beams on a variety of targets ranging from Al to W have resulted in determination of π^0 production cross sections. These results demonstrate convincingly that the nuclear many-body environment plays a key role, even in collisions of relatively light nuclei, enabling the almost total conversion of the incident kinetic energy into a coherent nuclear state. Thus high energy densities favorable for the observation of qualitatively new phenomena are achieved in the interactions of nuclei at intermediate energies.

The Nuclear Equation of State

When we consider the equation of state of most materials we examine the appropriate pressure-volume diagrams, searching for phase changes and other singularities or peculiarities.

In the equivalent diagram for nuclei, the nuclear equation of state, only the behavior in the vicinity of the normal nuclear matter minimum has been explored; we do not know whether there are additional local minima which would correspond to density isomers or to entirely new forms of matter. Simple fluid dynamic calculations of the yield of pions expected per nucleon in Ar + KCl and Ne + NaF collisions studied at the Berkeley Bevalac show no evidence for anomalies in the energy range from about 500 to 2000 MeV/nucleon in the laboratory. Hydrodynamic calculations, however, indicate the onset of high densities in collisions above about 80 MeV/nucleon and by 200 MeV/nucleon densities three times normal are expected, albeit for times lasting only 10^{-22} sec. Because of the limited energy range studied, it is entirely possible that measurements to date might have missed such secondary minima if they exist. Moreover, hydrodynamic phenomena may be most fully developed in collisions involving the most massive nuclei; experiments with relativistic uranium beams are just beginning and an early event is shown in figure II.8-C. Just as the collisions give rise to densities above normal in their compression phases, in the subsequent relaxations (or bounces) densities significantly below normal may also occur and it is here that present-day calculations suggest the possibility of another phase transition and the possible coexistence, for brief periods, of both gaseous and liquid phases of nuclear matter. Searches for this transition are planned for the near future.

Localization

A fundamental question concerning the dynamics of nuclear collisions and specifically the energy dissipation mechanisms is that of the possible localization of energy deposition—the formation of hot spots. As we move up in energy the collision times become so short that mean field effects become negligible and only a small fraction of the nucleons present might be expected to participate in the collision, the remainder functioning effectively as spectators.

There are several approaches to the localization question including use of a thermodynamic model for light product emission, of a so-called coalescence model and an interferometric method modelled on that evolved in astronomy for estimation of the size of Sirius. All are crude—but all agree that over the entire range of incident energies from 20-2000 MeV/nucleon, the effective source radius is about 3.5 fm—much smaller than the characteristic dimensions of the interacting systems, and surprisingly constant.

A wide variety of models has been developed for localization in terms of some variation of a participant-spectator situation (e.g., fireball, firestreak, hot spot). In most of these, the overlap region between the two interacting ions is assumed to constitute a very hot source of light particles. Further measurements are needed to determine the extent to which the models present a true picture of interactions between complex nuclei, and particularly, to determine the energy ranges where different phenomena may be dominant.

Fragmentation

As the energy of the projectile increases, the character of the peripheral reaction begins to make a transition at around 20 MeV/nucleon. Just below this energy, the dominant mechanism probably involves the transfer of "participant" nucleons from one nucleus to the other. The momentum distribution of the "spectator" fragment is constrained by the transfer process. With the increase in energy, the angular momentum of these participant nucleons is so large that they cannot be captured by the other nucleus. The momentum distribution of the spectator then attains the fragmentation limit which remains essentially the same up to relativistic energies.

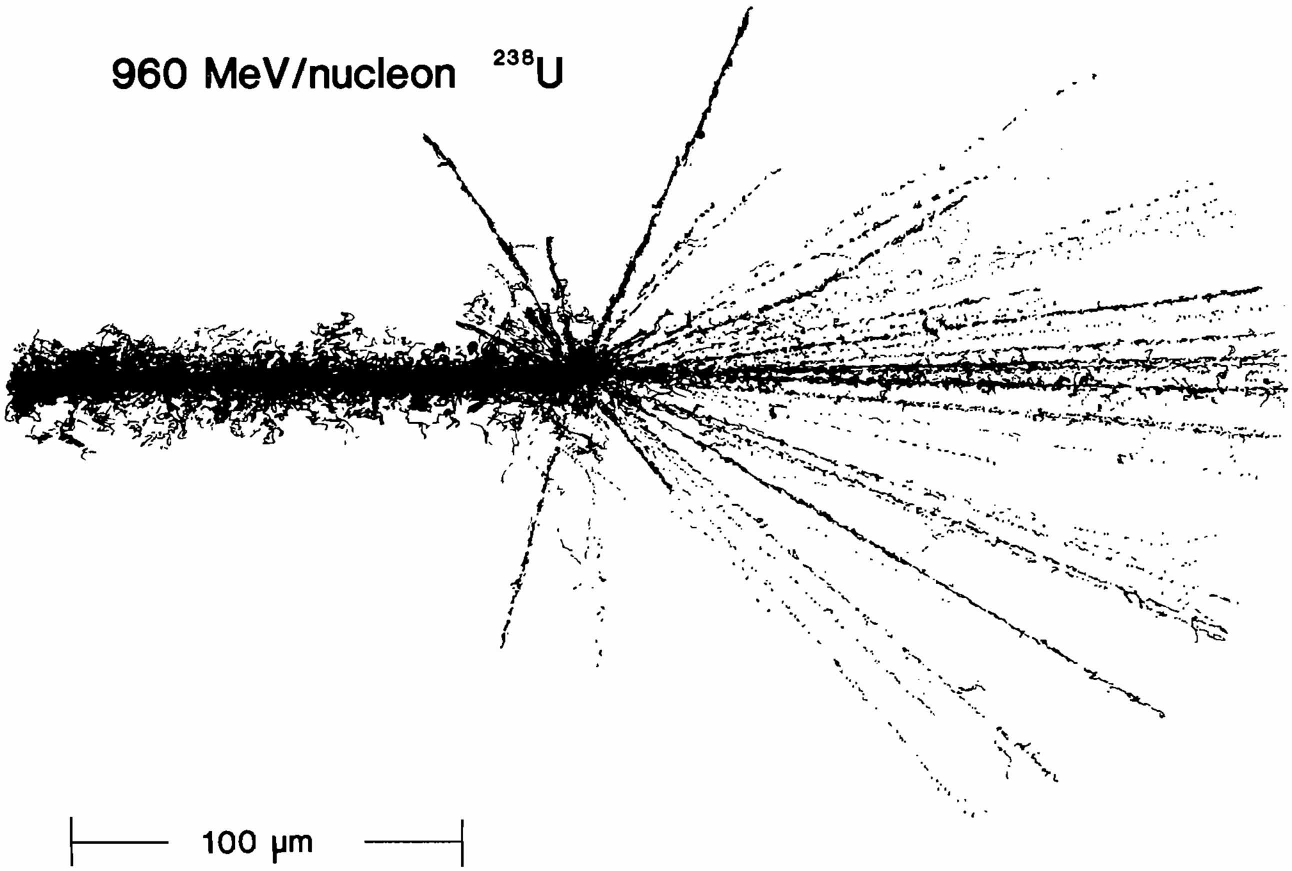

Fig. II.8-C. The pattern of tracks left by a 960-MeV-per-nucleon ^{238}U nucleus colliding with another nucleus in a photographic emulsion.

Supercritical Field Phenomena

In the study of heavy-ion collisions, much attention has been focussed upon the supercritical field phenomena anticipated in the collision of heavy nuclei carrying large mass *and* charge. In the charge case, the Coulomb field in the neighborhood of the colliding nuclei becomes supercritical in that the electron binding energy exceeds twice the electron rest mass. Under these conditions, a vacancy in the K shell, created in the early phases of the collision, can be filled by a negative energy electron from the Dirac sea with the consequent appearance of an unaccompanied positron. Such positrons have now been observed at GSI in the collisions of uranium beams with uranium or heavier targets, and an example of data is shown in figure II.8-D.

A somewhat analogous strong interaction is that of pion condensation, which may occur at densities several times normal nuclear values and would be characterized by a large pion field and the observation of numbers of pions with unusual correlations. Simple models suggest that such pion condensates might be expected for energies around 200 MeV/nucleon and at densities above about twice the normal density but, as yet, no experimental evidence for the condensates has been obtained. Experiments to date have been very much limited in the range of masses and energy involved. It is not yet clear whether the nuclei studied (e.g., Ne) are simply too small and diffuse to support a pion condensate or whether the effective nuclear correlations are perhaps too strong to permit condensation at the densities achieved.

The search for these pion condensates remains an outstanding challenge in elucidating the phase diagram for nuclear matter.

Nuclear Temperatures

It is rather remarkable that an enormous body of data on the emission of light fragments from heavy-ion collisions can be parameterized for many orders of magnitudes in terms of cross sections depending exponentially on an assumed nuclear temperature. The temperature extracted from such data increases with the available energy, reaching values $\sim$100 MeV for laboratory energies $\sim$1 GeV/nucleon. There appears to be growing evidence for a temperature saturation in nuclei at

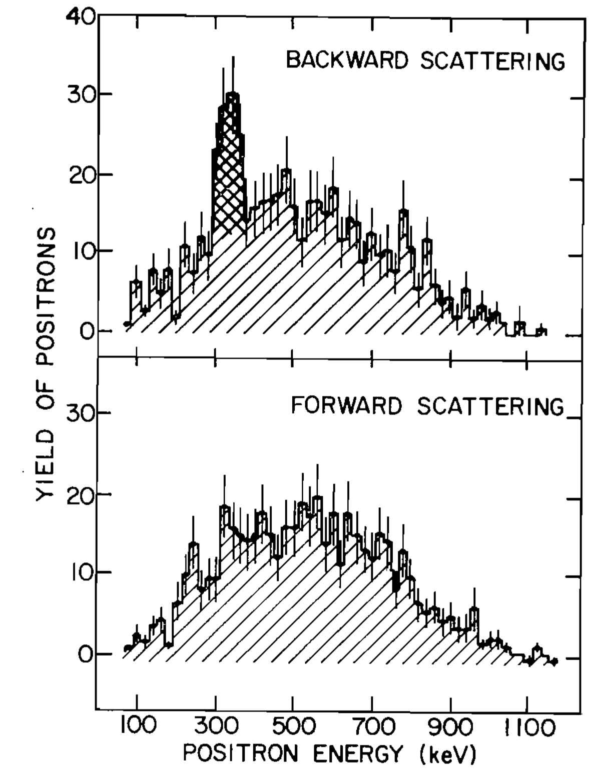

Fig. II.8-D. Positron emission from the "breakdown of the vacuum" in the extremely high electromagnetic fields produced during the collision between a uranium and a curium nucleus. Especially surprising is the presence of a sharp line for backward scattering (close collisions) which could only arise if the combined system were to exist for an unexpectedly long time. Such a long-lived state in the 486 nucleon system would indicate simple structural selection rules of very special character.

about 150 MeV as the available energy is increased. The behavior of the temperature in these high energy heavy-ion collisions may be related rather closely to the nature of the hadronic spectrum at high energies and this in turn could have the most profound consequences in arenas as different as the earliest instants of creation and the final death throes of giant stars, quite apart from its great intrinsic interest as a fundamental aspect of the most basic structure of all matter.

II.9 EXTREME STATES OF NUCLEAR MATTER

What is the nature of nuclear matter at energy densities comparable to those of the early universe? What are the new phenomena and physics associated with the simultaneous collision of hundreds of nucleons at relativistic energies?

Nuclear matter has been explored only over a very limited range of energy and nucleon densities. Probing its equilibrium and dynamic properties further is a problem of deep intrinsic interest in nuclear physics. Beyond needing to map out the gross features of the phase diagram and thermodynamics of nuclear matter, one needs its excitation spectra, and transport properties, such as stopping power for hadronic projectiles, mechanisms of energy dissipation, and particle absorption and emission. Understanding these properties tests our knowledge of the basic forces between nucleons—and at an even more fundamental level, between quarks—and our abilities to derive these properties from first principles in terms of these forces. Exploration of nuclear matter, using existing heavy-ion accelerators, and proposed ultra-relativistic ones, will open experimental and theoretical opportunities at the frontier of physics: most outstanding will be the creation of extended regions of matter at energy densities beyond those ever created in the laboratory over volumes far exceeding those excited in elementary particle experiments and surpassed only in the very early universe. One very exciting possibility at such energy densities is the discovery of new states of matter.

The properties of nuclear matter are of great interest outside nuclear physics as well. In astrophysics they are important to the mechanism of supernova explosions, in which massive stars undergo gravitational collapse to beyond the point where their nuclei are crushed together; to the properties of neutron stars composed in most part of bulk nuclear matter, including their birth and evolution, a determination of their upper mass limit and the transition to black holes; and in cosmology, to the behavior of the early universe in the period from 1 microsecond after the big bang until nucleosynthesis, when space was filled with bulk matter. The study of nuclear matter has direct interplay with the concerns of condensed matter physics, for example, states of broken symmetry, and with those of high energy physics.

Nuclear Matter at Normal Densities

Certain basic properties of nuclear matter are at present well-understood at low excitation energies and nucleon densities very near those found in undisturbed nuclei. While these are reviewed in greater detail in Sec. II-8, we recall salient features here. The "saturation" density ϱ_{nm} of nuclear matter, 0.16 nucleons per cubic fermi (or 1.6×10^{38} per cubic centimeter), and its binding energy, are determined from the properties of static nuclei. Observations on the "breathing modes" (electric monopole giant resonances) of nuclei indicate that nuclear compressibility is close to that of a noninteracting gas at the same density. Current theoretical methods for solving the many-body problem at zero temperature, based on variational techniques, yield results in agreement with these observations, provided two-nucleon forces derived from fits to scattering data are supplemented with many-body forces.

Phase Diagram of Nuclear Matter

On the other hand, the nature of matter under extreme conditions of high compression (or rarefaction) or high energy density remains uncharted experimentally. Calculations of the phase diagram of bulk nuclear matter at finite temperatures and varying densities suggest a very rich structure, as illustrated in figure II.9-A. For example, at particle densities below that of saturation, nuclear matter should undergo a liquid-gas phase transition at low temperatures, similar to the boiling of water, with a critical point. The nuclear medium can greatly modify the properties of particles, such as pions and delta resonances, propagating in it. As a consequence, at densities at least twice the saturation density, bulk nuclear matter is predicted to undergo a transition to a phase said to be "pion-condensed" in which the system should develop a coherent macroscopic pion field, similar to the electromagnetic field in a laser. A charged-pion condensed medium would also be a novel "superconductor," being able to carry electrical current with no resistance, for instance in neutron-star matter. Finally, under conditions of very elevated energy density, nuclear matter will exist in a wholly new phase in which there are no nucleons or hadrons composed of quarks in individual bags, but an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently. The phase diagram should also exhibit the transitions associated with nuclear pairing which have a low transition temperature. The structure indicated in the figure also depends on the neutron-proton ratio and on the nuclear angular momentum.

The full exploration of this structure of the phases of nuclear matter presents many exciting opportunities. The dynamics and thermodynamics of the liquid-gas phase transition can be studied in heavy-ion experiments that deposit enough energy in the nucleus for it to "boil off" or fragment into smaller droplets; preliminary experiments of this kind have been carried out on heavy-ion accelerators and also at Fermilab and further ones are in progress. Two major avenues currently being pursued promise new access to the nuclear equation of state. The first is study of the dependence on energy of the multiplicity of pions produced in a collision, a measure of the fraction of the total collision energy going into kinetic versus potential energy. The second is global analysis of particle flow in collisions. New observations on collisions of Nb on Nb at 400 MeV per nucleon provide evidence that the particles move in a coordinated or collective flow, suggestive of the behavior of a fluid described by hydrodynamics. Systematic study of the collective flow patterns of matter as a function of particle multiplicity, beam energy, and nuclear size will permit the magnitudes of the pressures generated in such collisions to be extracted.

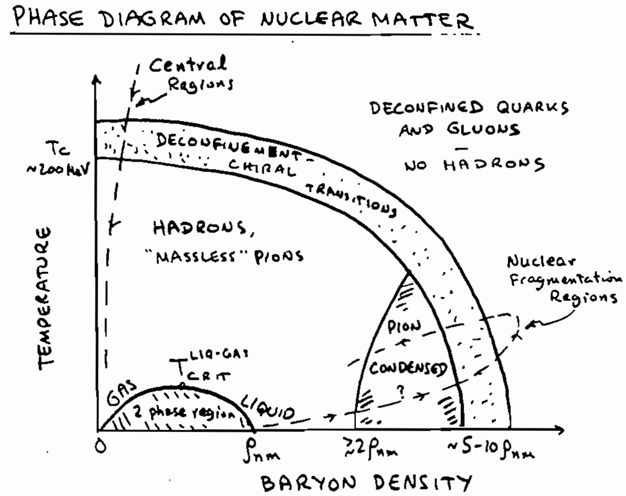

Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultra-relativistic heavy ion collisions.

The effects of nuclear matter on the pion field can be studied in pion absorption and production experiments and possible precursor effects of pion condensation may appear. Temporarily condensed regions may be formed in collisions of heavy ions designed to produce maximum nuclear compression. Pion condensation in the deep interiors of neutron stars would be detectable by satellite x-ray telescopes, such as the proposed Advanced X-ray Astrophysics Facility (AXAF) (likely to be launched in 1991), through the enhancement of the cooling rates via neutrino emission. More generally, the role of non-nucleonic degrees of freedom in nuclear matter is in need of further exploration.

Ultra-High Energy Densities

Ultrarelativistic nucleus-nucleus collisions offer the opportunity of producing high energy-density matter in a controlled laboratory environment, going well beyond the possibilities for study made available by natural laboratories, such as neutron stars, cosmic rays, and the early universe, and providing information complementary to that gained from very energetic scatterings of individual nucleons. With increasing incident energy in a head-on heavy-ion collision the nuclei at first transfer increasing amounts of energy to each other, producing an increasingly compressed and energetic central fireball. Theoretical estimates indicate that the energy densities achievable in collisions of heavy nuclei such as uranium at such energies are up to ~10 times those of ordinary nuclear matter. More importantly, in this regime maximum baryon density is expected. As the bombarding energy is further increased effects of transparency of nuclear matter set in, and the two nuclei begin to pass through each other, leaving highly excited and compressed remnants, and filling the space between them with a "firetube" of hot matter with relatively low baryon content. These two cases are illustrated in figure II.9-B. In collisions with energies about 30 GeV/nucleon in the center-of mass, the energy densities produced in both the nuclear regions and the central firetube can be at least 10-20 times that of ordinary nuclear matter. The energy densities in these situations are sufficient, by theoretical estimates, to produce a quark-gluon plasma. It is worth stressing that such collisions present a range of different physical systems simultaneously, from the nuclear fragmentation regions in which the initial target and projectile nuclei are broken up, with high baryon density, to the central region with negligibly small baryon density. The plasma that would be produced in the central region has the unusual feature of closely duplicating conditions present in the first few microseconds of the early universe. One should also note that to achieve such energy densities requires using heavy ions, in which many individual nucleon-nucleon collisions take place in the collision volume of many tens and perhaps hundreds of cubic fermis.

The production and detection of a quark-gluon plasma in ultrarelativistic heavy-ion collisions would not only be a remarkable achievement in itself, but by enabling one to study quantum chromodynamics (QCD) over distance scales as large as 5-10 fm it would make possible the study of fundamental aspects of QCD and confinement unattainable in few-hadron experiments. The deconfinement transition is expected, from numerical computations of the properties of QCD systems as well as other more phenomenological estimates, to take place when the energy density reaches $\sim$0.5-2 GeV/fm^3, some 3-10 times that of nuclei at rest. Such a transition may be first order, with a large latent heat, and with quite dramatic changes in the properties of matter. A second "chiral-symmetry" restoring transition, associated with the underlying mathematical symmetry, is also expected at somewhat higher energy density or perhaps coincident with the deconfinement transition. Such a transition would be heralded by the quarks behaving as massless objects, and low mass pion-like particles no longer being possible excitations in the system.

A further possible outcome of relativistic heavy-ion collisions is the production of stable or metastable exotic composite particles ranging from nuclei far from the valley of beta-stability, to high-density isomers, to quark "droplets" of enhanced strangeness, to objects with unusual stability arising from underlying mathematical or topological structure. Such unusual objects may be

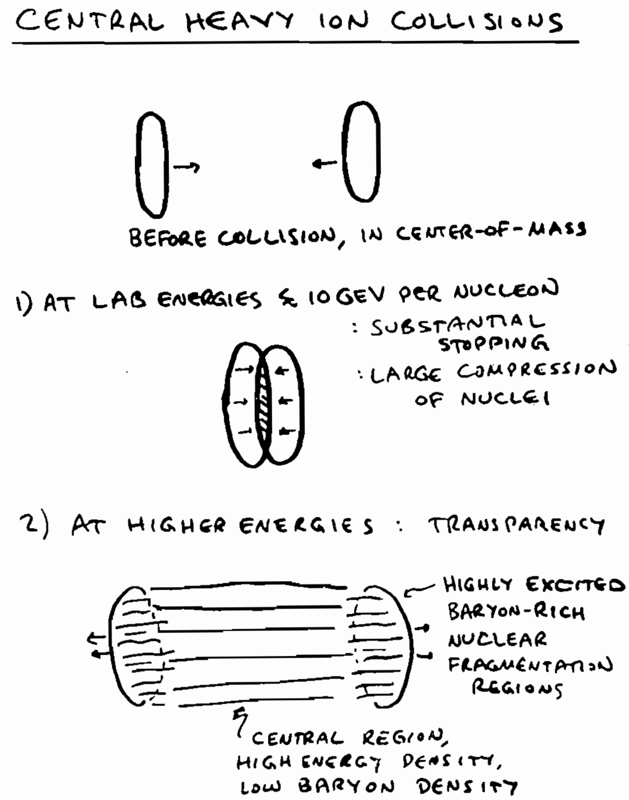

Fig. II.9-B. The possible outcome of collisions of heavy-ions at different energies. At lower energies (1) the two nuclei, in a central collision, stop each other producing a high degree of compression, while at higher energies (2), the nuclei pass through and highly excite each other, while at the same time leaving a highly-excited central region composed of matter similar to that in the early universe.

related to the observed "Centauro" and "Chiron" cosmic-ray events, and the reported phenomenon of nuclear states with apparently anomalously short mean free paths in matter (anomalons).

Investigations Feasible with Current Probes

Needed investigations, preliminary to embarking on a full-scale experimental study of nuclear and quark matter by relativistic heavy-ion collisions, include experiments that can tell us further the dependence of the energy and baryon densities achieved, on nuclear size and energy. Cosmic ray experiments, such as by the Japanese American Cooperative Emulsion Experiment (JACEE) collaboration, are an excellent source of preliminary information on the gross properties of nucleus-nucleus collisions, indicating that energy densities on the order of 3 GeV/fm^3 are achievable in heavy-ion collisions (an order of magnitude beyond that produced in current heavy-ion accelerators). Such experiments may also provide data on fluctuations, needed for planning accelerator experiments. A continued effort in studying high-energy cosmic-ray collisions, including balloon and space (e.g., Space Shuttle) flights of detectors will be valuable.

Also important are continuing systematic studies of scattering of protons (as well as pions and other hadrons) with large nuclei. Such experiments, interpreted in conjunction with proton-proton and antiproton-proton scattering experiments, can reveal coordinated or collective behavior of nuclear matter in stopping nucleons, a question of large practical as well as intrinsic interest. Detailed studies of regions of energy and momentum transfer in proton-nucleus collisions not accessible in proton-proton collisions would be very desirable. From proton- and pion-nucleus experiments one will be able to extrapolate to the energy densities and particle multiplicities that will be encountered in nucleus-nuclear collisions. The α-α scattering experiments at the CERN Intersecting Storage Rings (ISR) also provide a first look at the physics of collisions of ultrarelativistic nuclei.

Interactions of anti-nucleons with nuclei are an as yet little explored probe of nuclear matter; annihilation processes can tell us, for example, how nuclei respond to a localized deposition of a large amount of energy.

Much theoretical work is also needed to develop appropriate calculational methods for dealing with relativistic nuclear collisions. In particular, the regimes of validity of nuclear cascade calculations and hydrodynamic descriptions need clearer delineation; a greater understanding of dissipative mechanisms is called for. It is also crucial to learn how the degree of thermalization after a collision depends on the collision parameters, such as nuclear size, energy and impact parameter.

Further theoretical and experimental effort will be required to recognize fully the signals in ultrarelativistic heavy-ion collisions that a deconfined state has been achieved in the collision volume. Measurement of the gross properties of the collision will be needed to determine the energy densities and entropies achieved in early stages of the collision. Correlations of the mean momenta of fragments perpendicular to the collision axis with the mean multiplicities can signal a thermodynamic phase transition. Measurements of nuclear size dependences and fluctuations from the average event are particularly helpful for discriminating between signals arising from a quark-gluon plasma, and backgrounds from pre-equilibrium, or final state dynamics.

Leptons and photons produced in the plasma have long mean free paths, and escape with little interaction. They are also produced most copiously in the early stages of the collision when the plasma is hottest and most dense, and are thus a clean probe of the plasma dynamics. While their signal may be obscured by various backgrounds, the nuclear size and energy dependence should resolve the signal for a plasma from these backgrounds.

Strange-particle production may also provide a signal for a plasma. The equilibrium configuration of a high temperature plasma contains up, down, and strange quark pairs. As such quarks combine into hadrons, a large number of strange baryons and mesons are produced. If there is time and energy for such a configuration of quarks to form, and if the distribution of hadrons survives the expansion and cooling of the plasma, strange hadrons would be copiously produced.

Present heavy-ion accelerators, operating at laboratory energies up to $\sim$2 GeV per nucleon, are providing extensive information on collective behavior and dynamic correlations in heavy-ion collisions. However the energies and particle densities reached are well below the expected thresholds for quark-gluon plasma formation. Injection of ions into existing particle accelerators, such as at CERN, can carry out fixed target experiments in the relatively near future. Such experiments would be at a somewhat higher energy than that of the Bevalac and would begin to uncover further interesting physics of nuclear matter. However, exploration of the qualitatively new physics of nuclear matter will require going to higher energies and using beams throughout the periodic table; this can only be achieved in an ultrarelativistic heavy-ion collider.

II.10 NUCLEI AND THE UNIVERSE

How do the properties of nuclei, of nuclear matter, and of nuclear processes determine the structure and the evolution of stars and affect our understanding of the large-scale structure of the universe?

Nuclear processes and the properties of nuclear matter play a fundamental role in determining the basic structure and evolution of the Universe. Nuclear reactions are responsible for the synthesis of all the chemical elements, are the primary sources of energy driving the evolution of stars, and are, for example, the source of our sun's energy through the fusion of hydrogen into helium. In the near future, we anticipate the production of conditions which existed in the early instants of the big bang, in the collision of ultrarelativistic heavy ions.

The interaction between nuclear physics and astrophysics was initiated by the work of Bethe and has evolved from an interface between two previously isolated areas of science into the field of nuclear astrophysics, in which both disciplines are combined in the study of important and interesting physics problems. The 1983 Nobel Prize in physics was shared by William Fowler in recognition of his pioneering insights and the key importance of the developments in this field. The astrophysical interest frequently motivates the study of questions which have important nuclear physics content, while nuclear physics discoveries often have profound astrophysical implications. The nucleus provides a microscopic laboratory to study the basic elements responsible for the structure and evolution of the macroscopic Universe. Areas of research where present results point towards important opportunities in the coming decade include the study of high-density nuclear matter in supernova collapse and neutron stars, the study of beta-decay strength functions for decays involving highly excited states in nuclei far from stability, nuclear reactions involving short-lived radioactive nuclei, and the solar neutrino problem.

Creation of the Light Elements

While most of the chemical elements in nature are synthesized in stars, those lighter than carbon are mostly too fragile to survive the conditions found in stellar cores and must have been created at a cooler, or more tenuous, site. A simple description, involving creation in the big bang expansion, and in spallation reactions induced by the galactic cosmic rays, accounts for the abundances of these light elements in an elegant and economic fashion. This description also yields constraints on cosmology, as is illustrated in figure II.10-A, as well as on nuclear and particle physics. Measurements of nuclear spallation cross sections at cosmic ray energies have recently shown that the yields of ^{6}Li, ^{9}Be, ^{10}Be and ^{11}B can be accounted for as the by-products of galactic cosmic rays interacting with the nuclei of heavier elements, such as ^{12}C. The remaining light isotopes ^{2}H, ^{3}He, ^{4}He, and ^{7}Li are the *only* ones whose present abundances are relics of the big bang and must therefore reflect conditions at that time. Their absolute and relative yields are a function of the universal baryonic density, so that one can infer from their yields a value of the present density which is insufficient by itself to close the Universe by about a factor of ten.

Supernovae, Neutron Stars, and Nuclear Properties

One outstanding problem in astrophysics is to understand the late stages of evolution of more massive stars, and the physics of their eventual gravitational collapse, their subsequent explosion as supernovae and the formation of neutron stars (highly compressed stars with masses about that of the Sun but with radii of only about 10 km) or of black holes. After massive stars exhaust their nuclear fuel they can no longer resist the inward forces of gravity; their collapse and subsequent rebound is intimately tied to the microscopic properties of the nuclei in their interior. The collapse is initiated by the heating and dissociation of nuclei, and during the collapse the nuclei rebuild into much heavier, more neutron-rich species than are normally found in stars. An exotic aspect of this phase is that neutrinos produced by the capture of electrons in nuclei become trapped in the collapsing core as a consequence of the neutral-current weak interaction between neutrinos and nucleons. This trapping then inhibits further electron captures. The collapse is halted as the nuclei become crushed together, sending out huge pressure waves which form into a very energetic outward-moving shock wave which is believed to be responsible for the ejection of the outer mantle and envelope of the star. The remaining matter condenses rapidly into a neutron star, or if too massive, into a black hole.

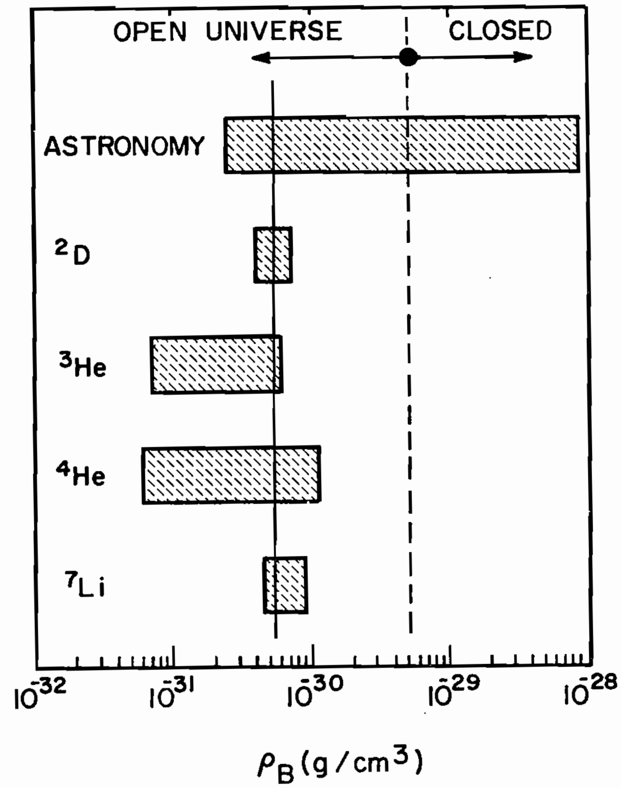

Fig. II.10-A. As determined by nuclear abundances, ours is an "open universe." The fraction of mass that is in the form of very light nuclei is a good measure of the universal density of baryons ρ_B. The values determined from various abundances are shown as shaded bars, the solid vertical line is the best fit to these. The dashed line is the dividing line between the density at which the universe would be closed upon itself, or open.

Many aspects of this scenario are in need of deeper understanding. The success of the shock in blowing off the outer layers depends critically on the temperatures, densities, and composition of the star before collapse begins; recent work has shown that these features are in turn highly sensitive to the rates of electron capture by the various nuclei present. Pre-collapse models employing refined electron capture rates are presently being constructed. The determination of the nuclei that are present during collapse requires knowledge, on the one hand, of the level densities and heat capacity of nuclei, and on the other, of the equation of state of hot nuclear matter and the properties of hot nuclear surfaces. As the nuclei are crushed together they form an extended nuclear-matter liquid, and the properties of this nuclear liquid (as it is compressed several-fold) determine the amount of energy transmitted to the outer layers. Although information on the compressibility of nuclear matter has been obtained from studies of the breathing modes of heavy nuclei, in the case of stellar collapse the matter is compressed to extreme conditions where measurements do not presently exist. Data on the behavior of nuclear matter under these conditions can be obtained from laboratory measurements of relativistic heavy-ion collisions. The dissociation of nuclei as the shock wave passes by them is a critical source of dissipation of the shock; present studies of heavy-ion collisions should further illuminate this process.

The shock wave forms outside a central core containing about one solar mass so that the collapse of a massive star leaves behind a highly condensed remnant. If the mass of the remnant is less than about two and a half times that of the sun, the remnant will rapidly evolve into a neutron star; but if a greater mass is left behind the remnant will instead collapse to a black hole. To date, well over 300 neutron stars have been identified, as pulsars and compact x-ray sources, in our neighborhood of the galaxy, and black holes may also have been detected. A knowledge of the nuclear equation of state at high densities is essential to understand these properties of neutron stars and to determine accurately their upper critical mass. Several unusual states of matter may occur at such densities, as is discussed in Sec. II.9, and further studies are needed of the properties of matter at high densities through heavy-ion collisions. Quite generally, the study of supernovae and neutron stars has opened up a new area of nuclear physics, and motivated both theoretical and experimental nuclear research which has led to a deeper understanding of the rich properties of nuclei and nuclear matter.

Two specific weak-interaction processes are of interest in studying the behavior of nuclei under extreme conditions: the beta decay of very neutron-rich nuclei near the neutron drip line and, as mentioned, electron capture at high electron densities and temperatures. Recent work on the beta decay of nuclei far from stability has led to improved calculations of the role of highly excited states of the daughter nuclei in terms of an average energy-dependent strength function. Beta-decay half lives are very sensitive to this quantity, and the recent calculations are in considerably better agreement with measured data than are earlier ones. These half lives are crucial for calculating the production of heavy elements in supernovae, and the refined values yield relative nuclear mass abundances that match observed values extremely well. In addition, the age of the universe obtained by using these half lives and the updated beta-delayed fission rates of heavy elements is now estimated to be about 20×10^9 years, consistent with the largest ages determined from astronomical measurements of the rate of expansion of the universe.

The Sun and the Solar Neutrino Question

Our understanding of hydrogen burning in the sun implies a detailed sequence of processes, with quantitative predictions of the number of neutrinos that should be produced and seen on earth. Since the sun is transparent to neutrinos, solar neutrino experiments sample the entire solar volume. Over the past 15 years, data have been collected from a solar neutrino experiment using ^{37}Cl as the detecting nucleus. There is a persistent discrepancy between the theoretical predictions and the experimental results: only one quarter the expected number of neutrinos is detected. This measurement is fundamental to our understanding of stellar structure, and therefore, the discrepancy has led to critical reexamination of the solar physics, nuclear physics, and particle physics components involved. The interpretation of the experimental result is particularly difficult because the ^{37}Cl detector is primarily sensitive to the high energy ^{8}B neutrinos, which are only produced by a weak (0.01%) branch of the hydrogen burning proton-proton chain. This detector is completely insensitive to the critical p-p neutrinos which comprise 90% of the flux. From another point of view this selective sensitivity for the ^{8}B neutrinos is an important *advantage* since it makes possible the sensitive determination of the conditions at the center of the sun; measurements of the p-p neutrino flux are relatively insensitive to those conditions.

A number of questions have been raised concerning the standard solar model and its predictions—questions involving the optical opacities, the determination of the relevant nuclear cross sections, the distribution of heavy elements and angular momentum in the solar interior, and the possibility of neutrino oscillations. Perhaps the least well understood are the questions on the macroscopic features of the solar interior, opacities and mixing involving angular momentum. But since at the present time no real solution has been found and since the understanding of our sun is a vital problem, the next logical step in solar physics seems to be the design and construction of alternative neutrino detectors with different sensitivities to the predicted solar neutrino spectrum and the solar interior; these will provide additional independent constraints on our models and the understanding of our sun.

Studies are currently under way to examine the practical feasibility of several proposed radiochemical solar neutrino detectors. Of these the ^{71}Ga detector, based on the ^{71}Ga(ν, e$^-$)^{71}Ge reaction, has been developed the furthest. This detector is sensitive primarily to the p-p neutrinos; most of the ^{71}Ge would be produced by such neutrinos and less than 2% by the ^{8}B neutrinos. Since the flux of p-p neutrinos is determined only by the average solar luminosity and is quite insensitive to the detailed conditions in the solar interior, the ^{71}Ga detector would provide (independent of the details of a solar model) tests of fundamental questions regarding neutrino oscillations and whether or not the Sun is even currently generating energy via nuclear fusion. A pilot project using 1.8 tons of gallium has shown that the recovery of ^{71}Ge is efficient to >95%. A full-scale detector will require 50 tons of gallium, and at the moment its fate is constrained by the high cost of the gallium.

Studies are currently also under way to examine the feasibility of several other solar neutrino detectors. None of them are sensitive to the p-p neutrinos, but they would have different sensitivities to the higher energy parts of the solar neutrino spectrum or average over different production time scales. For example, it has been suggested that suitably shielded geological deposits of ^{98}Mo could be used (because of the long half life of ^{98}Tc) to study the time-integrated solar neutrino flux over the past $\sim 10^6$ years. One might then determine whether the sun is in a transient nonequilibrium phase. A project to measure $\nu + e^-$ scattering in a liquid argon counter is also under development. Such a detector would also provide *directional* information, as well as time and energy, but would be sensitive only to the high-energy neutrinos (^{8}B).

The solar neutrino problem raises a number of important scientific questions, and has to be pursued. At the present time scientific grounds dictate the choice for the next neutrino detector to be ^{71}Ga, on the basis of its demonstrated feasibility and recovery efficiency, but options for alternate detector schemes which could help resolve the present problem should be explored further.

Rapid Proton Capture

In other areas of stellar energy generation and nucleosynthesis, recent interest has been concentrated on hydrogen burning via the MgAl cycle (as possibly in red giants) or the hot CNO cycle and the rapid proton capture process (on the surfaces of white dwarfs). This is illustrated in figure II.10-B. The interest in the MgAl cycle was triggered by the discovery of excess ^{26}Mg in aluminum-rich minerals in meteorites, suggesting that they were originally accreted onto the meteorite as ^{26}Al (with a half life of 700,000 years) produced just before the formation of the solar system. The hot CNO cycle and the rapid proton capture process both involve capture such as ^{13}N(p,γ)^{14}O and ^{15}O(α,γ)^{19}Ne on time scales short compared to beta-decay lifetimes. The study of such reactions presents clear technical challenges, requiring the development of intense secondary beams of radioactive nuclei. At least four different methods have been proposed to produce these beams, and these proposals are still in various stages of design and development. The construction of a full scale facility for short-lived radioactive beams will provide both the information necessary for the understanding of these astrophysical processes as well as the means for studying nuclear reactions that would otherwise be inaccessible.

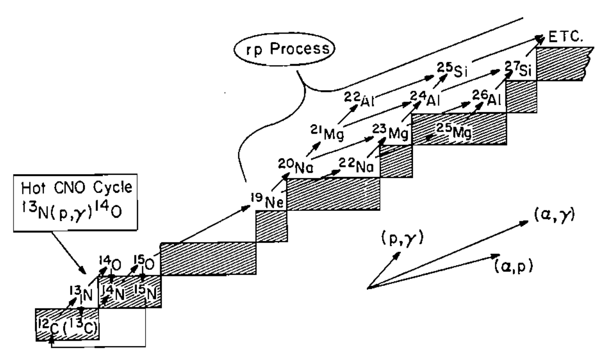

Fig. II.10-B. The path of nuclear reactions in "rapid proton capture" followed in the formation of elements on the surface of white dwarf stars.

III. APPLICATIONS

III.1 CONNECTIONS OF NUCLEAR SCIENCE WITH OTHER FIELDS OF BASIC RESEARCH

The world we live in is made of atoms, most of whose mass is in the atomic nucleus. The major sources of energy in our world are the end result of nuclear processes in the sun and the stars. So it is that nuclear science has common frontiers with other basic sciences, and that the tools and concepts of nuclear physics have found wide application in other disciplines. The understanding of nuclear forces, structure and interactions, the heart of nuclear science, has profound implications for many branches of physics and chemistry. The machinery of nuclear science: the accelerators, the radioactive species, and the detectors, developed and built specifically for nuclear science, have provided tools and methods applicable to many diverse areas of research from studies of fundamental biological processes, to atomic physics, geology, or astrophysics. The overlap with elementary particle physics in the developments in the quark-gluon structure of QCD and the theory of electroweak interactions is too profoundly interwoven into the fabric of our science to be separately discussed in this section, as is much of nuclear astrophysics, which was discussed in Sec. II.10.

Throughout the last half century radioactive materials as well as beams of particles have been applied to studies in most areas of modern scientific investigation. Radioactive tracer techniques, for example, are used regularly in basic research in chemistry, biology, medicine and metallurgy to name just a few sciences. So too, the use of particle and gamma-ray beams and particle detectors is commonly found within many scientific disciplines. The production and characterization of the radioactivities, the properties of the fundamental interactions of the beams with matter, the development of the detectors and of particle accelerators are all products of nuclear science.

The myriad applications of this knowledge and these techniques cannot be described here. In this chapter we present some of the more exciting new developments on the interface areas with other sciences (some contributions from nuclear science to applied technology areas appear in the next section). The selection is intended to demonstrate the ongoing connections of nuclear science and scientists to other sciences by presenting a few relatively new techniques and fields of study made possible as a result of recent advances or as a result of the suitability of the accelerator equipment and techniques developed in nuclear laboratories.

That nuclear science has profited immeasurably from advances in other sciences—chemistry, solid state, mathematics—pure and applied—to name a few is, of course, understood. In large measure the *interface* areas are two-way communications of enormous benefit to the sciences involved; they are also frequently the areas of greatest excitement and promise. Typical of the two-way benefit is the magnetic interaction of nuclei in crystals discussed below, whose understanding allows unique measurements of nuclear properties as well as the properties of solids.

A. CONDENSED MATTER PHYSICS

Nuclear physics has a deep intellectual unity and interrelation with condensed matter physics, in the varied physical phenomena in each of the fields that arise from the cooperative action of large numbers of interacting particles, in the mathematical techniques and concepts used to describe such phenomena, and in the extensive practical uses of nuclear techniques and concepts in condensed matter research.

Through both fields runs the concept of "dynamical symmetry breaking," in which nuclei as well as solids and liquids often prefer states that are less symmetric, and richer in structure, than might have been expected. The tendency of nuclei to deform spontaneously away from spherical shape is akin to the formation in a magnet, by the alignment of the fields of the individual particles, of a large scale magnetic field which spontaneously chooses one spatial orientation from among many equivalent ones. Closely related also are the phenomena of superconductivity, in which many metals and alloys at low temperatures lose all resistance to flow of electricity, and pairing phenomena in nuclei, which cause the inner parts of certain nuclei to remain stationary when the rest of the nucleus rotates; underlying these phenomena is the spontaneous breaking of a deep mathematical "phase" symmetry. Techniques for describing interacting particles in nuclei were applied in the development of the theory of superconductivity, and in turn this theory was used to explain nuclear pairing. Recent experiments on rapidly rotating nuclei are exploring phenomena that in many ways parallel the behavior of superconducting materials in a strong magnetic field. Similar pairing effects exist in liquid ^{3}He, and possibly in the nuclear matter of neutron stars.

The interplay between the two fields has been strikingly illustrated in recent studies on the properties of nuclear matter and of helium liquids. Motivated by the desire to derive the properties of nuclear matter in terms of the basic forces between nucleons, theorists have developed very accurate calculational techniques, which have been tested on liquid helium systems, and have yielded greatly improved *ab initio* calculations of the properties of the helium liquids themselves. Furthermore, working in common on both systems they have realized that the behavior of particle "effective" masses in nuclei and that of the heat capacity of liquid ^{3}He involve the same underlying physics, and have exploited this unity to make significant advances on both problems.

At present many further concepts of condensed matter physics, such as energy dissipation and hydrodynamics, are being applied in nuclear physics. Particularly noteworthy are ongoing and planned attempts to search for phase transitions of nuclear matter, such as that from liquid to gas, or the deconfinement or unbinding of quarks—the most elementary building blocks of matter known. Such studies, on the one hand, allow exploration of these phenomena over a range of system sizes and other features not readily available to condensed matter experimentalists, while on the other hand the insights they can give into the question of the fundamental structure of matter has important potential consequences for many branches of physics.

Nuclei are also ideal microscopic probes of the environment in which they find themselves in condensed matter. The ubiquitous hyperfine interaction between nuclei and their host structure results from the interplay between the nuclear moments and the electronic configurations as influenced by crystal structure and dynamics. Short and long range interactions between like ions, or between impurities and hosts are of primary importance, for example, in the preparation of new magnetic compounds and alloys or high ionic conductivity materials required for batteries. The distinct signal produced in nuclear decays allows the study of the behavior of single atoms isolated in matrices. Defects and radiation damage in metals, semiconductors and insulators have been extensively studied.

The hyperfine interaction techniques have been applied to the study of almost every type of magnetic system, to phase transitions and to critical phenomena. Recent studies have pushed the frontiers to the investigation of dynamics of surfaces and to the interaction of fast ions with magnetic solids. The transmission or blocking of fast ions in crystalline channels has greatly extended the intellectual overlap between nuclear physics and condensed matter physics. Channeling and blocking in crystals have yielded detailed descriptions of impurity location, surface conditions, radiation damage, interatomic potentials and electron densities in crystals and have led to direct measurements of the shortest time intervals (attoseconds or 10^{-18} sec and below) yet attained in nuclear physics.

Surface Physics

The surface structure and dynamics of materials can now be probed by new very sensitive microscopic techniques, Mössbauer spectroscopy, perturbed angular correlations and deposition or implantation of polarized heavy ions. The measurement of the electric and magnetic interactions between atoms at surfaces or interfaces is an essential element in the understanding of the chemical absorption processes, and of diffusion and alloying mechanisms that are involved in the preparation of materials.

Perturbed angular correlation techniques have recently been used most effectively to test electric field gradients at the surface of indium metal. It was found that the surface electric field gradient is four times larger than the bulk value and is perpendicular to the surface.

The magnetic properties of the interface between metallic iron and silver have been studied by Mössbauer spectroscopy. The surface magnetic field is smaller than the bulk value at room temperature, but larger at 4°K. The variation of the magnetic hyperfine interaction as a function of depth has been examined for the first time by such techniques, and it was shown that the field reaches the bulk value in only two or three atomic layers.

Extensive theoretical work is in progress to explain the exchange interactions and structural variations that operate in these quasi-two-dimensional systems; the techniques are in their infancy, but as they are uniquely suited to an interesting area of investigation, they are being pursued actively.

Magnetic and Electric Interactions in Solids

Nuclear techniques of angular correlations, Mössbauer spectroscopy, and μ-meson spin rotation (μSR) are very powerful tools for the determination of the magnitude, direction and origin of magnetic and electric interactions in solids. An example is shown in figure III.1-A. Recent technological developments including the extension of pulsed-beam techniques, the discovery of the induced polarization of ions emerging from tilted foils and the very strong magnetic interactions acting on swift ions traversing ferromagnets shown in figure III.1-B, have opened new areas of research. The nucleus provides a very sensitive probe in the investigation of static and dynamic properties of solids, and of ion-solid and ion-surface interactions.

The interest in the μSR technique lies in the fact that a spin-polarized beam of positive or negative muons can be implanted in almost any sample. The time evolution of the polarization then yields information about the muon's local magnetic environment, either at an interstitial or a lattice site in a crystal. As a light interstitial particle, the muon is used to study localization and diffusion phenomena for a particle with mass intermediate between those of the proton which is about ten times heavier, and the electron which is two hundred times lighter. Considering the muon as an ultra light isotope of hydrogen allows one to study non-classical diffusion phenomena unseen in previous experiments using hydrogen.

Finally, muonium (μ^+e^- atoms) centers can be compared with hydrogen in semiconductors, muonium and hydrogen reaction rates can be compared in liquids and gases, and unique information is obtained when hydrogen solubility is low or where no hydrogen paramagnetic states are seen.

Channeling, Blocking and Steering of Charged Particles in Single Crystals

It has been nearly 20 years since the effect of crystal blocking of charged particles was first discovered. It has been applied to the measurement of ultra-short time intervals, to try to determine elementary-particle lifetimes, down to perhaps 10^{-20} sec and even less. An interesting by-product of these experiments was the discovery that by

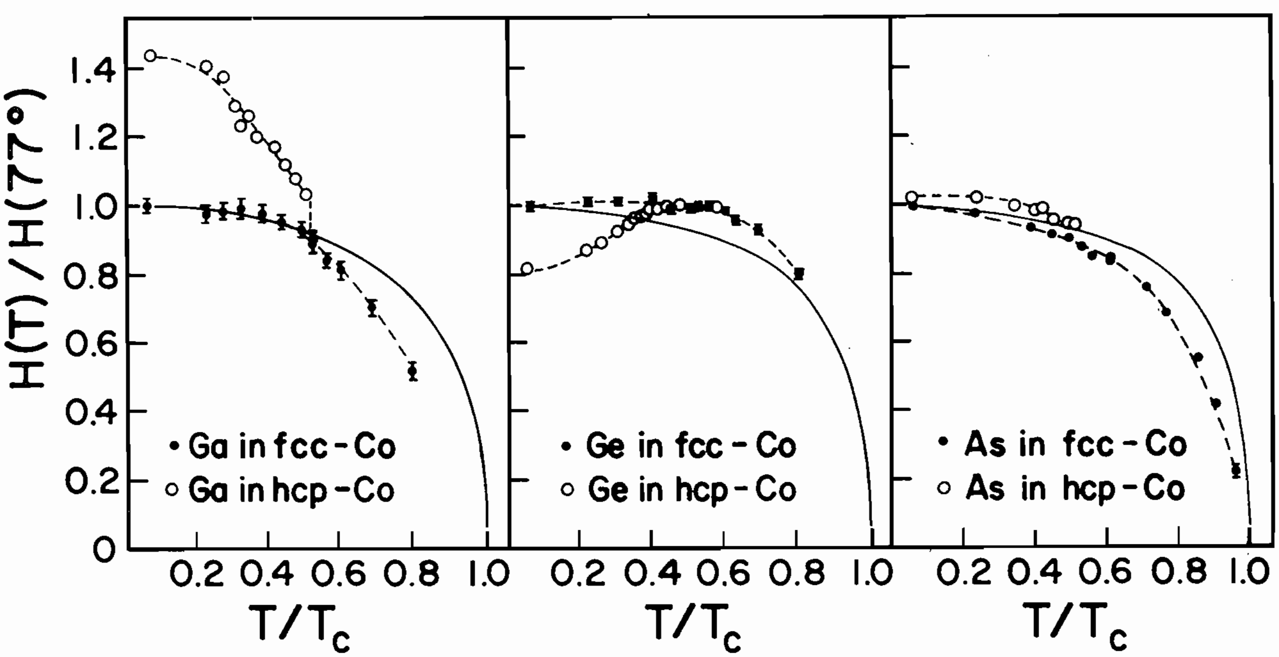

Fig. III.1-A. Measurements of the anomalous magnetic hyperfine field at various substitutional impurities in various (face-centered cubic and hexagonal closed packed) single cobalt crystals. Gallium, germanium and arsenic excited nuclei are implanted using high energy beams and the method of perturbed angular correlations afford the field measurement. The normal field variation as a function of temperature for the host atom (cobalt) is shown as the solid curve. The implanted ions exhibit anomalous fields. These measurements are important for the understanding of material modifications.

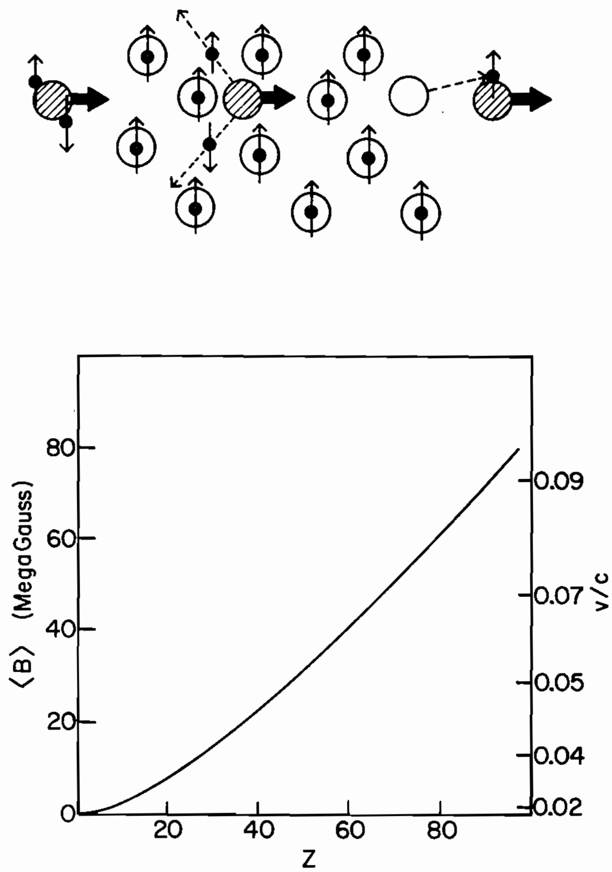

Fig. III.1-B. A schematic representation of a fast ionized atom (shaded circle) traversing a magnetized ferromagnetic material at high speed and exchanging polarized electrons with the medium, is shown on top. The preferential filling of vacancies with electrons of one spin orientation causes very large transient magnetic fields $< B >$ at the nucleus of these atoms. The data for ions with a mean effective charge $< q > \approx 0.4\,Z$ traversing magnetized ferromagnetic iron at a speed v, in units of v/c, is plotted below.

bending the crystal target mechanically, the charged particles could be made to follow the curvature even at the highest energies—hundreds of GeV—through angles which would require huge superconducting magnets to obtain equivalent deflections. Recent studies on the photons generated by channeled electron or positron beams have demonstrated that there exist exciting possibilities for the production of intense, bright sources of monochromatic x-rays or γ-rays that are tunable in energy.

B. ATOMIC PHYSICS

Ever since the discovery of the isotope effect in optical spectra, nuclei have played an important role in atomic spectroscopy; and in general, much unique information on the properties of nuclei has been extracted from nuclear effects on atomic phenomena. Recently, however, the reverse has happened, as accelerators built for nuclear physics research provide intense beams of ions whose state of ionization and excitation can be varied readily. At these energies two atomic nuclei come very close together and transient atomic configurations not encountered in ordinary systems are formed. Atomic structure calculations can be tested in unique ways on the observed systems. Both experiments and calculations have a bearing on the description of the high temperature stellar environments (as well as those encountered in fusion plasmas for instance in a Tokamak reactor). The production of highly stripped heavy atoms ($Z > 18$) with only one or two bound electrons remaining (hydrogen or helium-like atoms), have afforded systems for study of fundamental atomic physics such as the Lamb shift.

More complicated, but extremely interesting phenomena have recently been accessible to experimentation. The effects of nuclear resonances on K-shell ionization, the details of electron capture by relativistic heavy ions interacting with solid targets, the observation of spontaneous positron creation in superheavy quasi-atoms, and the search for x-rays from superheavy collision systems are only a few of the many problems in "high-energy" atomic physics which have been examined in nuclear physics laboratories and which are controlled by the nuclear reaction rates and energies.

One spectacular example is in collisions between very heavy ionized nuclei, where, for a short time a pseudo-atom with holes in the continuum of negative energy states exists. The filling of these holes results in the emission of positrons, which have indeed been detected. Surprisingly, they exhibit a discrete structure superposed on the continuum spectrum. The origin of the features is not known. Speculations arise as to whether these monochromatic positron lines, which seem to exhibit a distinct collision energy dependence, are due to the formation of giant nuclear complexes or to other new physics.

Rapidly moving atoms, when passed through thin films or low pressure gas, lose much of their complement of atomic electrons. Thus atomic species with reasonably heavy nuclei can be "undressed" and have only the number of atomic electrons characteristic of much lighter atomic systems, but with a much larger positive charge on the nucleus. For example Ar or Cl ions with one electron (hydrogen-like) are produced easily at existing accelerators. Similarly, heavy elements with several tens of electrons can be produced. The study of the atomic spectra of these species both by conventional optical spectrometers and by resonance colliding beam experiments between highly stripped atoms and laser light afford the possibility of stringent tests of theoretical atomic structure calculations. The Lamb shift in one electron Cl, and more recently in He-like Ne atoms has been measured. Recent experiments to study the structures of the rather simple atomic species H^-, a proton with two electrons, have demonstrated the usefulness of the application of very high-energy (800-MeV) beams to the study of atomic excitation. This atom has "excited states" involving both electrons which are reached by photon absorption in the presence of very high electric fields. In these experiments the highly relativistic beams are passed through magnetic fields which produce very high effective electric fields up to 1.3 million V/cm. Interaction with extreme Doppler shifted laser light in a "crossed beam" experiment, allows a unique detailed study of the fundamental structure and Stark mixing of this simple atom.

Studies on the collisionally-induced dissociation of energetic molecular-ion beams have recently demonstrated in a novel way the interactions ("wake effects") between fast ions and the electron gas that resides in solid targets. Such studies also offer unique methods for determining the stereochemical structures of the molecular projectiles. When fast ions emerge from gaseous or solid targets, there is an associated spectrum of emerging electrons. Recent work on cusp electrons (which are just unbound in the projectile frame) and on emerging Rydberg atoms (where the electron is just barely bound in a high quantum state) have been very fruitful in elucidating the electronic aspects of collisions between fast ions and matter.

C. GEOLOGICAL AND COSMOLOGICAL STUDIES—ACCELERATOR MASS SPECTROMETRY

The revival of high-energy mass spectrometry of nuclides in the 10^{-15} natural abundance range has been accomplished mainly in nuclear physics research laboratories, employing counter telescopes developed for heavy-ion studies and a variety of accelerator types. Cyclotrons and linacs have been used, offering the selectivity of a resonance machine and intrinsic pulsing for time-of-flight particle identification. Tandem Van de Graaff's are widely used and offer their simplicity, economy, and ease of operation, with special advantages for certain ions such as ^{14}C.

Accelerator mass spectrometry is becoming an increasingly important part of the research program in a number of nuclear physics laboratories in the U.S. and other countries. In addition to the possible nuclear science application (so far confined to measurements of half lives, e.g., ^{32}Si and ^{44}Ti) this technique is now widely used in a number of cross-disciplinary fields including archeology, geology, and hydrology, in studies of meteorites, lake and ocean sediments, atmospheric methane, cosmic flux variations, oceanic manganese crust growth, island arc vulcanism, tektites and the growth rate of manganese nodules. Although the field is in relative infancy, the number of other probable applications is increasing rapidly. The importance of the field stems from the small sample sizes required (micrograms to milligrams) and the sensitivity of detection (10^5 to 10^7 atoms per gram in geological samples for example). Several nuclear physics tandem Van de Graaff facilities in this country are involved in the field. Not only can the techniques be used to measure long-lived radioisotopes produced by cosmic rays, but it has also been used to detect stable isotopes such as platinum and iridium in geological samples.

The detection of ^{10}Be atoms with a half-life of 1.5×10^6 years in sea sediments, polar ice, subducted crustal material in volcanic arcs, and meteorites and tektites, has shed understanding on a variety of phenomena that occur on a slow time scale. For instance, growth rate of Mn nodules containing ^{10}Be deposited on the sea floor can be determined as a function of depth and thus some understanding of the formation mechanism for the sea floor is emerging. It has been shown that subducted crustal matter is transported over thousands of years. The composition of tektites has been compared with that of terrestrial and extra-terrestrial rocks, and now it is certain that tektites are of terrestrial origin.

This technique has also been used to search (unsuccessfully) for superheavy elements in various ores. Similarly, several accelerator "mass spectroscopic" experiments with very high sensitivity to possible stable quarks have been carried out or are in progress. Finally, this technique may well offer the best way to measure the small number of atoms of long-lived radioisotopes that are produced by solar neutrinos in suitable geological samples.

III.2 Societal Applications of Nuclear Science and Instrumentation

The direct societal contributions of nuclear physics have been manifold and substantial but not always readily apparent in the complex technological world of recent decades. In fact, one can hardly walk through a hospital without seeing numerous examples of nuclear science—and nuclear scientists—at work. Nuclear energy provides 13% of our electric power, nearly every household is protected by a nuclear smoke detector, and nuclear techniques in the form of ion implantation have revolutionized the semiconductor industry. Food preservation using nuclear techniques offers the possibility of alleviating nutritional problems worldwide, and nuclear defense and the enforcement of nuclear non-proliferation are major elements of our nation's security policy.

A. Nuclear Medicine

The development of nuclear medicine has seen nuclear scientists, physicians, chemists and computer scientists join together in a highly successful attack on some of the most pervasive health problems facing society. In a recent study by the National Research Council, Dr. Richard C. Reba, from the George Washington University Medical Center, stated that

> *"the solution of almost every serious medical problem in patients sick enough to require hospitalization may be facilitated to some degree by a nuclear medicine study."*

Diseases are diagnosed and their treatment monitored with radioactive tracer techniques, and nuclear accelerators and radioisotopes play important therapeutic roles. Radioisotope tracer technology is also important in related health studies involving nutrition, food science, metallobiochemistry and environmental toxicology.

A recent study by the National Research Council has estimated that 5-15 million *in vivo* nuclear medicine procedures were performed in the United States during 1980. A typical diagnostic nuclear medicine procedure involves intravenous administration to the patient of a tissue-specific "radiopharmaceutical" agent, containing a small amount of radioactivity. The gamma-ray emissions, which reflect the tissue distribution of the agent, are recorded by radiation detectors positioned about the patient. These radiopharmaceuticals are designed for selective uptake in a particular organ, region or type of tissue. The detected gamma-rays thus provide a detailed image of the region of interest. Evaluation of the image by a physician specialized in nuclear medicine can reveal abnormalities and lead to more complete diagnoses than might otherwise be possible. The goal in these studies is to evaluate the differences in tissue distribution of radioactivity between normal and diseased tissue. Very recent work on accelerator produced ^{18}F labelled dopamine and on-line PET scans have made possible real time evaluation, for the first time, of the areas in both normal and abnormal human brains engaged in various tasks. In addition, the rates of tissue uptake or loss of radioactivity can be measured with these techniques and differences detected between normal and diseased tissue. Thus, nuclear medicine techniques uniquely measure tissue function and anatomical and structural properties. The principal characteristic of procedures in nuclear medicine is that they are "non-invasive" and require only the intravenous administration of small amounts of radioactive agents; there is generally no trauma, discomfort or danger to the patient. Because of the important clinical information these inexpensive tests can provide, annual sales of radiopharmaceuticals easily exceed 100 million dollars in the U.S. alone.

Nuclear cardiology provides several striking examples of nuclear science at work. One out of every six Americans suffers from heart disease or related cardiovascular disorders, and over 70,000 deaths are reported from heart attacks in the United States each year. Preventative therapy can be of significant value, but symptoms of cardiac and arterial disease can be difficult to detect: many victims are simply unaware of their disease until it is too late for effective treatment. About a decade ago scientists realized that the element thallium, once introduced into the system, rapidly becomes selectively localized in heart muscle; the radioactive isotope thallium-201 could be an effective diagnostic tool for early detection of those diseases if a means could be found to produce the isotope inexpensively at high purity and in commercial quantities. Nuclear physicists and chemists responded to this challenge, with the result that cardiological tests using thallium-201 are now used routinely, and were administered to some 250,000 patients in 1981. A similar example involves the development of the radioactive tracer technetium-99m, the isomer of ^{99}Tc, over the last two decades. A variety of tissue-specific agents labeled with this radioisotope are important for the evaluation of brain, liver, thyroid, lung, skeletal system, kidney, heart, and hepato-biliary disease. Technetium-99m radiopharmaceuticals were used on 5 million patients in the United States in 1981 and involve annual sales of $50 million. Again quoting Dr. Reba,

> *"Clinical nuclear medicine is perhaps the best example of rapid transfer of government supported basic research to the private commercial sector and to the general public."*

Instrumentation for nuclear medicine procedures is another area where nuclear scientists have contributed to improved health care. A recent example is the development of tomographic systems in which gamma-ray emissions are detected by a series of detectors positioned around the patient. These data are reconstructed by computer systems to provide invaluable "pictures" of the patient's internal organs. Alternate techniques involve a single detector that moves around the patient to collect data from different views. In principle, these new "emission" techniques are similar to the well-known reconstruction "transmission" techniques developed for computerized axial tomographic (CAT) scanning using X-ray irradiation of the patient. Emission tomographic techniques can measure the distribution of radioisotopes that decay with the emission of single low-energy photons (e.g., technetium-99m) in a procedure known as single photon tomography. Although these techniques have been applied successfully to a variety of clinical problems and commercial instruments are available, improvements are required and offer future challenges to nuclear scientists. Methods are needed to correct for the attenuation of photons as they pass through dense tissue such as the chest region, and further improvements are needed in detection systems and computer reconstruction methods. Similar development is required in positron-emission tomography, where the tomographic reconstruction is accomplished by the coincident detection of the two photons produced by the annihilation of positrons from short-lived radioisotopes such as fluorine-18 and carbon-11. An example is shown in figure III.2-A.

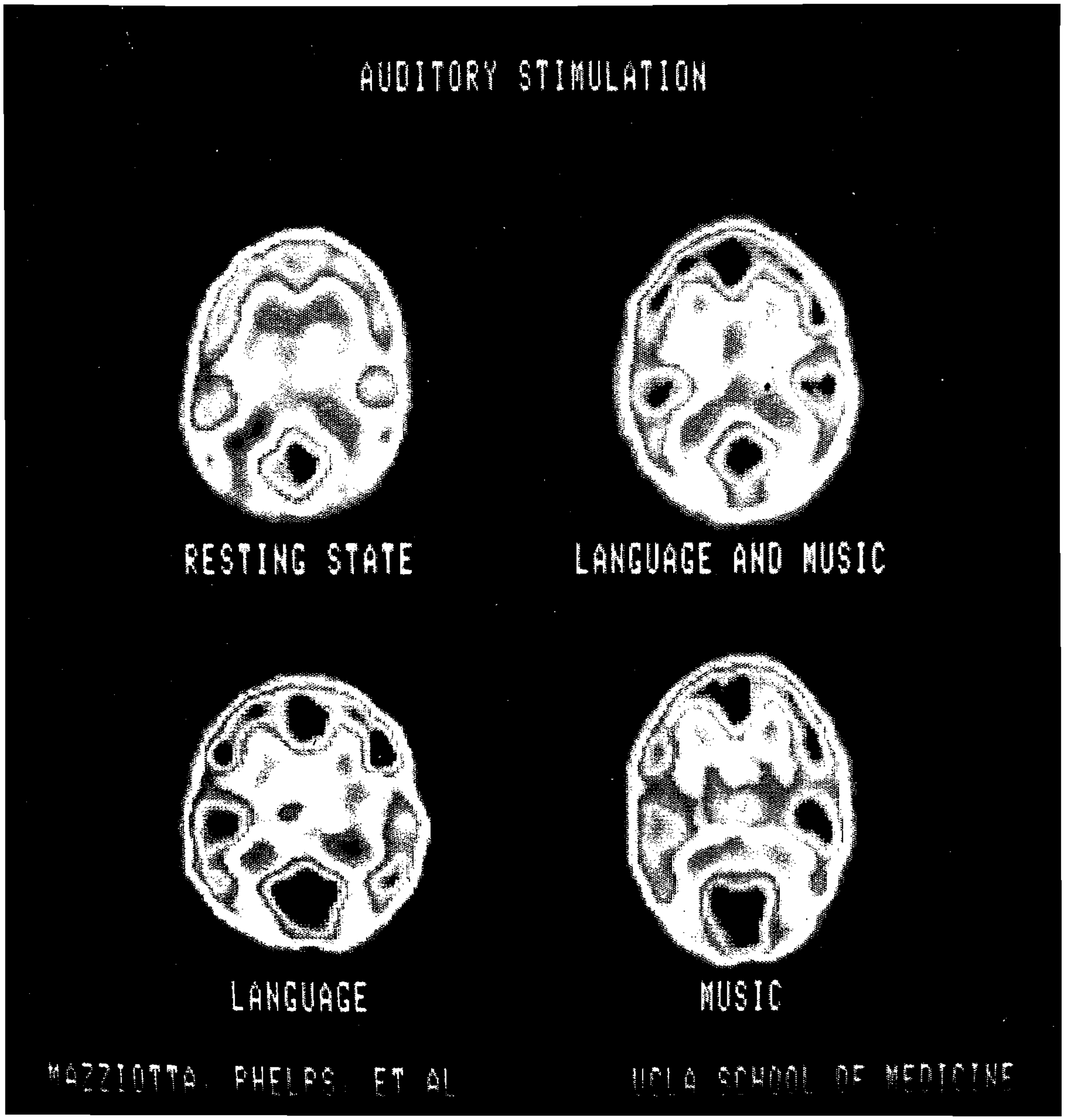

Fig. III.2-A. Radioactive nuclei that emit positrons form the basis for a technique that probes glucose metabolism in the human brain. Shown here are spatially localized responses to various forms of auditory stimulation, as measured by the positron emission tomograph (PET) technique.

The increasing use of diagnostic procedures of nuclear medicine for the evaluation of routine clinical problems has created a corresponding need for dependable, versatile medical cyclotrons for the production of short-lived positron-emitting radionuclides such as carbon-11, fluorine-18, oxygen-15 and nitrogen-13. The short half-lives, less than two hours, of these important radioisotopes require that they be produced at the clinical facility. The only commercial manufacturer of medical cyclotrons in the United States is in difficulties, and medical cyclotrons must be purchased from foreign manufacturers. This certainly represents a unique challenge for U.S. technology to develop economical, dependable and efficient cyclotrons to meet this need. In addition, there is a continuing need for improved target design, for development in cyclotron radioisotope technology, and for future development in the enrichment of stable isotopes for radioisotope production by advanced systems such as laser separation.

In addition to the pervasive role of nuclear techniques in medical diagnosis, nuclear science also plays a key role in the treatment of disease. There are approximately 800,000 new cases of cancer each year in the U.S. and about one half of these receive radiation therapy, either as the main modality or in conjunction with surgery or chemotherapy. The success rate of radiotherapy could be increased further by (1) improving dose localization, thereby sparing normal tissue and (2) improving the biological effect of the delivered dose. Optimization of either of these factors would result in an increased differential between damage to tumor tissue and damage to normal tissues. Dose localization may be improved by using nuclear charged particles heavier than electrons, e.g., protons, heavy ions and negative pions. Biological effectiveness depends, in part, on stopping power and can be increased by using neutrons, heavy ions, and pions in their stopping region. Clinical trials are underway with these nuclear particles to gauge their promise for significantly improved treatment of localized cancers via radiotherapy.

Nuclear science contributes importantly to this research. Nuclear cross-section data and models are being developed to determine the primary beam type and energy, production target material, and shielding requirements, and also to calculate dose distributions. Differences of about 5% in dose can be clinically observable due to the slim margin between tumor control and normal tissue complications, and in some cases better cross-section measurements and nuclear models will be required to permit a closer approach to safe limits with consequent improved tumor control. As in the case of diagnostic nuclear medicine, progress will depend on close collaborations among chemists, physicians and physicists, and coordinated advances in accelerator physics and instrumentation.

Gamma radiation is used in another application of nuclear science to sterilize about 30% of all medical and surgical products used in American hospitals today, and in many cases consumer goods such as talcum powder, milk cartons and cosmetics are routinely sterilized with this procedure. The radiation kills or disables microorganisms, bacteria and insects that otherwise could either spread disease or cause spoilage. Gamma-irradiated foods have been served on the Apollo 17 and space shuttle flights and gamma-treated foods are available to consumers in several countries. The World Health Organization concluded in 1981 that low radiation doses produce no adverse effects on foodstuffs. In the United States, the Food and Drug Administration has proposed new rules that would permit irradiated foods such as spices, fruits and vegetables to be sold to American consumers. Since relief organizations estimate that at least 10% of the crops that are grown in third-world countries are lost either to spoilage or to insects, food preservation via gamma-irradiation may prove to be a significant factor in reducing hunger on a worldwide basis.

Very recent work on the corrosion and wear of surgical alloys used for devices such as artificial hip-joints provides one final example of health benefits made possible by nuclear science. Each year in the United States more than 75,000 total hip joint replacement (THR) operations are performed. This involves surgical implantation of an alloy "ball" working inside a polyethylene "socket." There are several problems associated with this procedure. First, the rubbing wear of this ball and socket in the presence of corrosive body fluids can eventually lead to a poor fit and the failure of the assembly. Second, metallic flotsam is released to the body and can poison and inflame it, leading to undesirable histological effects. These effects have become increasingly serious as the average life span increases, causing many older people to have two THR's in their lifetime. Using ion source and accelerator technology originally developed by nuclear physicists for basic research, materials scientists have found that the ion implantation of nitrogen into the surface of a typical surgical alloy leads to a substantial reduction of this painful problem. By implanting nitrogen over a depth of 1000 angstroms, R. A. Buchanan and J. M. Williams were able to reduce the wear corrosion by a factor of at least 400. The successful clinical application of these very new results could be of enormous benefit to patients requiring artificial articulating joints.

B. Energy

Basic research in nuclear physics has created, and continues to create, a legacy of advanced technology that pervades energy-related research and development. The impact of this legacy extends far beyond the obvious example of nuclear energy into areas as diverse as fossil fuel prospecting and energy conservation.

Nuclear techniques are used by the **drilling industry** to help probe geological formations and to locate hydrocarbons and other substances in strata deep underground. Passive forms of nuclear well-logging employ gamma-ray detectors to distinguish regions containing clean sands and carbonates of low natural radioactivity from the less productive and more radioactive regions containing clays or shaly rock. Gamma-ray and neutron detectors operated in conjunction with neutron sources provide more detailed information. The more sophisticated of such logging techniques generate neutrons with the aid of miniaturized nuclear accelerators that can be lowered into the test bores. The apparatus produces fast neutrons, and the interactions of the neutrons with the surrounding material provide the logging information. In one application gamma rays following inelastic neutron scattering are measured, and the log is inspected for the characteristics that indicate the presence of carbon, a major constituent of oil and gas. In another application, neutron detectors are used to measure the duration of the well-defined slow-neutron pulse that results when the initial fast neutrons from the accelerator encounter hydrogen in the surrounding material. Rapid disappearance of the slow-neutron pulse suggests that the hydrogen in the region is accompanied by chlorine, which has a high efficiency for the capture of slow neutrons, and indicates the presence of salt water. A long-lasting pulse shows that chlorine is not present, and provides a good indication of petroleum deposits. The sensitivity of these and related nuclear techniques helps identify oil or gas-bearing regions that might otherwise be overlooked.

Oil shales are being investigated as a possible source of domestic energy with the aid of small angle neutron scattering (SANS). This technique measures the sizes of pores or voids that might contain petroleum products, thereby identifying shales that could contain potential sources of energy.

Energy conservation results whenever research and development efforts lead to increased efficiencies in existing energy technologies. Examples of nuclear physics contributions are found throughout this area. Nuclear tracer techniques have been used to study friction and wear in gasoline engines by incorporating radioactive carbon in steel piston rings. Ion implantation, initially a by-product of low energy nuclear physics research, is used to modify the surface properties of materials to inhibit friction and wear. Wire-drawing dies, ion implanted with nitrogen at a cost of only a few dollars per die, can be kept in service about five times longer than non-implanted dies, with consequent savings in tooling costs, plant downtime, etc. Ion implantation also shows promise for fabricating corrosion resistant surface alloys while conserving expensive, rare or strategic alloying materials such as chromium, platinum, cobalt and tungsten. The conservation occurs not only through the reduction of corrosion, but also because ion beam accelerators permit the implantation of these scarce elements selectively into the surface of the material—precisely where they are needed for corrosion resistance.

The development of the new alloys and ceramics that would permit fossil fuel power plants to operate at higher pressures and temperatures, with correspondingly higher efficiencies, is another area where nuclear diagnostic techniques such as neutron and charged particle scattering as well as ion beam implantation, with its ability to introduce essentially any element into any substrate, make important contributions. These efforts, aimed at increasing fossil plant steam conditions from the current state-of-the-art 1000°F at 3500 psig to 1400°F at 7000 psig, would result in annual fuel cost savings of 13 million dollars in a typical (800 megawatt) power plant.

The historic role of nuclear physics in the development of **nuclear energy** needs little elaboration, but perhaps less well known are the ongoing research efforts in support of national programs to develop advanced nuclear energy resources. Today, in the United States, approximately 13% of our electrical power is supplied by uranium-fuel thermal neutron spectrum reactors. In some regions of the country, such as Chicago, New England, and the Tennessee Valley areas, the percentage is much higher.

The design of advanced fission and fusion reactors capable of meeting the projected future demand for electricity depends upon detailed knowledge of neutron interactions over a wide range of neutron energies. Even though nuclear-data programs for reactor design have been active for many years and many data requirements have been met, several important ones remain unfulfilled and a few have not been seriously addressed.

Several accomplishments in the last few years can be selected to illustrate the diversity of these neutron data. These are (1) a precise 0.2% measurement of the average number of neutrons per fission from spontaneous fission of ^{252}Cf, used as a standard for all related measurements; (2) capture and fission data on several actinides (Np, Am, Cm) in the fission reactor waste stream to allow definition of its composition for the various reactor options; (3) resonance data for ^{238}U and to a lesser extent ^{232}Th to permit adequate resonance-capture calculations for thermal light-water and graphite-moderated reactors; (4) the fission cross section of ^{238}U, the fission and capture cross sections in $^{240,241,242}Pu$ and the total cross section of sodium needed for fast reactor design; (5) the neutron total and reaction cross sections to 50-MeV neutron energy of many materials for shield design of the Fusion Materials Irradiation Test Facility, and (6) measurement of the $^{7}Li(n, n\alpha)T$ reaction that will be important for breeding performance in tritium-fueled fusion reactors.

Future needs for the liquid metal fast breeder reactor technology include more accurate data on ^{238}U capture at neutron energies above the resonance region, inelastic neutron scattering for ^{239}Pu and ^{238}U, neutron capture in fission products, and measurements of self-shielded cross sections for ^{238}U and ^{239}Pu in the resonance energy region. Optimal design of thermal reactors requires more accurate knowledge of neutron cross sections at energies through 1 eV on ^{235}U, $^{239,240}Pu$ (and ^{233}U if the thorium cycle is to be thoroughly understood). All fission designs need better-defined neutron spectra from fission, starting with the ^{252}Cf standard. For fusion-energy systems, the higher energy of the primary neutron source at 14 MeV requires extending the energy range of the nuclear-data measurements. Other reactions become important in induced radioactivity in structural materials or in the production of charged particles forming gas inclusions within the structural materials. Adequate nuclear data for shielding materials are yet to be measured. The strongly asymmetric angular distributions, which impact neutron streaming calculations, must be determined.

Intimately intertwined with these ongoing studies are efforts by metallurgists and other materials scientists to understand the effects of intense radiation on the properties of structural materials and to design new materials for service in advanced fission and fusion reactor systems. The nuclear physics and materials science research efforts both depend crucially on the availability of well instrumented, state-of-the-art facilities for nuclear measurements, such as high-flux research reactors and intense-beam pulsed electron and proton accelerators for neutron production.

Low energy Van de Graaff accelerators also contribute in a variety of ways. For example, Rutherford scattering of low energy ions is used to determine the suitability of various nuclear waste containment materials, as well as to characterize the surface properties of new reactor alloys under various conditions. The swelling and other effects that occur when helium is produced in structural reactor materials are being studied under controlled conditions by bombarding the material simultaneously with helium from a Van de Graaff accelerator and with neutrons from pulsed or steady-state sources. Such studies have helped identify metallurgical techniques for trapping the helium in a high concentration of small cavities or bubbles to minimize high temperature swelling and grain-boundary embrittlement.

C. Semiconductor Doping and Ion Implantation

Armed with ion sources, accelerators, and experimental techniques developed in low energy nuclear physics research, investigators in numerous disciplines are discovering that energetic ion beams can be used to alter and study the near surface properties of materials in a selective and often unique manner. When these beams impinge on a solid, ion implantation occurs which can alter or even dominate the electrical, mechanical, chemical, optical, magnetic, or superconducting properties of the material.

The results are often dramatic and several examples have been discussed earlier in this chapter. Perhaps the most impressive application of ion implantation concerns semiconducting materials. Most semiconducting devices require the selective doping of silicon or germanium with impurity atoms and ion implantation has rapidly become the dominant doping technique in the semiconductor industry. Responsible not only for new devices—such as high frequency transistors, improved MOS transistors, and integrated circuits—ion implantation also increases yields of old devices by orders of magnitude during fabrication and permits tremendous miniaturization. As a result, most semiconductor devices and integrated circuits for watches, calculators, computer chips, etc. are fabricated by ion implantation. The billion-dollar-a-year portable calculator industry is but one consequence of ion implanted integrated circuits; other examples ranging from color television to personal computers could be cited in complete analogy.

Ion implantation has been exploited in a myriad of other applications beyond those already mentioned. Controlled ion damage to insulators and semiconductors has been used to alter the index of refraction of materials to fabricate optical waveguides and mixers, and to selectively modify magnetic bubble memory devices. Ion implantation holds promise as a fabrication tool for high temperature superconducting materials, since these involve the formation or stabilization of a metastable phase which need exist only within a few hundred angstroms of the surface. And ion bombardment has proven effective in bonding thin films to substrates via the recently discovered enhanced adhesion phenomenon.

Fig. III.2-B. Neutron autoradiography of the painting *Saint Rosalie Interceding for the Plague-Stricken of Palermo*, by Van Dyck, reveals a hidden underpainting. The painting and its x-ray radiograph are shown in the upper left and right panels, respectively. The neutron radiograph in the lower panels reveal a self-portrait of Van Dyck (upside down, near the bottom of the painting).

D. Fine Arts

Nuclear science even contributes to the study of art history. One technique involves exposing oil paintings to a broadly spread, highly purified, thermal neutron flux of approximately 10^9 neutrons/cm^2/sec for periods up to one hour, generating within these paintings temporary, mild radioactivities. At various periods after activation x-ray film is placed in intimate contact with the painting to record images of the distributions of the radioactivities most predominant during these periods of contact. These images typically show significant differences from one another, as they are the records of radioactivities of quite different half lives. All of them are quite different from the conventional x-ray of the painting, which is largely determined by the distribution of the dense pigment lead white, a material that does not activate strongly with neutrons.

An interesting example of what can be revealed by autoradiography is provided by the study of the painting *Saint Rosalie Interceding for the Plague-stricken of Palermo* by Sir Anthony Van Dyck, which is in the collection of the Metropolitan Museum of Art. A photograph of this painting is shown in the upper left of figure III.2-B and its x-ray radiograph in the upper right. The radiograph reveals details of a hidden underpainting, the face of a man, upside down near the bottom of the picture. It is difficult to interpret this overpainted face in the x-ray as it is masked by many details of the surface painting.

An early neutron activation autoradiograph of this painting, at the lower left taken only a few hours after activation, largely records the distribution of manganese throughout the painting, which is probably present as a component of the dark earth pigment umber. This radiograph shows details of the canvas where it has been filled in by an umber-tinted ground paint layer. Also very noticeable in the upper center are two regions of loss, where original areas of the painting have been replaced by modern repairs, which are free of manganese. The details of the figures in the Saint Rosalie painting can be seen to have the quality of drawings, and indeed are thought by the art historians who have examined this autoradiograph to be the underdrawings, in umber, of the original figures of the painting. It is interesting to note that the angel above and behind Saint Rosalie's head does not appear in the original underdrawing. This angel appears to have been added later in the development of the painting, a change in its initially conceived composition.

A later autoradiograph, started four days after activation, lower right, shows the overpainted man's head in remarkable detail. This autoradiograph is largely from the element phosphorus present in the bone black used in defining the head. Comparison of this autoradiograph with a self portrait of Van Dyck, also in the Metropolitan Museum collection, shows that the overpainted picture was a portrait of Van Dyck himself.

Obviously, this ability to unravel a painting gives the art historians an entirely new dimension of their craft.

IV. RESOURCES

IV.1 Manpower and Training

The crucial element of any science, more important than facilities, instrumentation, or funding, are 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 government service, in addition to providing the basic resource for continued research in the discipline.

It is becoming apparent that the rate at which nuclear scientists are being trained will not be adequate to meet the country's needs within the decade. Every year a large number of fresh Ph.D.'s trained in nuclear physics, and particularly in experimental nuclear physics, are hired by industrial laboratories with extraordinary alacrity. Their training in many aspects of advanced technology, the hands-on experience with relatively small-scale experiments where the student gains a measure of self reliance, seem to be factors in this phenomenon. And the forces of the marketplace are such that salaries in basic research positions cannot compete with those offered by industrial laboratories. The training in experimental nuclear science seems to be valued and this skilled manpower represents a major contribution of the field to the nation and to our society.

A healthy program of training nuclear theorists is also vital to the science. With the new construction plans, further upgrades, and fuller use of existing facilities, the theoretical efforts, presently severely limited by manpower, must also be strengthened. We recommend that the trend of the recent past, of increased funding for the buildup of strong theoretical programs be continued.

One reason that the shortage of nuclear scientists is not more acute now is that the condition in a number of countries is the inverse of that in the United States—more scientists are being trained than there are open positions. Some of the best young scientists from abroad come to the United States shortly after getting their doctorates, and either return to their home countries after having spent their most productive years in American laboratories, or sometimes stay on permanently. This influx of young scientists is mutually beneficial, and even healthy—leading to long term international ties—but it is not a viable long term solution to our manpower problems, since the training patterns and needs of other countries are also subject to change.

The reasons for the decline in U.S. graduate student enrollments in physics are complex. The fact that declining college enrollments have led to static and in some cases decreased faculty size at universities has had an especially strong impact on physics departments. For example, the ratio of junior to senior faculty positions in universities is lowest for physics among all the natural sciences. The fact that this has been widely discussed has caused many young people to decide not to take up physics as a profession. It is probably also true that the well-documented deterioration of the secondary school system in the United States is having an especially serious effect on basic training for the physical sciences. Students who have never been exposed to the excitement of science are unlikely to choose physics as a career path. Another effect is more peculiar to nuclear science. Unlike high-energy physics, which has been mostly a "user field" since its inception, university nuclear physics groups usually started with the operation of small in-house accelerators. With much research shifting to the larger facilities, the shutting down of many small university accelerators was inevitable. The psychological impact of having a facility at one's own institution closed down can be devastating and has slowed the momentum of Ph.D. training at the universities thus affected.

While it is important to upgrade science education at all levels, the following recommendations, if acted on, would make physics in general and nuclear physics in particular more attractive to young people.

1. Programs which involve undergraduates in nuclear science research are extremely important in attracting students to the field. Many outstanding scientists were first attracted to a career in science through participation in such programs. A number of laboratories and universities have programs of this type; efforts should be made to strengthen and expand these, or to start them where they do not exist, if necessary with specific funding from the agencies. Similar programs to involve secondary school students in nuclear science research can also lead to long term benefits, and the involvement of secondary school science teachers in physics research will benefit the field and the nation.

2. Competitive predoctoral fellowships can contribute significantly in encouraging the best young people to study nuclear science. Any increase in the number of NSF Fellowships will naturally help all disciplines and is strongly supported. In addition, we suggest to the Department of Energy that it consider committing funds specifically for fellowships in nuclear science.

3. A competitive program of temporary direct support of new research initiatives by young nuclear scientists should be funded. This would encourage scientists starting in the field to develop new initiatives and an increased measure of independence.

4. Many existing small user groups in nuclear science are so constrained that they put all available funds for manpower into hiring research associates. With no direct technical or engineering staff working with these groups, they either become too dependent for instrumentation development and technical planning on the facility where they are users or an undue burden falls on in-house students and research associates. While clearly some such work should properly be part of a training in nuclear physics, it would considerably strengthen small university user groups to be able to hire their own technical staff, either engineers or scientists specializing in technical problems. The impact on developments of instrumentation, on the style and quality of research and on the attractiveness of doing research as a graduate student in the user mode could be considerable. We recommend that the agencies seriously consider funding supplementary requests for such manpower.

5. Educational aspects, the importance of attracting high caliber graduate students to nuclear physics and giving them the best possible training, should be given consideration in decisions on new facilities.

With the variety of challenging and important research opportunities outlined in Chapter II, both qualitative and quantitative aspects of our manpower and training ultimately determine the viability of the field. The steps outlined here will help the United States to continue to play a leading role in this area of basic research and to continue to train young scientists in skills and techniques which society puts to excellent use in numerous applications.

IV.2 Accelerator Facilities

The particle accelerator is the basic tool of the nuclear physicist and the development of accelerators is tied intimately to the development of nuclear science. Accelerators have also found powerful applications in almost every science ranging from nuclear medicine, through condensed matter and materials research to archeology and geophysics, where use of accelerators as ultra sensitive mass spectrometers has recently had dramatic consequences. The development of accelerators is an essential part of our science that has suffered all too often in times of budget stringencies and manpower shortages. There are major opportunities in the field of accelerator physics, many of them outside the immediate concerns of basic nuclear physics research, and our field must train specialists in this area of applied physics in numbers sufficient to meet the challenges in the future.

During the last decade a number of important advances have been achieved in accelerator physics: the uses of superconducting magnets, of superconducting resonators capable of producing high radiofrequency fields for the acceleration of particles, of beam cooling in storage rings, to mention just a few.

The accelerator facilities of nuclear physics are here separated into two groups. There are nine major national facilities whose operation and research programs account for about 80% of the budgets for experimental nuclear physics. These facilities are used for an important share of the research effort by the national and international community of scientists, with experimental time allocated with the help of Program Advisory Committees. The remaining support is largely for dedicated smaller university research accelerators that play an important role in the education and training of graduate students (along with the major facilities), and in the pursuit of many important research goals.

A. MAJOR NATIONAL FACILITIES

The nine facilities listed here are all "user facilities" in the sense that, because of their unique characteristics, they are generally available to scientists throughout the U.S. and the world, and their experimental priorities are set on the basis of recommendations of Program Advisory Committees. These facilities vary in size from the large U.S. meson factory LAMPF and the one relativistic heavy-ion accelerator in the world the BEVALAC (which between them account for about two-thirds of the above mentioned 80%), to some much smaller and less costly—though still very important accelerators.

For each of these facilities we list present capabilities and future aspirations, without making specific priority recommendations on the implementation of the latter.

1. INTERMEDIATE ENERGY ACCELERATORS

The Los Alamos Meson Physics Facility (LAMPF) is a national facility providing both primary and secondary particle beams for an extensive program of research including nuclear, elementary particle, and condensed state physics. The heart of the facility is a linear accelerator providing a beam of protons of variable energy up to 800 MeV, intensity of 1 mA and a duty factor of 9%. A separate H^- ion source provides the capability of accelerating simultaneously a low current H^- beam with a high current of H^+. The 800 MeV proton beam is used primarily for the production of secondary beams of pions, muons, and neutrinos. Several magnetic channels allow experimentalists to select independently the desired beams of secondary particles. Part of the proton beam is also used for neutron production, and with the completion of the proton storage ring (PSR), will provide an intense pulsed neutron source. H^- beams, polarized or unpolarized, can be obtained at different energies (down to 218 MeV) and used for studies of proton induced reactions. The H^- beam is split between the high-resolution proton spectrometer facility where nuclear structure studies predominate and the nucleon physics laboratory where a comprehensive program of measurements of the two nucleon system is carried out. An extensive program of nuclear structure studies with pions is carried out using the high-resolution pion spectrometer, EPICS. Other major hardware facilities include a π^0 spectrometer capable of measurements with energy resolution of ~1-2 MeV, a time projection chamber, and a large NaI($T\ell$) "crystal box" facility. A new low-energy pion spectrometer, currently under construction, will be installed in the Low Energy Pion Channel to extend the capabilities for high resolution pion spectroscopy to 10-100 MeV.

The LAMPF user group currently has a membership of more than 900 scientists. Approximately 300-400 scientists from ~90 universities are participating in research at LAMPF in any given year.

Future facility plans include an upgrade of the PSR area to provide a pulsed muon facility and a high intensity neutrino source. In addition to numerous planned developments and improvements in the present LAMPF accelerator, a design effort is under way for a major new future accelerator (LAMPF II) that would be based upon a 16-32 GeV synchrotron and stretcher ring injected by LAMPF. This accelerator would provide K-meson beams 100 times as intense as present facilities, as well as improved pion, muon, neutrino and antiproton beams.

The **Bates Electron Accelerator Center** of the Massachusetts Institute of Technology centers on a high-intensity pulsed S-Band electron linac covering the energy range 50-750 MeV. The typical average current and duty cycle at present are 40 μamp and 0.5%, respectively. This laboratory is recognized worldwide for its leading contributions to high-resolution electron scattering. In the past five years, there has been substantial progress toward expansion of the facilities which includes: (1) increase of the energy to 750 MeV by a single recirculation of the beam through the linac, (2) construction of a second experimental hall (120′ x 80′), (3) construction of two large solid-angle spectrometers capable of measurement of momenta up to 400 MeV/c and 1300 MeV/c, respectively, (4) construction of a large opening angle π^0 spectrometer. In addition, a polarized injector will be installed in the immediate future for use in nuclear polarization studies and parity violation experiments.

The further stages of improvement under way are: (1) beam-sharing capability, allowing simultaneous 50 μamp beams in each experimental hall, and (2) the addition of a sixth two-klystron modulator and some increase in the peak-power capability of the existing modulators to achieve both greater reliability and energy capability of at least 900 MeV. In addition, a pulsed stretcher ring to provide ~100% duty factor beams for South Hall experiments is being planned. Provision will be included in the ring design for internal target experiments and for delivery of polarized beams. Bates serves a large community of outside users; about 180 scientists coming from approximately 40 universities and national laboratories. About 50% of the beam time goes to outside users.

The **Indiana University Cyclotron Facility** provides a variety of light-ion beams over a range of bombarding energies and momentum transfers. The ion beams are generated by a coupled pair of separated sector cyclotrons. Proton currents typically are ~1 μamp and proton energies are in the range 12-210 MeV. Light ions including polarized protons and deuterons are available with energies up to 220 q^2/A MeV and with pulse widths of 0.35 nsec. Present major experimental facilities include a beam swinger for time-of-flight measurements with path lengths up to 160 m, a QDDM spectrograph, a QQSD spectrograph for low rigidity particles such as pions, two scattering chambers, and a polarized neutron beam. Presently, a dual spectrometer facility, one spectrometer to be high resolution ($p/\Delta p \cong 35{,}000$) is under construction. Accelerator improvements underway include the construction of a storage ring, with electron cooling to reduce dramatically the phase space of the beam and internal targeting, which is to be completed by 1986-1987. Upon completion, three internal target experiments may be carried out simultaneously. Future plans include the possibility of an additional cyclotron to triple the energy, or ramping the energy in the storage ring to 500 MeV, and/or addition of a two-ring collider.

IUCF has been in operation since late 1975 as a national user facility. More than 250 scientists from 47 U. S. institutions have been actively involved in the research program.

A new **4-GeV Electron Accelerator Laboratory** operating at a beam current of 240 μA and a duty cycle of about 90%, to be built by the Southeastern Universities Research Association (SURA), was recommended for construction by NSAC earlier this year. The main components are a 2-GeV pulsed linac with a single-pass recirculator and a beam-stretcher ring system. With double-pass, head-to-tail recirculation, the linac will produce a 4-GeV beam having a pulse length and intensity that allow single-turn injection into the stretcher ring. The accelerator could be upgraded in the future to achieve energies of 6 GeV or higher, should the physics in this region make such an upgrade desirable.

SURA plans to build a tagged-photon facility and two end stations for coincidence experiments and spectroscopy. The designs and specifications for the spectrometers available at each experimental area will be set in close consultation with the user community. As presently envisioned one end station may receive beam from either the linac or the pulse stretcher ring; it will be the location for a moderate-resolution spectrometer with a high-resolution spectrometer to be added later. The second end station will receive beam only from the stretcher ring and will house a moderate-resolution and a low-resolution (large acceptance) pair of spectrometers suitable for coincidence experiments. A tagged-photon facility will include a moderate-resolution spectrometer.

2. HEAVY ION ACCELERATORS

Six of the national user facilities are classified as **heavy-ion facilities**. In most respects, the characteristics of these accelerators are complementary rather than competitive, since none of the technologies are the same and the beam energies and other capabilities of the several machines are quite different, as required by the wide range of research objectives. At all of these facilities, outside users participate actively in much of the research, are involved in the development of new experimental apparatus and, in a variety of ways, influence the accelerator-operating policies. Typically, outsider users are allocated at least 50% of the running time. The total numbers of outside users during a given year varies from about 50 for the smaller facilities to several hundred for the largest.

The **Double MP Tandem Accelerator at Brookhaven**, which came into operation in 1970, covers the low-energy end of the range of heavy-ion projectiles of interest to nuclear physics, providing precise high-resolution beams with energies above the Coulomb barrier for ions in the lower third of the periodic table. Two upgraded model MP tandem electrostatic accelerators can be operated separately or jointly, in several different configurations. The highest energies are obtained with the 3-stage mode in which a negative-ion source is mounted in the high-voltage terminal of the first machine, operated at a negative potential. The heavy-ion performance of this 3-stage system is roughly equivalent to that of a single tandem with 18 or 19 MV on the terminal. The system is also used to accelerate light ions and provides energies as high as 42 MeV for protons.

Brookhaven National Laboratory has proposed major expansion of its present facility by combining it with the AGS (the 30-GeV Alternating Gradient Synchrotron) to accelerate heavy ions to relativistic energies up to $\sim$15 GeV per nucleon. Using direct injection of the AGS, ions up to $A = 32$ and currents $>10^9$ pps would be available. Construction of a modest intermediate booster accelerator would permit injection of heavier ions, up to about $A = 130$, into the AGS. This system would provide significantly higher-energy relativistic heavy-ion beams than are now available at the Bevalac. Present studies indicate that beams accelerated in the AGS are suitable for injection into a relativistic collider system which BNL is designing for possible future construction.

The **88-Inch Cyclotron at the Lawrence Berkeley Laboratory** emphasizes nuclear-structure physics with heavy-ion beams in the lower fifth of the periodic table. The accelerator is a variable-energy isochronous cyclotron with spiral sector focusing. Light ions are produced by an internal filament source, polarized protons (up to 55 MeV) and deuterons by an external polarized ion source, and heavy ions by an internal heavy-ion PIG source. One third of the beam time is used for light ions. The high intensity polarized ion source produces a microampere of beam on target. A pair of 110° analyzing magnets are dispersion matched for the QSD spectrometer.

The energy range of the 88-Inch Cyclotron will be enhanced considerably and the mass range will be extended to 100 amu by the installation of an electron-cyclotron resonance (ECR) ion source, now under construction. This accelerator improvement is being accompanied by the construction of a major new experimental tool, a compact assembly of 21 Compton-shielded germanium detectors and 44 bismuth-germanate detectors designed to study high-spin nuclear states.

The **Holifield Heavy-Ion Research Facility at Oak Ridge National Laboratory**, completed in 1982, consists of a new 25-MV tandem, the K = 100 Oak Ridge Isochronous Cyclotron (ORIC) which has been modified to serve as an energy booster for tandem beams, and experimental apparatus to utilize beams provided by these accelerators operating both in stand-alone and coupled modes. The beam energy is easily varied in both modes. For ions in the intermediate region of the periodic table (say $40 < A < 110$), the coupled system provides beams in an energy range that is not available at this time elsewhere in the United States for nuclear-structure research. This advantage and an extensive complement of experimental apparatus (4-π, 70-detector gamma-ray spectrometer, on-line isotope separator, two high-resolution magnetic spectrometers, time-of-flight spectrometers, etc.) provide an opportunity for the facility to be especially productive during the next few years.

Two approaches to an extension of the energy and mass range of the Holifield facility have been studied, both involving an improved cyclotron injected by the 25-MV tandem. One approach would increase the beam energy by about 40% and reduce power consumption by using superconducting coils for ORIC. The second option would extend the energy into an entirely new range (200 MeV/nucleon for light ions and 40 MeV/nucleon for uranium) by adding a K = 1200 superconducting cyclotron of the kind under construction at Michigan State University.

A heavy-ion accelerator-collider is being studied as a possibility for a major new facility at ORNL. As now conceived the system would consist of a linac injector, a conventional synchrotron booster, a stacker-stretcher ring, and a pair of superconducting intersecting acceleration-storage rings. For uranium ions the system would provide $\sim$10 GeV/nucleon with a luminosity of $\sim 10^{29}/cm^2$-sec and intensities of 10^{10}-10^{11} particles/sec for fixed target experiments. Straightforward modifications to this design to extend the energies to 30 GeV per nucleon and above are also being explored.

The **Argonne Tandem-Linac Accelerator System (ATLAS)** at Argonne National Laboratory is the world's first successful accelerator to use r.f. superconductivity for the acceleration of projectiles heavier than the electron. It is being built in two phases. The first phase, completed in 1982, consists of a small (9-MV) tandem injecting into a 20-MV superconducting linac which was originally constructed as a prototype machine designed to develop a new technology, but is now used routinely as a research tool. The performance characteristics of the tandem-linac system are similar to those of a very large stand-alone tandem, and consequently the system is most useful for precision nuclear-structure research. Noteworthy features of the performance are the ease with which the energy may be changed and the availability of ultra-short beam pulses.

In the second stage of construction, the present facility is being expanded to form ATLAS. This project will double the size and accelerating power of the linac and add a large, well-equipped experimental area. At the interface between the present prototype linac and the ATLAS addition the beam will be separated into two components, one of which is accelerated to the full energy and the other is directed simultaneously, without further acceleration, into the present experimental area.

Because of the modular character of the tandem-linac system, it can rather easily be modified or expanded. Future options for ATLAS include (a) improving the overall performance of the system by replacing the present FN-model injector by a better machine for the purpose and (b) extending effective acceleration to the heaviest nuclei by modifying and enlarging the linac.

All of the heavy-ion accelerators described above have beam energies that are within an order of magnitude of the Coulomb barrier. The remaining two facilities are designed to provide much higher energies with which to investigate quite different physics.

The accelerators at the **National Superconducting Cyclotron Laboratory** at Michigan State University are two superconducting cyclotrons, which are designed to be operated either as independent machines or in 2-stage acceleration. The phase I machine, the world's first operating superconducting cyclotron, was used to develop a new technology and is now being turned to research. It has a bending-limit parameter of K = 500 and a focusing limit of 80 MeV/nucleon for q = A/2. The first beam was extracted from this prototype machine in 1982, and since then a variety of ion species in the lower part of the periodic table have been developed and used for research. Beams have been extracted at the full K = 500 design limit of the superconducting magnet.

The second phase of the MSU project is now in progress. This work includes the addition of a second, larger superconducting cyclotron (K = 800) and the development of an advanced set of experimental apparatus. In the 2-stage mode of acceleration, this system will provide intense beams with energies up to 200 MeV/nucleon for $A < 40$, thus opening up an unexplored region of energy for investigation.

An attractive option for future improvement of the MSU system is the installation of an external ion source and axial injection; with an ECR source, the coupled facility could yield 80 MeV/nucleon uranium beams.

Bevalac Complex. This is the only facility in the world that can provide relativistic beams of ions over the entire range of the periodic table. It is also at present the only source in the U.S. of very heavy ions with energies above the Coulomb barrier. This unique facility is heavily used by researchers from the U.S. and abroad. One-third of the operating time of the machine is devoted to biomedical research. Major nuclear science facilities include: HISS (Heavy Ion Spectrometer System), a large acceptance spectrometer using a 3 T superconducting magnet in conjunction with an extensive array of detectors to measure many-particle final states associated with projectile fragmentation processes, large momentum transfer processes, and other few particle correlation studies; Plastic Ball/Wall, 4π electronic detector with approximately 1000 elements for obtaining exclusive charged-particle information on an event-by-event basis; Streamer Chamber, a 4π visual detector for charged particles allowing full event reconstruction; Low Energy Beam Line, for studying nuclear reactions in the 30-200 MeV/nucleon range. In addition, several smaller detector facilities are available for studying heavy-ion collisions. A dilepton spectrometer (DLS) to study the electron-positron mass spectrum is being planned. Other experimental facility upgrades include (a) modifications to the Low Energy Beam Line (1984) to raise beam intensities; (b) improvements to the Bevalac Switchyard (1985) to enhance operating flexibility and permit delivery of a wide range of rare isotope beams; and (c) installation of a high-resolution system for delivering secondary beams of rare isotopes to the HISS facility.

To increase the intensity of the heaviest ion beams some 10 fold, improvements will be made during 1984 to the transfer line connecting the SuperHILAC to the Bevalac. Another accelerator upgrade project to be completed in mid-1984—replacement of the present Bevatron local injector's pre-accelerator with a radiofrequency quadrupole linac—will enable more efficient switching between the lighter ions (up to silicon) used for biomedical research and the heavier beams needed for the nuclear science programs.

Over the period of the last few years LBL has been studying new machines to provide beams at substantially higher energies than those available at the Bevalac. Present plans center around a two-ring superconducting accelerator complex optimized for acceleration of heavy ions throughout the periodic table which would be capable of both fixed-target and colliding-beam operation. The SuperHILAC will be improved and used as the injector.

B. DEDICATED UNIVERSITY FACILITIES

There are roughly a dozen facilities at universities supported by the agencies for basic research in nuclear physics. These have an important dual role to fulfill. They carry out first-rate basic research within their range of capabilities, often involving the more difficult and time-consuming measurements, and at the same time and most importantly, provide an in-house facility for the training of students in experimental physics. Some of the scientific frontiers of nuclear physics are driving the field to large unique user facilities, but many other important scientific questions are well within the scope of these smaller accelerators. The role of university accelerators in training scientists has been stressed before by the NSAC Subcommittee on University Research and Education in Nuclear Science. These accelerators provide the opportunities for students and young scientists not only to do research and develop their all-around research skills, but to develop the independence and self reliance that is essential in an effective researcher. First-rate scientists can be, and are, effective in the user mode. But the influence of an in-house accelerator within a strong university physics department can be very important in attracting the best graduate students and training them in nuclear physics, in a variety of experimental and technical skills, and most importantly in becoming self-sufficient and strongly motivated researchers.

The "dedicated university facilities" are in general also made available to users from other institutions.

1. CURRENT AND RECENT ADDITIONS AND UPGRADES

A number of the university facilities have been and are in the process of being modified by having major changes or additions implemented.

The **State University of New York at Stony Brook** has recently installed a superconducting linac, based on lead-plated copper resonators (rather than the niobium ones used in the ATLAS project and discussed earlier). This parallel successful development of superconducting radiofrequency technology for accelerators is a major technical achievement. Operation of the facility at Stony Brook for research started in 1983; the maximum beam energies finally expected are about 10 MeV per nucleon for heavy-ion beams around mass thirty and 5 MeV per nucleon for mass eighty—a qualitative step above the energies of the FN tandem injector.

The continuing development of 100% duty cycle electron microtrons at the **University of Illinois, Urbana** has provided a first-rate research tool with electrons up to 70 MeV. Further developments underway will increase the energy to 100 MeV. An additional microtron stage is planned that will increase the energy to 250-300 MeV.

Major upgrades are under way at **Yale University** and at the **University of Washington.** At Yale the MP tandem is to be rebuilt into an ESTU accelerator—which is expected to operate at almost double the present terminal voltage and greatly increase the research capability of that facility. At Seattle a superconducting linac booster is planned that will provide light ions, including protons up to 37 MeV, as well as heavy ions through 4.3 MeV per nucleon ^{56}Fe.

Florida State University is completing a superconducting linac accelerator-booster based on Nb technology, for their FN tandem. It will provide enhanced heavy-ion capabilities to about ten MeV per nucleon for mass forty. **Texas A & M University** is building, from university and other private funds, a superconducting cyclotron to accelerate lighter ions with mass below twenty, to about 80 MeV per nucleon and heavier ions ($A \approx 100$) to 10 MeV per nucleon. The new 3 MV tandem accelerator at **Caltech** promises to be an interesting facility for low-energy experiments, including measurements important for nuclear astrophysics. All of these upgrading and improvement projects involve a large number of students, undergraduate and graduate, whose participation in the solution of complex problems on the frontier of high technology will have substantial beneficial impact.

We do not mention here all the university facilities, many of which are world renowned for their research and have unique features in the accelerators or associated instrumentation. There are additional university accelerators not listed here that are supported partially for their work in basic nuclear physics.

C. OTHER FACILITIES

Nuclear physicists are making important use of facilities operated primarily for the High Energy Physics Program. The *hypernuclear spectrometer "Moby Dick"* located at the low-energy kaon beam line of the AGS at Brookhaven is the only facility for the study of hypernuclear physics and the science that was outlined in Sec. II.6.

At the Stanford Linear Accelerator Center (SLAC) a new electron injector is being built for nuclear physics experiments. It uses the last six sections of the linac and provides electron beams up to 3.0 GeV of about 20 μA average current, with a duty cycle of 0.04%. The beam is brought into *End Station A* where spectrometers appropriate to electron scattering experiments already exist. This facility is suitable for some of the single-arm measurements that will lead into the physics to be studied at the 4-GeV electron accelerator.

Very interesting pioneering nuclear physics studies with high energy proton beams have been carried out at the *internal gas target facility* of the Fermilab accelerator.

Important studies of nuclear structure severely testing predictions of current models are performed with neutron capture gamma-ray studies at the High Flux Beam Reactor (HFBR) at Brookhaven. The on-line isotope separator *TRISTAN,* on another HFBR port supports an active user program studying nuclei far from stability, produced in the fission of uranium.

Although the large majority of facilities for basic nuclear research are supported by DOE (Office of Energy Research) and the NSF, there are some smaller accelerators (e.g. various machines at the Lawrence Livermore National Laboratory, Los Alamos National Laboratory and including the new 200 MeV microtron soon to be completed at the National Bureau of Standards) that receive their support for basic nuclear research from other federal sources. There are many other accelerators that are funded from a variety of federal programs, in atomic physics, in materials science, or for measurements of cross sections needed in the nuclear energy programs, that often contribute significantly to nuclear physics research. Indeed, sources of slow neutrons at research reactors and pulsed neutron sources are among these.

D. ACCELERATOR TECHNOLOGY DEVELOPMENT

The vitality of nuclear physics as a discipline depends critically on the continuing refinement of its experimental tools, and for most of the subject the primary tool is now the particle accelerator. The immense changes during the past two decades in the nature and the scale of the accelerators required for forefront nuclear-physics research, demonstrate graphically the speed with which the subject is advancing. In the 1960's, the typical nuclear-physics projectiles were electrons, protons, neutrons, deuterons, and α particles with maximum energies of a few tens of

MeV. It was the era of the Van de Graaff, small cyclotron, and small electron linac, of which there were a large number, mostly similar in character and commercially built. In contrast, now the number of active accelerators is much smaller, the range of projectiles includes all stable nuclei, GeV electrons and secondary mesons, many individual accelerators are an order of magnitude larger and more complex, beam energies are being expressed in GeV rather than MeV, and there is a strong emphasis on uniqueness of performance characteristics.

Clearly, accelerators are increasingly important to nuclear physics and, as a consequence, nuclear physics is becoming more important to accelerator technology, as is evident from the changing subject matter presented at the biannual National Accelerator Conference. These trends are almost sure to continue and to require nuclear physics as a discipline to have a more systematic approach to the development of accelerator technology.

It has been the experience in the past that advances in the technology of basic-research accelerators soon found their way into more practical applications. Chapter III of this report discusses a number of such applications—ion implantation, the generation of medical isotopes, radiation therapy, numerous materials-diagnostic techniques, and so on. Undoubtedly, some of the recent advances in accelerator technology mentioned below will be the basis for future applications that have not yet been realized.

This section attempts to give a brief overview of the technical developments that are now important to nuclear-physics accelerators; the treatment is intended to be illustrative rather than comprehensive. A few of the more clearly foreseen needs for the future are also mentioned.

1. Examples of Past and Present Developments

a. Ion Sources

Progress in the development of ion sources has been very rapid during the past decade. Sources have been developed for almost all elements of the periodic table through uranium, at up to fully stripped charge states, and with steadily improving current, quality and reliability. There are numerous source development programs at present. For example, at the University of Wisconsin-Madison, improvements are being made in the colliding beam source of polarized negative ions and in SNICS, an unpolarized heavy negative ion source. Development of an intense laser driven polarized negative ion source is also under way. Particularly important developments in negative ion sources have been made at the University of Pennsylvania. At ORNL, new versions of the Aarhus and axial-geometry cesium plasma sources and a new universal Li-vapor charge-exchange negative-ion source for Group IA and IIA elements are being tested.

The development of intense polarized electron sources producing a high degree of polarization will be important in order to exploit the polarization observables; a promising new opportunity that becomes realistic with the CW-electron beams available in the future.

At LBL, an electron-cyclotron resonance (ECR) source under construction will axially inject highly stripped heavy ions into the 88-Inch Cyclotron, providing increased energies and 100 percent duty factor. Most of the early development of this source occurred in Europe, as is the case also with the electron beam ion source (EBIS). These sources, various ideas for laser-driven sources, and polarized ion sources will be important elements of future nuclear physics programs. A final example of source work is the interesting area of radioactive ion-beam production, under active development at Ohio State University and at other facilities.

b. Electrostatic Accelerators

Electrostatic accelerators were the earliest accelerators used to study the nucleus, and the Van de Graaff has been the yeoman performer since its invention. Improvements were constantly made. These machines were relatively inexpensive, and form a backbone of research and teaching facilities to this day. It is also interesting to note that the market stimulated commercial suppliers.

Even though the Van de Graaff has been worked on throughout several decades, there is still worldwide interest in the technology. A novel new approach, developed at the University of Strasbourg, could, if successful, lead to the construction, at a moderate cost, of a 35 megavolt tandem Van de Graaff which would be able to accelerate ion species up to uranium to energies exceeding 5 MeV per nucleon. A more modest development now in progress is a method first used in Japan for cleaning accelerator tubes by means of a glow discharge. This technique is exciting interest because it promises to increase the maximum voltage of accelerating tubes by as much as 20%, a large increase in the mysterious business of high-voltage technology. Another notable development is the demonstration at Brookhaven that a tandem Van de Graaff can be used to accelerate exceedingly intense pulses (200 μA) of highly-stripped ions, a technique that may prove useful for the production of intense beams of relativistic heavy-ions.

c. Linear Accelerators - Microtrons

The need for higher energies and intensities required larger machines. LBL pioneered development of accelerator technology in linacs and circular machines that has been used worldwide. In the 1960's, the very large LAMPF project produced firsts in a number of important areas—particularly in automatically controlled rf fields, and in basing its operation from startup on a computer control system. Aspects of these innovations had a wide influence in both private and public sectors; for example, the accelerator structure developed for the high-beta section formed the basis for most of the electron linacs used in medical x-ray machines today.

A few years ago, a fundamentally new type of accelerator for low-velocity ions, the radiofrequency quadrupole (RFQ), was pioneered at Los Alamos following theoretical concepts developed in the USSR. This structure, now under development at many laboratories, allows adiabatic bunching and acceleration, resulting in very efficient capture (>90%) and high beam quality. This device is ideal for many applications that require the acceleration and bunching of relatively slow-moving ions, particularly as the initial stage of an accelerator system. An RFQ for ions as heavy as silicon is being built at LBL to replace a Cockcroft-Walton preaccelerator at the Bevatron. The structure has passed its high-power tests, and preparations for beam tests are proceeding.

The need for electron accelerators resulted in extensive development of the rf-efficient microtron. The University of Illinois Nuclear Physics Laboratory has pioneered use of the superconducting linac in microtrons. Higher energy and intensity requirements spurred development of room-temperature technology in Europe and in an NBS/Los Alamos collaboration, and this approach is a candidate for CW electron machines in the GeV range.

For several decades, one of the most challenging tasks for the future has been to harness the remarkable characteristics of superconducting materials. This goal is now being achieved. Superconducting resonators operating at radiofrequencies have a reputation for being especially perverse, but by now they have developed into an established technology, with numerous applications to heavy-ion acceleration and beam bunching and to electron acceleration. The pioneering recent work at Argonne on niobium accelerating structures shown in figure IV.2-A demonstrated the practicality and the power of the technology for heavy ion acceleration. In an alternate approach, an effort involving Cal Tech, Stony Brook, and the Weizmann Institute has used lead plated on copper to form superconducting accelerating structures that are relatively easy to fabricate. These various devices are now being used or seriously considered for use in at least 9

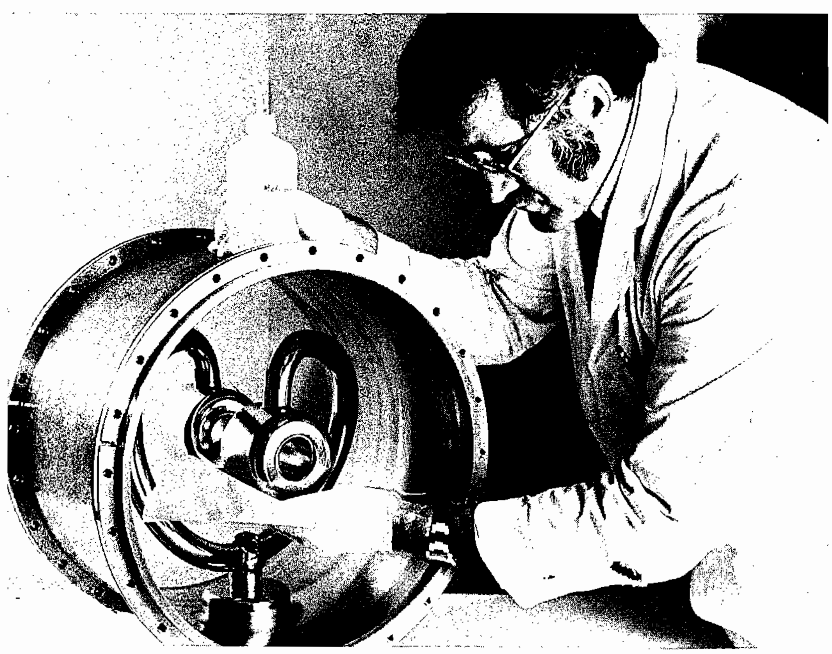

Fig. IV.2-A. Niobium resonator developed for the acceleration of heavy nuclei. These resonators operate at very low temperatures as superconducting radiofrequency cavities. Surface fields as high as 36 million volts per meter, and accelerating fields as high as 8 MV/m have been attained in resonators very similar to this one. Such devices are now being used routinely in accelerators.

linacs in 6 countries. The next step, already under way, is to extend the velocity range for which the superconducting accelerating structures are effective.

d. Superconducting Cyclotrons

Another advanced application of superconductivity is the superconducting cyclotron. This effort, started in the mid-1970's at Chalk River and at Michigan State University, has now been taken up by about a dozen groups around the world. The advantage of this approach is that the immense magnetic field obtainable with superconductors reduces the size, the power requirements, and hence cost of the cyclotron. The cryostat for the K = 500 cyclotron at Michigan State is shown in figure IV.2-B. The small size is also the main developmental challenge; successful operation of the cyclotron at Michigan State shows that the challenge of developing accelerator hardware consistent with this small size can be met.

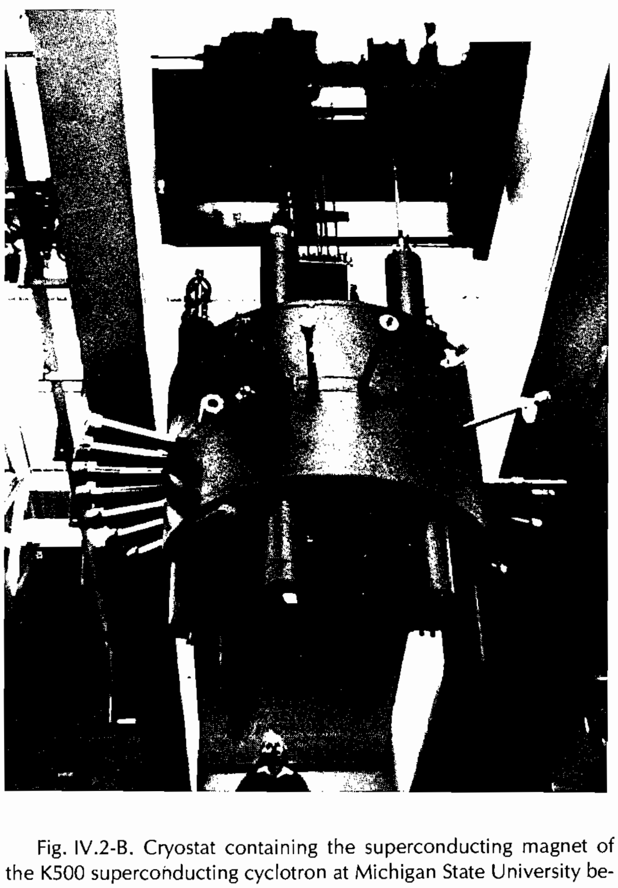

Fig. IV.2-B. Cryostat containing the superconducting magnet of the K500 superconducting cyclotron at Michigan State University being lowered into position in the magnet iron.

e. Superconducting Magnets for Beam Transport

Superconducting magnets have to date played little role in the beam-transport systems and spectrometers associated with nuclear-physics accelerators. This will soon change, however, since such components will be used extensively at the Michigan State cyclotron; and some superconducting beam-line elements, including a beam splitter, are also being developed for the Argonne heavy-ion linac. The requirements for nuclear physics are in some respects more challenging than the corresponding work for high-energy physics, since the beam must often be bent through large angles and also because the cost effectiveness of the superconducting approach is less clear cut.

f. Beam Cooling — Target Development

The need by experimentalists for increasing beam intensity and beam quality refinement provides a strong stimulus for progress in accelerator development. What appears to be a major new departure is an effort to couple the Indiana cyclotron to a storage ring in which the energy spread of the stored beam will be greatly reduced by "cooling" the beam. This circulating beam will pass through an internal target that is thin enough to preserve the exceptional beam quality of the cooled beam, thus providing a previously-untouched level of precision for experiments with energetic protons. Clearly, an internal target is the cost-effective way to achieve unusual capabilities at other accelerators also, and the technique is likely to be extensively developed during this decade. A big step in this direction is the plan by an Argonne group to develop an internal polarized-deuteron target for the electron storage ring Aladdin.

2. Future Needs

The accelerators in current use for nuclear physics research will continually require additional development to meet new research needs. All of the areas discussed above will see further evolution. Beyond that will be a new set of accelerator development needs specifically associated with new major facility plans. These might include, for example: the development of larger superconducting magnets for cyclotrons that provide ion focusing and bending capability well beyond that of the MSU K-800 now under construction; development of superconducting bending and focusing magnets, new relativistic heavy ion accelerators, which may require magnets with good magnetic field quality over a wide range of magnetic fields and capable of fast cycling. Larger, high current proton accelerators may require development of efficient fast cycling magnet systems much larger than built heretofore, high power accelerating stations, and fast beam switching systems for injection, extraction, and external beam manipulation. The NEAL electron accelerator will require the development of new high power klystrons. These needs for the next generation of facilities will require significant new investment in accelerator development.

New accelerator systems that would provide new levels of experimental capability will require an extensive development in accelerator technology. This program must include research on techniques which are not needed for a specific project but which could lead to dramatic advances in accelerator capabilities. It is hoped that such a program would encourage more scientists and engineers to work in this crucial endeavor. This is necessary to assure that new accelerators be successful and completed in a timely and cost-effective fashion.

IV.3 INSTRUMENTATION FOR NUCLEAR SCIENCE

Nuclear physics rests on a triad of resources: manpower, whose collective knowledge, wisdom and drive for understanding is the motive force; accelerator facilities that provide the essential probes for investigation of the physics of the nucleus; and instrumentation that detects and characterizes the physical processes as they occur. The rate of progress in any scientific area is in large measure fixed to the rate at which hypotheses can be tested and refined or unexpected results uncovered. By its very nature experimental research involves the investigation of new phenomena or the observation of known phenomena with new techniques.

As measurements become more difficult and complicated, the overall design of the experiment becomes increasingly critical. In addition to more advanced detectors capable of handling more information at a faster rate, the methods of data collection and analysis have to be well planned. It is not at all unusual to find the real computer time required for the analysis of data to be twenty times longer than the time for data acquisition. With the advent of higher-energy machines and more sophisticated detector systems, it is evident that instrumentation for data acquisition and data handling must be optimized and make full use of the latest applicable developments in computer technology, otherwise we face a major bottleneck that could absorb huge fractions of the available skilled manpower.

With constrained budgets, the investment in instrumentation and in the expert manpower required for its long-term development has lagged in U.S. nuclear science. This lag was identified in the 1979 Long Range Plan and has been corrected in some measure since then. This is not an isolated problem in nuclear science and "Revitalization of Laboratory Instrumentation" was a subject of a recent workshop by NRC-NAS where the general problem and its possible solutions were discussed. There are major needs and opportunities within nuclear science and it is difficult to establish firm budgetary quotas. Certainly some fraction of the enhancement that has been recommended to the Operating Budgets for FY 1985 should be devoted to instrumentation, to the development of instrumentation, and to manpower associated with it.

A. INSTRUMENTATION TO BE APPLIED TO PRESENT RESEARCH

Modern computing facilities are at the heart of every nuclear physics laboratory. They are essential to the recording, sorting and analysis of data. The computer industry continues to provide a stream of products that allow one to deal ever more effectively with the complexity of energetic nuclear reactions. The newer 32-bit super minicomputers have become the accepted standard at most laboratories and most recent developments are built around such systems. Memory size is no longer an obstacle (at 2 K$/MB) and 500 MB discs are available at 20 K$. As the CAMAC dataway rate can be pushed to 400 kHz with suitable hardware, it appears to be able to handle most experiments for the next 5 years. Those few experiments requiring higher rates can avail themselves of either parallel CAMAC systems or the new FASTBUS system. This system is 10 times faster than CAMAC, operates on a 32-bit structure and allows for more efficient and modern circuit design. FASTBUS with intelligent processors will be especially useful for experiments requiring fast complex triggers. Every effort should be made to keep these data acquisition systems up to date since the new technology permits the basic sharing of software and ready assimilation of technological advances.

Spin polarized projectiles and targets have played an important role in the study of nuclear phenomena. Significant increases have been obtained in polarized hydrogen beam currents and the incorporation of these advances into facilities using polarized beams can provide a 10-fold increase in current. Further work in developing these polarized sources will be actively pursued, partly because of the potential gain they can provide to the thermonuclear fusion process.

Very considerable progress has been made in obtaining increased performance from large NaI photon detectors. Resolution of 2% at 20 MeV has been achieved and an $E^{-1/2}$ dependence of the resolution has been observed from 15 to 45 MeV. These detectors now routinely achieve 2 to 3 times better resolution than was the case just a few years ago. Large arrays of photon detectors subtending nearly 4π are now possible to construct and operate; one is shown in figure IV.3-A. These systems are seen to be essential tools in dissecting the gamma ray

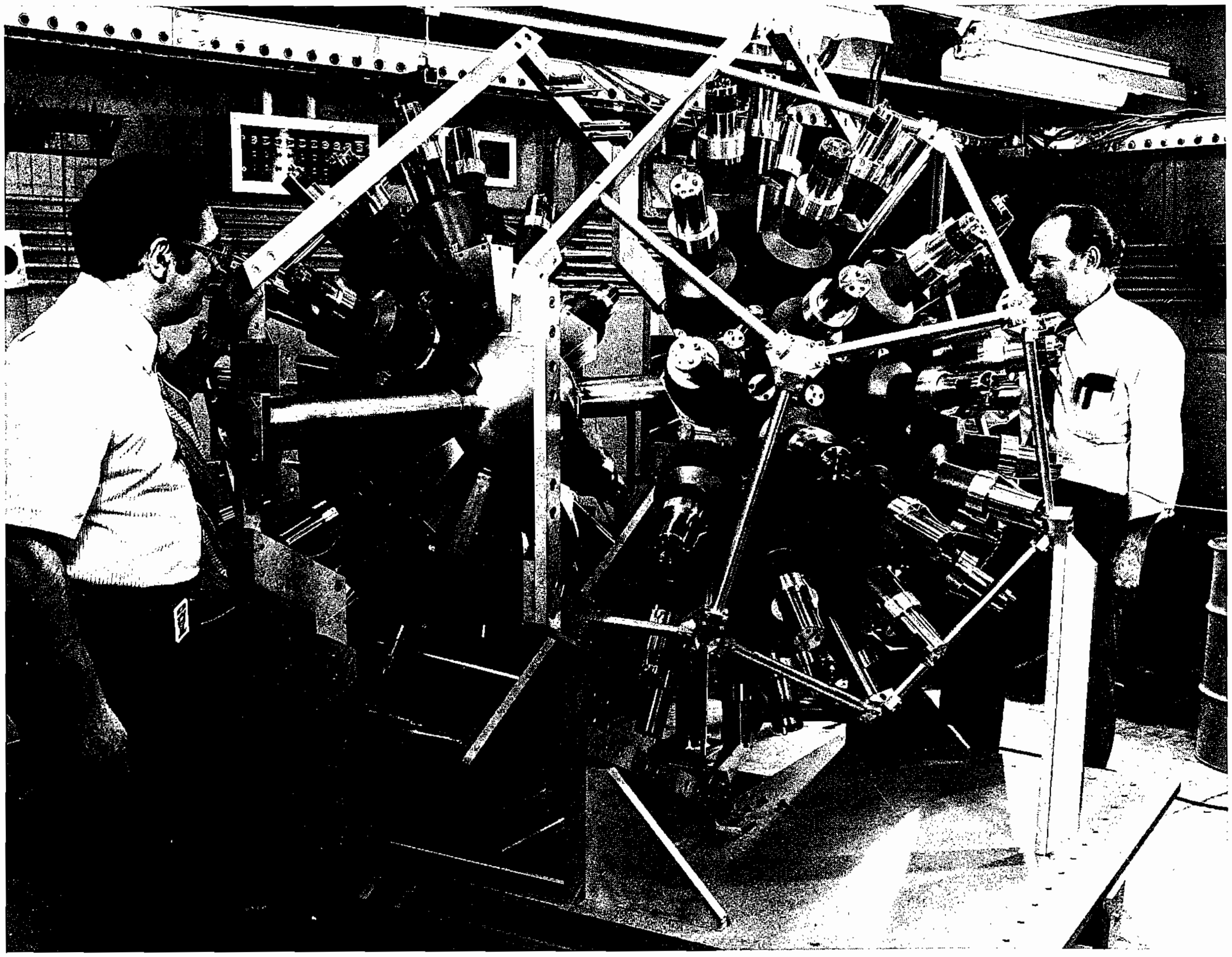

Fig. IV.3-A. An array of NaI photon detectors consisting of 72 elements used at the Holifield Heavy Ion Facility.

cascades in the decay of very high spin ($J \geqslant 40$ units) nuclear states. Many interesting systems which combine features of the very high resolution of Ge with the high efficiency of NaI or BGO have been proposed. The best of these proposals should be funded. If coupled with appropriate systems for analyzing the resulting multiparameter data, they offer unsurpassed power for extracting the properties of nuclei at high excitation energy and particularly, at high angular momentum.

B. PROMISING AREAS FOR NEAR TERM INSTRUMENTATION R&D

Very real opportunities exist to aggressively push certain important areas of instrumentation development that offer high hope for success. The following is not meant to be exhaustive but to indicate the nature of the opportunities.

The complexity of many nuclear reactions now under study and envisioned for the future requires that many parameters be simultaneously recorded to obtain sufficient characterization of the process. Such multiparameter data is not readily analyzed in conventional mainframe computers which function as serial or vector processors. In addition to the analysis of multiparameter data, several classes of problems in a variety of scientific areas would benefit greatly from employing multiple processing elements operating in parallel on the same problem. A development project at LBL using this notion has been able to demonstrate a system with the data analysis capability of a CDC 7600 at 1/20 the cost. Such systems seem capable of extension at modest cost to achieve the order of 100 times the data analysis capability of the 7600. For such systems to be broadly useful, they should be readily transferable and highly interactive. The development of such systems and their widespread use by physicists over the next few years will allow for the timely and effective analysis of the experiments required to further deepen our understanding of nuclear processes.

Polarized beams and targets can be further developed to produce more than a ten fold increase in yield. Particularly exciting and new is the possibility of using polarized gas or vapor in targets. Increases in densities of these targets up to 10^{14} atoms/cm^2 would be highly desirable. In fact, a development program to produce unpolarized jet targets of a variety of materials would greatly enhance the utility of stored circulating beams for nuclear research.

Effective use of the intense neutrino beams produced at LAMPF requires detection of electrons in the energy interval 20-200 MeV. Electrons of this energy have a propensity to readily radiate photons with the attendant problem that it is difficult to measure the energy and direction of the electron. In order to produce high event rates in detection, it is desirable to use inert and inactive material to increase the mass of the detector at low cost. Therefore a careful study should be made of the proper balance between the amount of inert material versus active scintillator that allows adequate determination of the electron energy and direction.

The development of noble liquid ionization detectors offers a real opportunity for breakthroughs in detector technology. They could serve both as high resolution (100 keV at 100 MeV) photon detectors and if operated as time projection chambers, as extremely fine grained detectors (1 mm × 1 mm × 1 mm) with extremely good differential energy loss resolution. The problem to be solved is how to produce large volumes of noble liquids with high enough purity to allow full charge collection.

C. AREAS IN NEED OF DEVELOPMENT

The physics to be done in the future with higher energy beams and particularly with heavy ions requires the development of detection systems far beyond any that have been used in nuclear physics to date. For example, as discussed in Sec. II.5 the search for hidden color via exclusive channels in deeply inelastic electron scattering will involve detection of the decay of excited baryonic states. Such experiments would be very difficult to carry out with present-day spectrometers, which have solid angles of 50 msr, and magnetic systems with acceptances on the order of steradians would be very important. To achieve such a large solid angle requires an extensive R&D program, first to identify the background sources in order to determine how to adequately shield the detector systems, then to design appropriate magnets and particle detection systems, and construct prototypic devices.

The challenges presented to detector physics by relativistic heavy ion collisions are impressive. The extremely high multiplicity, on the order of a thousand or more of final particles, requires a finely segmented detector with a wide dynamic range (10^3). In order to obtain good mass resolution detectors, large area detectors with fast timing properties will be required and again the difficulties presented by the large dynamic range must be dealt with. Potential candidate detectors to perform these tasks exist, but they must be developed, tested and engineered before they become components in the large, expensive detection system that will have to be constructed if we are to efficiently extract the exciting physics from these spectacular collisions.

In general, fine-grained detectors can facilitate whole classes of experiments in which background rejection is a principal concern. In nuclear research, fine-grained detectors with much greater sensitivity are required than are employed in high energy experiments because of the lower energy of the radiations characteristic of nuclear processes. Fine-grained detectors for position measurement and simultaneous good (10%) energy determination would greatly impact experiments such as the search for double beta decay, or neutrino scattering, especially from nuclei, where determining the final state greatly enhances the information content from the experiment.

Thus we are entering a new phase in experimental nuclear physics which requires development of new detector components and their integration into large-scale detection systems. This subject will have to get much more attention over the next ten years than it received in the past decade.

Finally, important areas of our science in which U.S. nuclear theorists require capabilities for large-scale computations are being dangerously impeded by lack of adequate access to Class VI computers.

D. ENRICHED ISOTOPES

The need for enriched isotopes is a continuing one for basic research in the nuclear sciences. It is ironic that the tremendous success of nuclear techniques and the use of special isotopes in medicine and other applied fields has created such heavy demand on the facilities which produce them that the broader inventory of enriched isotopes for sale to basic researchers has been severely depleted. In almost all aspects of nuclear science the need for enriched isotopes is akin to the need of a chemist for pure chemicals. Without them the interpretation of results often becomes less clear and precise. The United States is effectively the world's only supplier of most of the enriched stable isotopes. Users should pay for the replacement cost of the isotopes they consume, and an adequate inventory must be reestablished and maintained.

E. NUCLEAR DATA COMPILATIONS

The ready availability of up-to-date information on the properties of individual nuclides and on nuclear transitions and reactions is an essential resource to our science. The compilation of such data is crucial in making such information generally available to scientists in useful form. It is a matter of some concern that, while experimental data are certainly being obtained and published at a continuing rate, the *compilation* of new data in the areas of interest to basic research activities in nuclear science has slowed down very substantially. While this matter has not been studied by NSAC in some time, it is one of serious concern and should receive more systematic attention in the future.

IV.4 INTERNATIONAL COOPERATION

The benefits from international cooperation arise both from access to unique facilities not available at home and also from the mix of people and ideas at the highest international levels of excellence.

A long-range plan for nuclear science in the U.S. must be viewed in a worldwide context. Nuclear research is an international enterprise carried out at a network of laboratories in the developed countries of Europe, in Canada, Japan and in the U.S.A. The evolution in style of nuclear research toward concentration in a small number of large facilities is also a global phenomenon. The U.S. basic nuclear research program is substantially the largest national program in the world, both in manpower and resources; it leads the world in many important areas of the field. Yet the U.S. program cannot and should not attempt to dominate across the entire spectrum. Our long-range plan must maintain balance between two competing requirements. On the one hand, it must be sufficiently broad in scope and rich enough in new initiatives to ensure internal viability. On the other hand, it must avoid weakening itself by trying to cover all eventualities, duplicating in the process major facilities that exist elsewhere.

The development of a worldwide network of facilities is relatively recent in the history of nuclear physics. After the Second World War, when the field began to grow rapidly, much of the work was carried out with small low-energy accelerators—cyclotrons, electron linacs, and Van de Graaff accelerators. The United States was in a position of world leadership and, by the late 1960's, developed a system of over 100 such accelerators, many of them university based. This program was followed by the development of many similar accelerators elsewhere in the world. In the pursuit of nuclear structure and nuclear reactions, much was gained by competition between similar laboratories in different countries and by the free exchange of ideas and of people.

Building on the knowledge of the nucleus established with smaller accelerators, new directions in nuclear physics were initiated in the 1970's as nuclear physics developed a number of large user facilities, which brought the need for international cooperation into sharper focus. These large facilities cannot encompass all of the possible experimental facilities important for basic nuclear research. In a number of cases, the facilities in the United States are (or will be) unique and attract considerable interest from abroad. In other cases, facilities abroad are complementary to those in the United States and attract American users.

The new experimental facilities—the 4-GeV CW electron accelerator previously recommended by this Committee and the colliding-beam relativistic heavy-ion accelerator—identified here as major opportunities for the future, are unique; they will attract users from all over the world. The Bevelac, too, is unique and has attracted long-term user groups from Germany and Japan who have brought with them millions of dollars for ancillary instrumentation. LAMPF has unique features in energy and intensity, and attracts users from around the world, even though there are two other "meson factories" in Switzerland (SIN) and Canada (TRIUMF) operating at lower energies and beam currents, though with higher duty cycle. The new injector of SLAC will be unique for nuclear physics in the world, and will surely attract scientists from abroad. Many other facilities have significant international user groups.

On the other hand, many American groups and individual scientists are carrying out nuclear research at various installations outside the United States, at facilities which have capabilities unmatched within this country. Examples of such capabilities are the energetic uranium beams at the German heavy-ion facility (GSI), the polarized proton and deuteron beams up to 3 GeV/c at Saturne II in France, the good duty cycle pion and muon beams at TRIUMF and SIN, the low-energy antiproton storage ring LEAR at CERN in Switzerland, the intense thermal, cold, and ultracold neutron beams at ILL in France, and the separated kaon beams at KEK in Japan. Approximately three to four million dollars were spent on such work in FY 1983.

Another important aspect of the international nature of our science is the investment by one country in equipment placed at unique research facilities of another country. Examples are the plastic ball detector at the Bevalac (built largely by GSI, Germany), the π^0 spectrometer at LAMPF (built with major participation from Tel Aviv

University, Israel), and major new detectors at the Bevalac (built by the INS, Japan), the possible participation by the Max Planck Institute (Germany) in the construction of the gallium solar neutrino detector, and the participation by the U.S. in heavy-ion acceleration by the PS and the SPS at CERN. Such international collaborations should be encouraged. They enable scientists in a country to play a major role in an area of physics in which their country has no existing facility. In addition, they also can help ease the financial burden of instrumentation on the country constructing a new facility. Nevertheless, one must be careful that the construction schedule and useful implementation of such a facility not be unduly delayed by the vagaries of international negotiations.

As more large facilities come into existence, their unique properties have to be considered not only as a national but as a worldwide scientific resource. At present, exchange arrangements are handled on a person-to-person or laboratory-to-laboratory basis. We believe that these arrangements are working well and see no present need for a more formal administrative structure.

Visits by American scientists to foreign laboratories and by foreign scientists to the U.S. should be encouraged in whatever ways are feasible. This is an important and cost-effective part of scientific activity, especially with the recent advances in the scientific importance of many European laboratories. The costs are low and the beneficial impact can be enormous. The worldwide network of nuclear laboratories and the international participation of scientists in research at American laboratories is a vital resource for nuclear science in the United States.

IV.5 BUDGETS

The sociology and economics of science is a complicated matter. How much should a society spend on basic research? How does the long-term development of high technology, of technically skilled and innovative manpower, of industrial development in general, of the standard of living and of the quality of life depend on a society's investment in basic research? This broad and complex subject cannot be treated here in detail. The scientific questions confronting the field of nuclear science at this juncture represent a major opportunity for an increase in our knowledge and understanding of the physical world and a potential source of many societal benefits. The role of the United States as a technological and scientific leader among advanced nations is an important one and the financial support of this basic research effort is crucial for our country's future productivity. The primary economic resources for the pursuit of basic nuclear research in the United States are the budgets allocated by the Federal Government annually through the Department of Energy and the National Science Foundation.

In this section we summarize the past and present funding levels, compare the United States budget to that of other countries, and then present our recommended budget projections for the next decade.

A. PAST AND PRESENT FUNDING OF BASIC NUCLEAR RESEARCH IN THE UNITED STATES

As a standard of comparison for the funding of basic nuclear research, we show the history of funding in the U.S. in two ways. In figure IV.5-A, we see the combined DOE/NSF budgets for basic nuclear physics research, converted into 1983 dollars by the Consumer Price Index. It is certainly true that the cost of research, particularly in instrumentation, has risen more sharply than the consumer price index—we have not attempted to correct for such effects here. But even so, the total level of funding of basic nuclear research averaged about 210 million FY 1983 dollars annually in a five year period centered about 1970 and declined to 170 million FY 1983 dollars in the five

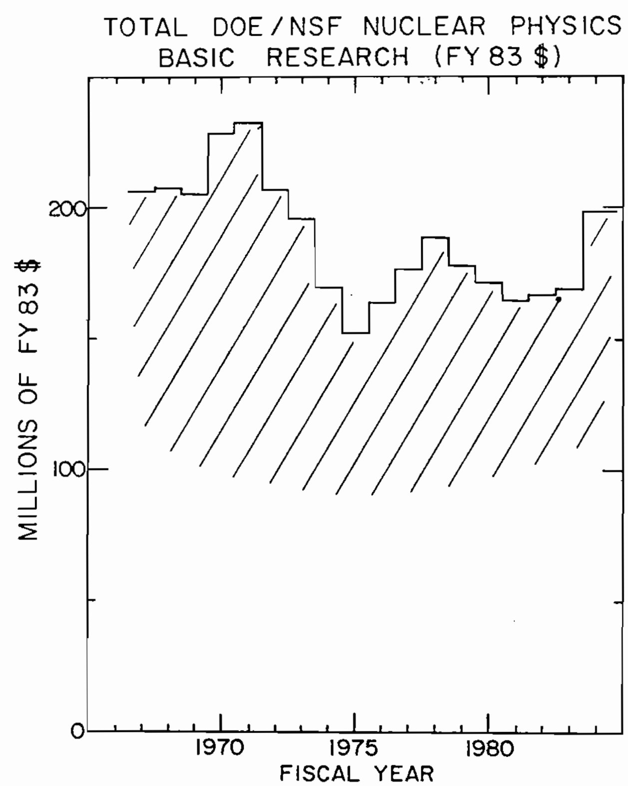

Fig. IV.5-A. The total DOE/NSF budget for basic research in Nuclear Science since 1967, in constant FY 1983 dollars, as measured by the Consumer Price Index. The eventual value for the FY 1984 budget will be somewhat lower than shown since the 1983 CPI was used for the value shown in this plot.

year period centered on 1980, a 25% decline for the decade.

But should basic research be maintained at a fixed level of dollars? Or should a nation and a society invest in its future by putting at least a constant fraction of its effort, the Gross National Product, into basic research. Figure IV.5-B shows the combined nuclear physics budgets as a fraction of our Gross National Product and the decline of the early 1970's becomes even more dramatic.

While each way of analyzing these budgets is open to some criticism—the qualitative impression from both is correct—that the United States investment in basic nuclear research decreased substantially about ten years ago and has remained at this lower value until recently. This puts it considerably below both the *absolute* level of investment of a roughly comparable unit, the European Economic Community, and also substantially below Europe in the *relative* fraction of GNP in this investment, as we will see later.

The vitality of science rests on a delicate combination of factors: historical, social, psychological and economic. There is no question that the real decreases in funding of a decade ago had a depressing impact on U.S. science, out of proportion to the strict economic impacts of the cuts. This impact manifests itself in a number of aspects, such as the attractiveness of the field to graduate students and the incentive to invest in new instrumentation rather than make do with existing equipment. Yet training of skilled manpower and challenging technological frontiers with advanced instrumentation are important by-products of basic research.

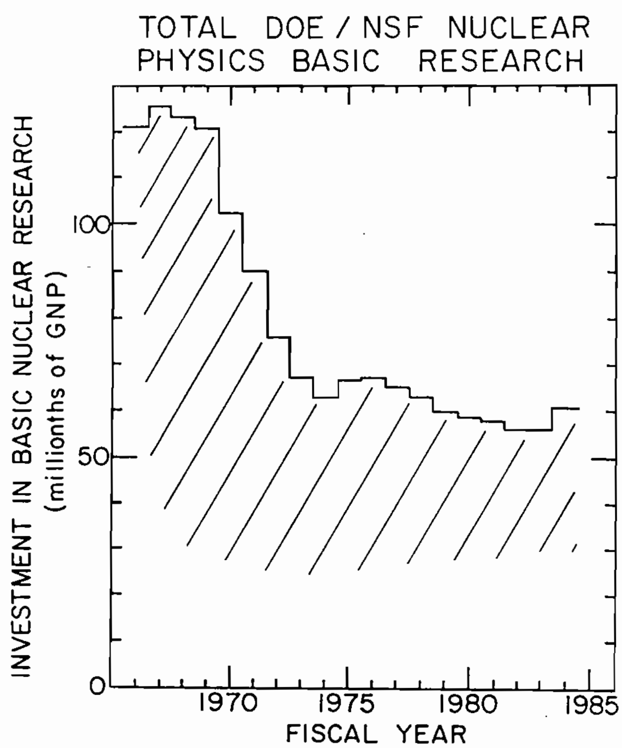

Fig. IV.5-B. The total DOE/NSF budget for basic research in Nuclear Science since 1967 as a fraction of the Gross National Product. The FY 1983 and FY 1984 budgets are likely to be somewhat lower than shown here since the Gross National Product was not yet known for those years.

B. INTERNATIONAL COMPARISONS

Since the rate of investment in basic research for a society is poorly defined, we compared the U.S. investment in nuclear physics to that for countries with similar levels of technology and standards of living: some of the major countries of Western Europe and Canada. Such a comparison is obviously complicated by significant differences in methods of funding and accounting systems. The numbers quoted below have been compiled with some effort to eliminate bias resulting from such differences.

In Europe we obtained data for Belgium, Germany, France, Italy, the Netherlands, Switzerland and the United Kingdom, which between them account for over 85% of the population and of the gross national product of western Europe.

The support for research in nuclear physics abroad is generally from two sources: 1) DOE/NSF-like agencies that support both national laboratories and university-based research groups. Such support accounts typically for about 80% of expenditures for basic nuclear research and fairly reliable numbers are available. 2) University support to research groups, mainly the salaries of physicists and technical support staff. Direct support of research other than salaries is, in general, small. In certain countries there are major university contributions to the operation of experimental facilities; these have been included. For the salaries of university-based researchers, we used, as a rule, 50% of their estimated salary, with the other half assumed to be for teaching. The cost for university administration and overhead has not been included since it is largely directed towards education rather than research. The budgets were extracted from the reports of agencies, long-range plans of individual countries, national studies giving the breakdown of support from different sources, and estimates of the university salaries prepared by either faculty members in the individual countries or by the agencies. For the countries with the larger fraction of the expenditures, Germany, France, Switzerland and the United Kingdom, the relevance of the numbers extracted, corrections and consistency checks were established by discussions with scientists experienced in the funding patterns of the individual countries; these checks indicated that the numbers are reasonably accurate.

The budgets for the U.S. were obtained from the DOE and NSF, with the university contribution estimated from the number of DOE/NSF supported university-based physicists and the average salaries deduced from DOE/NSF summer salaries. The budgets for Canada were obtained in a similar fashion.

The numbers on manpower result from a recent survey carried out by the European Science Foundation (ESF), which, in 1982, determined for all European countries the number of Ph.D. physicists, technicians and graduate students working in basic nuclear research.

The budgets for 1982 were related to the gross national product also for 1982, to avoid fluctuations in exchange rates. The results are summarized in Table IV.5-1.

TABLE IV.5-1
Comparison with Other Countries

	U.S.	Other Advanced Countries[a]
Population (millions)	233	284
1982 GNP (Billions of 1982 US$)	3059	2377[b]
Per Capita GNP (Thousands of 1982 US$)	13.1	8.4[b]
1982 Investment in basic nuclear research (Millions of 1982 US$)	170	305[b]
Ratio of 1982 investment in basic nuclear research to 1982 GNP (Millionths)	56	129[c]

[a] Includes Belgium, Canada, Germany, France, Italy, Netherlands, Switzerland, and United Kingdom.
[b] Currency conversion rates for 1982 from U.S. Statistical Abstracts, Dept. of Commerce 1983.
[c] Ratio computed in country's own currency to avoid fluctuations in exchange rates. Averaged by weighting each ratio by the 1982 GNP for that country.

As may be seen, an average of ***129 millionths*** of the GNP was invested in basic research in nuclear physics in 1982 for Canada and the European countries considered, while for the United States, this fraction is about ***56 millionths,*** more than a factor of two lower. Since for the different countries the total investments in basic research in nuclear physics vary greatly, we also considered this investment as a function of *per capita GNP.* This is shown in figure IV.5-C. For Europe and Canada, the investment, as a fraction of GNP, is described by a roughly linear function of the per capita income, with the scatter of points not very much larger than the uncertainties and the arbitrariness introduced by fluctuating exchange rates. The U.S. is almost exactly a factor of three below this line, considering its per capita GNP.

As may be seen in figure IV.5-C. a high level of economic productivity is closely related to substantial investment in basic research. This effect goes in two directions: (1) Research in basic and applied science and the related education in the development and use of frontier technology leads to the broader application of high technology and an increase in productivity and the standard of living. (2) Conversely, a country with a higher level of technology both *needs* to invest in research to maintain its lead, and can also afford to invest an increasing fraction of its national effort in basic research with long-term payoffs.

Comparison between the U.S. and Europe and Canada, demonstrates that the U.S. effort and investment in basic nuclear research is significantly and substantially lower. This is probably also true of other areas of physical research for which we do not have the detailed data available.

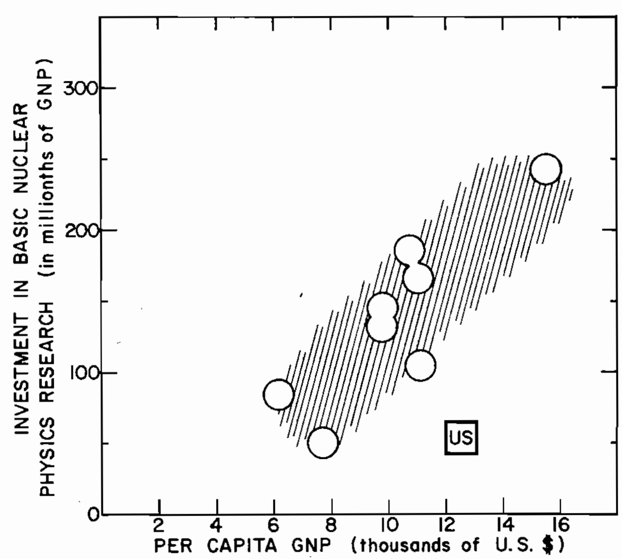

Fig. IV.5-C. Comparison of the level of investment in basic research in Nuclear Science with per capita income in 1982 in various advanced countries listed in the text. There appears to be a systematic trend of higher investment for the wealthier countries, but the U.S. is conspicuously low.

A comparison can also be made of the number of Ph.D. physicists working in basic nuclear research. Again, there is a rough correlation with the GNP per inhabitant, although the scatter is larger. There are about six nuclear physicists per million inhabitants in the U.S. compared to ten in European countries with similar per capita GNP.

Quite apart from all such quantitative data, visits to European laboratories give an even more compelling picture. The judicious investment by many European nations over the past decade in instrumentation and technical support has paid off: these laboratories are characteristically better equipped for frontier research in nuclear physics than are their U.S. counterparts, and this difference is evident to even the most casual observer. Moreover the number of students involved in nuclear physics in Europe is relatively much higher than in the U.S. and their level of commitment, of excitement and of dedication is impressive. That these things are so is no accident, they reflect more than a decade of severe constraints and slow starvation of nuclear science in the U.S. and a corresponding period of well-considered investment in Europe.

C. BUDGET PROJECTIONS

The major incremental elements entering into our budget considerations are as follows:

1) The level of funding for nuclear science has been very severely constrained in the past decade. The strong recommendation of NSAC to increase the operating and capital equipment funds by a $20 million step was transmitted in a letter of April 29, 1983. This was our estimate of the *minimal funds* required to bring the field of nuclear physics to a level of funding commensurate with the challenges confronting it by adequate utilization of the relevant facilities in existence and under construction. We recommended that these incremental funds be used for instrumentation programs associated with major scientific opportunities, for better utilization of facilities, and for programs to encourage user groups and young investigators. *We strongly recommend that this total of about $220 million (FY 1983 dollars) per year, be maintained as a minimal level of support for the continuing program of research with facilities in existence and now under construction in order to face up to some of the opportunities discussed in Chapter II.* In our plan we assume this level to constitute the base program.

2) We assume the NEAL 4-GeV electron accelerator will be constructed, as discussed in the report of the NSAC Panel on Electron Accelerator Facilities, and that the concomitant budget for operating this facility will be incremental to the base program, in accordance with the transmittal letter of April 29, 1983. Since the 4-GeV electron accelerator is at one of the most exciting frontiers of our science, and will be a national user facility, it will require incremental support for user groups in addition to the resources allocated for the operation and in-house research efforts of the NEAL facility. We estimate these incremental costs for user support to reach their full level of about $6 million in FY 1989, the scheduled start up year for NEAL, but to begin gradually at least three years earlier.

3) Finally we estimate, very roughly, the cost of a new colliding beam, relativistic heavy-ion facility at about $250M (FY 1983 dollars) including initial major detection apparatus. A similar rough estimate for the operating and in-house research costs is about $35M (FY 1983 dollars) annually. The detailed refinement of specifications for this facility and for the associated instrumentation, and thus of cost, will have to be the subject of more careful future study.

The projected funding we recommend for basic nuclear science research is shown in figure IV.5-D. After construction of the relativistic heavy ion collider the equilibrium budget level we estimate at $270M per annum in FY 1983 dollars.

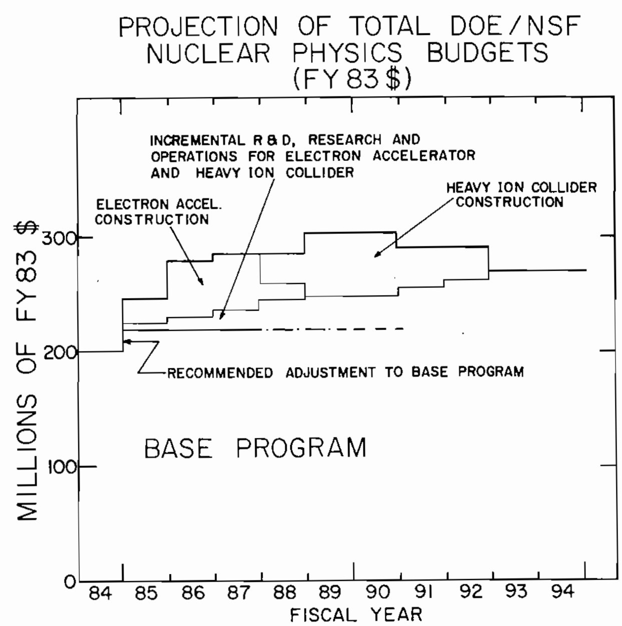

Fig. IV.5-D. Projected DOE/NSF budgets for basic research in Nuclear Science through 1994 in FY 1983 dollars. The present base program and the increment recommended by NSAC is shown for FY 1985. The estimated construction budgets for the 4-GeV electron accelerator facility and for the Heavy Ion Collider are shown as well as the incremental levels of operating funds.

D. TRENDS WITHIN THE BASE PROGRAM

The budgetary implications of pursuing the most important scientific goals will have to be considered carefully over the next decade in the context of specific decisions and programs. A comparison of major categories between FY 1977 and the average of the last three years (1982-1984) is shown in Table IV.5-II. The fraction of the budget in construction projects in 1982-1984 was about 9%—we recommend for the coming decade that a similar fraction of the base program be used for the most attractive new smaller construction and upgrade projects. The fraction of the total budget for instrumentation is approaching 10%, including not only the Capital Equipment budgets in DOE but also estimates of DOE operating funds used toward this goal and the fraction of operating funds used for instrumentation within the NSF budget. We comment on long term instrumentation development and planning needs elsewhere in this report—both DOE and NSF appear to be sensitive to the crucial importance of these activities.

TABLE IV.5-II
Fractional Distribution of Expenditures

	FY 1977	Average of FY 1982, 1983 1984
Theoretical Research	5.3%	6.2%
Experimental Research	35.3%	35.6%
Facility Operations	42.3%	39.8%
Instrumentation	8.2%	9.3%
Construction	8.9%	9.1%

The fraction of the nuclear physics budgets devoted to theory has increased by $\sim$20% since 1977. The 1979 Long Range Plan stressed the need for increased support of nuclear theory. It is gratifying to see that this recommendation has been implemented even under the very stringent budgets of the past years, but we certainly recommend that opportunities for supporting strong theory programs not be neglected and that resources be made available as suitable opportunities present themselves. A strong theory program is an important component in the national effort in nuclear science.

V. IMPLICATIONS OF SCIENTIFIC OPPORTUNITIES

Many important and challenging scientific opportunities are confronting our field, as is apparent from the Scientific Questions posed in Chapter II. We here wish to present the major implications of these opportunities in terms of resources.

Recognition of some of the simplicity and symmetries underlying nuclear structure has enabled us to begin to work toward a new level of correlation of nuclear data and an understanding of the microscopic origins of that structure. The discovery of entirely new structural phenomena such as the observation of spin-flip giant resonances, have been matched by the observation of entirely new reaction mechanisms, such as deep inelastic scattering, that are not yet fully understood. New classes of accelerators are beginning to permit study of the structure of the nuclear continuum and of how the nuclear many-body system responds to increasing energy and angular momentum. Whole new parameter ranges are being opened for the first time to precision study.

There are interesting and vital open questions in nuclear physics that require investigation and understanding in nuclear structure and in the dynamics of nuclear interactions that hitherto were inaccessible. We will be able to address these now or in the near future with new or newly upgraded facilities, or ones that are presently under construction. These provide advanced new capabilities for the study of electromagnetic interactions at energies below 1 GeV, of nucleus-nucleus collisions with improved capabilities in the regime of normal nuclear dynamics and in the transition region around the nuclear "sonic barrier," and of light-ion reactions using the high resolution capabilities of stored and cooled beams. Exploitation of these capabilities holds great promise for scientific advances in the near term.

A new theme in nuclear physics that emerges in this report concerns the implications of *QCD*, the fundamental framework for our characterization of the strong interaction, in the nuclear many body system. This theme shines through a number of the topics that are discussed in Chapter II. In particular, the 4-GeV electron accelerator recently endorsed by NSAC is an important tool to address these questions. Both in this field and in the domain of electroweak interactions, traditional dividing lines between nuclear physics and particle physics are shifting. This is certainly healthy; the divisions are perhaps somewhat historical and sociological in origin, but there are also real, important differences in intellectual perspectives, particularly in the appreciation by nuclear physicists of the importance of many-body dynamics and the real possibilities that collective phenomena contain new physics and qualitatively new insights into the fundamental nature of matter.

The facilities and instrumentation needed to confront a variety of important opportunities in the future are discussed below by classifying them according to the types of particle beams.

Relativistic Heavy Ion Collider

In this Long Range Plan, we identify the scientific opportunities presented by an accelerator that can provide colliding beams of very heavy ions at about 30 GeV per nucleon and recommend that it be the next major construction project for nuclear science.

Having made the above recommendation, we note that this will be a project of unusual magnitude for our field. Both the accelerator ideas and the underlying physics concepts of this recommendation were pioneered in the United States. Considerably more R&D will have to be expended, both prior to formal proposals and during the construction phase of the accelerator. Although the design of the accelerator is within the framework of existing technology, many problems and alternative solutions will have to be studied. Various possible ion sources, techniques of injection and acceleration of the heavy ion beams, and the design of the appropriate magnet structures are among the features that need attention.

The detector problems will be formidable. Although multiplicities (the number of particles produced in a single collision, that will have to be detected simultaneously) will, in general, be substantially higher than in nucleon-nucleon collisions at very high energies, the requirements on spatial resolution of detectors, or granularity, may not be much greater. Important physics may be signalled by the number of strange particles relative to ordinary hadrons, by di-lepton pairs, or simply by the flow pattern in the thousands of reaction products. Detector systems for all these experiments will have to be thought out, designed and built with the same amount of care as the main facility. Since the scale of these detectors will be comparable to those used in high energy physics, that experience will have to be used as a basis of further R&D efforts.

The only present facility for research with relativistic heavy ions in the U.S. is the Bevalac, and with the variety of beams and energies available, it is a unique facility anywhere. Some beams at higher energies will probably be available sporadically at CERN over the next few years. In order to begin to understand the problems associated with the physics of the future colliding beam accelerator, it would be desirable to carry out experiments in the U.S. with heavy ions at energies significantly higher than those of the Bevalac. Such measurements would provide needed data concerning nuclear stopping power, particle multiplicities and detector technology. Exploratory experiments at energies that will begin to test our ideas about nuclear compressibility and attainable nuclear densities can attract the new generation of scientists, as well as provide the experience that will be essential to the development of the physics program over the next decade at this new collider facility.

In the preconstruction phase it is especially important that NSAC and suitable workshops and subcommittees be charged with giving advice periodically on the best course for the physics program, accelerator characteristics, and detector needs associated with this major scientific endeavor. Since this is a border area, of close interest to high energy physicists, some attention should be given to including leading members of that community in the process of helping specify the course of this new undertaking.

Pions, Kaons, Muons, Neutrinos, and Antiprotons

The pion capabilities of LAMPF are being utilized in a strong program of experimental studies. The use of pions in nuclear structure physics, exploiting their sharp spin-isospin selectivity in the delta region, is an outstanding and unique opportunity. There is a possibility for enhancing our present capabilities through a new pion channel, allowing access to higher energy pions as well as improved resolution, counting rate, and possibly duty factor. Such a new pion beam should be coupled to a new high resolution pion spectrometer. The characterization and understanding of the behavior of the delta (the simplest nonnucleonic excitation) in the nucleus is an important element in much of hadronic nuclear physics. A large solid-angle multiparticle spectrometer may be important for this work.

The electroweak theory of Glashow, Salam, and Weinberg has had spectacular confirmation with the discovery of the intermediate vector bosons, the $W^{\pm}$ and Z° at CERN. This theory and QCD constitute the Standard Model which forms the basis of nuclear interactions. Numerous opportunities exist for probing the validity of this model. Improved kaon beams can be used to search for decays and other processes not present in the Minimal Standard Model. Better neutrino beams coupled with high granularity, high mass, tracking detectors can search for new interactions beyond those of the standard model, and for neutrino oscillations. Muon beams with improved duty factor can be used, for instance, to search for muon number nonconserving processes. Neutrino-nucleus scattering could further probe the structure of the weak neutral current. Such reactions also provide a tool to probe new aspects of nuclear structure.

Improved kaon facilities could provide much better counting rate and better resolution for important studies of hypernuclei. Higher energy kaon beams and spectrometers would allow searches for the as yet unobserved doubly strange states of hypernuclei. These same facilities would make possible the use of kaons for inelastic scattering and for studies of strange resonances in nuclear matter.

Antiprotons can provide a unique tool for probing the foundations of the strong interaction, for studying possible exotic quark configurations, and for producing a very hot small region within nuclear matter. A new source appears to be beyond the resources of our community. However, an antiproton storage ring, or possibly a new time separated antiproton beam, at an existing facility may provide a unique opportunity for cost-effective experimentation with antiprotons.

A major new "Kaon Factory," a 10-30 GeV proton accelerator with 10^{14}-10^{15} protons per second, would provide substantial opportunities for physics in all of these areas. This physics is clearly very fundamental, important, and exciting. Given our commitment to the construction of the National Electron Accelerator Laboratory and the heavy ion collider discussed above, the financial assumptions of this report preclude a major additional facility. But as circumstances change, we want to keep this important option readily available: it clearly presents many unique opportunities.

In the meantime we have many opportunities for physics which can be done without such a major new accelerator. Among these opportunities are new experiments on solar neutrinos, experiments on nuclear beta decay and double beta decay, and opportunities to take advantage of new kaon beams, new muon facilities, new neutrino beams and detectors, and new pion beams and spectrometers at existing accelerators.

Electromagnetic Facilities

It is clear that electromagnetic probes will play an increasingly important role in many areas of nuclear physics. Questions about the nucleon-nucleon interaction, about connections to QCD and the quark structure, about the hadronic structure of nuclei, elementary excitations and nuclear-structure symmetries, all require electromagnetic probes. The **new 4 GeV electron facility at NEAL is clearly the major near-term new initiative in nuclear physics**. Its completion is awaited eagerly by our community. The cost of this accelerator and that of its first generation of experimental facilities was discussed and estimated in the report of the NSAC Panel on Electron Facilities, which also noted that a strong scientific case can be made for CW electron capability with high resolution below 1 GeV. We see such a lower-energy capability as a major opportunity for the field in studies on the deuteron, on hadronic degrees of freedom, particularly in the delta regime, on many aspects of the elementary excitations and structural symmetries of nuclei and, with longitudinally polarized electron beams, on the structure of semileptonic neutral weak currents.

Light Ion Facilities

Light ions are the oldest probes of nuclear structure. Yet as the scientific questions show, refinement of these probes has yielded qualitatively new discoveries of fundamental importance, and holds great promise for the future. Scientific opportunities call for the upgrade of existing facilities to yield variable energy protons in the energy range from 200-500 MeV, polarized protons in this region and below with substantially improved intensity and reasonably intense polarized proton beams at variable energies up to several GeV. They also call for secondary polarized neutron beams of useful intensities with energies to at least 200 MeV (up to perhaps 60 MeV this can be accomplished with upgrades of existing facilities, but the higher energy neutrons may require a new facility).

Heavy Ion Facilities

With energies below 200 MeV per nucleon, the facilities that exist or are under construction have many of the features that are required to study the key scientific problems in the area. The completion of the National Superconducting Cyclotron Laboratory and of ATLAS will be major innovative technical achievements and provide important new capabilities. One still needed is the ability to obtain very heavy (up to uranium) beams of variable energy between 3 and 20 MeV per nucleon, a capability that is important in nuclear structure studies, and that could become critically important if present indications of long-lived nuclear molecules in very heavy systems are confirmed. There are needs for larger detector systems in heavy-ion physics, in arrays of photon detectors and in large area systems for charged particles, all requiring adequate data handling systems.

Manpower

The importance of having sufficient skilled and innovative scientists is evident, especially in view of the new initiatives considered here. This is not an issue readily amenable to administrative action. In Sec. IV.1 we identified a number of measures that should be taken to assure adequate training of new manpower, though the intellectual vitality of the problems facing us is likely to be the most important advantage in attracting a new generation of physicists.

The support for nuclear theorists has increased since the last Long Range Plan from 5 to 6% of the total nuclear physics budgets. This is a necessary trend, since much of the physics confronting us requires careful prior theoretical thought and substantial theoretical interpretation of the results. We recommend that this trend be continued.

International collaborations are becoming of increasing importance to nuclear physics around the world, and we are pleased that the funding agencies are doing their best to facilitate these. An important issue is the ease with which foreign travel can be arranged, both for U.S. scientists abroad and for arranging visits by foreign scientists in the U.S. The easy interchange of people and ideas is essential to a healthy science and should be facilitated.

Budgets

The U.S. investment in basic nuclear research in FY 1984 will be close to 200 million dollars. This can be compared with the trend in other highly developed countries, as shown in figure IV.5-D, which would correspond to a budget of $400-600 million per year. Such comparisons merit serious consideration, not only in nuclear physics but in all areas of basic research in the physical sciences. Enormous benefits to the nation, direct and indirect, would accrue from a major long term initiative to upgrade American investment in basic science to a level approaching that abroad.

It is beyond the scope of this Committee to recommend such an overall initiative. But it *is* our responsibility to recommend what we consider a *minimal* budget to maintain the vitality of nuclear science in the United States and to address some of the most urgent and important current issues. We thus reaffirm our recommendation of April 29 this year, that as a base program, the 200 million dollars of the 1984 budget be augmented by 20 million dollars as soon as practical to improve the utilization of our existing resources for research in nuclear science. We also reaffirm our endorsement of the recommendation for a 4-GeV electron accelerator facility. In the longer term, we identify a new opportunity to explore the behavior of matter at extremely high energy densities, densities which hitherto have occurred only in the early moments of the creation of the Universe, and recommend construction of an ultra-relativistic heavy-ion collider to address this opportunity. These studies have great potential for fundamental discoveries.

There are profound and challenging scientific issues confronting nuclear physics. With the requisite scientific manpower, facilities and budgets, nuclear science in the United States will be in a strong position to lead the international process of scientific discovery and of increased knowledge and understanding of the world we live in.

APPENDIX A

Department of Energy
Washington, D.C. 20545

June 23, 1983

John P. Schiffer, Chairman
DOE/NSF Nuclear Science Advisory
Committee
Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Dear John,

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee (NSAC) conduct a study of scientific opportunities and priorities in U.S. basic nuclear research and that NSAC develop a long range plan which will serve as a framework for coordinated advancement of the Nation's basic nuclear research programs over the next decade. The 1979 Long Range Plan is an appropriate and important reference document for the long range plan which you will be formulating. However, because our field has evolved so rapidly over the past four years, you should naturally expect to identify exciting scientific opportunities not cited in the 1979 Plan and, alas, should expect some of the bright hopes of 1979 to have proved to be blind alleys. Please submit your report to the Department of Energy and National Science Foundation by September 1, 1983.

The requested NSAC study comes at a most interesting and critical time in the history of American basic research. While the United States has a distinguished record of accomplishment and leadership in basic nuclear research, we face formidable challenges from Western Europe, Japan, Canada, and other nations. These countries have enormously strengthened their basic nuclear research programs over the past decade. The new long range plan should discuss both the steps needed to maintain America's position of leadership and also identify opportunities for cooperation with other countries on projects of mutual interest.

The new long range plan must first and foremost attempt to identify the most important nuclear physics questions to be attacked in the next decade. Having identified the scientific opportunities, the long range plan should tell us what resources are required to pursue these opportunities. The resources to be discussed include capabilities of nuclear physics facilities, instrumentation, manpower, and funding. The discussion of manpower requirements must include examination of ways in which some of the best minds may be attracted to nuclear physics.

We admire and appreciate your courage as you begin this task. The effort will be considerable, but the importance of this work to basic nuclear research in the United States will also be considerable. We look forward to your advice.

Sincerely,

James E. Leiss
U. S. Department of Energy

Marcel Bardon
National Science Foundation

APPENDIX B

Agendas for the 1983 Meetings of the Nuclear Science Advisory Committee

DOE/NSF Nuclear Science Advisory Committee

January 12, 1983
Room 338
National Science Foundation
1800 G Street, NW.
Washington, DC

Tentative Agenda

9:00 a.m. - Opening remarks by the Chairman (Schiffer)

9:30 a.m. - Remarks by representatives of the funding agencies (Leiss/Bardon)

10:00 a.m. - Discussion of DOE and NSF budget situations for FY 1983 (Ritter/Willard)

* 10:30 a.m. - Status of the Long Range Plan (Schiffer/Feshbach)

11:00 a.m. - Discussion of procedure for proposal evaluation (Schiffer/Leiss/Bardon)

12:30 p.m. - LUNCH

1:30 p.m. - Continuation of discussion of procedure for proposal evaluation (Schiffer/Leiss/Bardon)

* 2:30 p.m. - Discussion of procedure for developing the new Long Range Plan (Schiffer)

3:00 p.m. - Discussion of subcommittee reports and other business (Schiffer)

4:30 p.m. - ADJOURN

The items on the agendas where the Long Range Plan was discussed are marked with an asterisk.

REVISED
February 8, 1983

DOE/NSF Nuclear Science Advisory Committee

February 16, 1983
Room 8E-089
Forrestal Building
1000 Independence Avenue, SW.
U.S. Department of Energy
Washington, D.C.

Tentative Agenda

9:00 a.m. -- Discussion of DOE and NSF budgets for FY 1983 and FY 1984 (Ritter/Willard)

* 9:30 a.m. -- Presentation and discussion of scientific plans at Lawrence Berkeley Laboratory

* 11:00 a.m. -- Presentation and discussion of scientific plans at Brookhaven National Laboratory

12:30 p.m. -- LUNCH

* 1:30 p.m. -- Presentation and discussion of scientific plans at Los Alamos National Laboratory

3:00 p.m. -- Discussion with Alvin W. Trivelpiece

3:30 p.m. -- Discussion of draft report of the Subcommittee on University Research and Education in Nuclear Science (Huizenga)

* 4:00 p.m. -- Discussion of the Long Range Plan

6:00 p.m. -- ADJOURN

The items on the agendas where the Long Range Plan was discussed are marked with an asterisk.

Tentative Agenda for NSAC Meeting

U.S. Department of Energy
Room 1E-245, Forrestal Bldg.
1000 Independence Ave., SW
Washington, D.C.

April 22 and 23, 1983

April 22 -- Friday:

	9:00 - 12:00		Discussion of the Draft Report of the Electron Facilities Panel D. A. Bromley
*	1:30		Discussion of Long Range Plan
	Working Group Reports:		
*	2:00	Theory	G. E. Brown
*	2:30	Light Ions	S. M. Austin
*	3:00	Heavy Ions (non-relativistic)	D. A. Bromley
*	3:30	Eletromagnetic Probes	J. D. Walecka
*	4:00	Pions, Kaons	E. W. Vogt
*	4:30	Weak Probes	F. Boehm
	5:00	Relativistic Heavy Ions	G. A. Baym

April 23 -- Saturday:

*	9:00	Information on Facilities and Accelerator Techniques H. Grunder
*	9:45	Relationship to Other Basic Sciences A. Schwarzschild
*	10:00	Application to Societal Needs K. A. Erb
*	10:15	Instrumentation

The items on the agendas where the Long Range Plan was discussed are marked with an asterisk.

* 10:30	Other Aspects of Long Range Plan Budgets Manpower Training Scope Organization
	Mechanics of Workshop D. Cline
* 1:00	Synthesis of Scientific Questions
* 5:00	Adjourn

The items on the agendas where the Long Range Plan was discussed are marked with an asterisk.

DOE/NSF Nuclear Science Advisory Committee

DATE AND TIME:	October 15, 1983	9:00 am -- 6:30 pm
	October 16, 1983	9:00 am -- 5:30 pm
PLACE:	Room R-150 Building 203 (Physics) Argonne National Laboratory Lemont, Illinois	
TYPE OF MEETING:	Open	
AGENDA:	October 15, 1983	9:00 am -- 6:30 pm
	Discussion of the 1983 Long Range Plan for Nuclear Science	
	October 16, 1983	9:00 am -- 5:30 pm
	Continuation of the discussion of the 1983 Long Range Plan for Nuclear Science	

APPENDIX C

LONG RANGE PLAN WORKSHOP, Wells College, Aurora, New York (July 11-15, 1983)

Preliminary Agenda

Monday	Morning (9:00--12:30)		
		Discussion of Procedures	
		Elementary Excitations	S. Austin
		NN, Hadron-hadron Force (free and effective) Many-Body Forces and Currents	S. Vigdor
	Afternoon (2:00 - 5:00)		
		Nuclear Symmetries	F. Iachello
		Accelerator Facilities	J. Martin
	Evening (7:30 -)		
		General Discussion and/or Working Group Meetings	
Tuesday	Morning (9:00 - 12:30)		
		High Angular Momenta, Extreme States	R. M. Diamond
		Dissipative, Statistical and Quasistatistical aspects	D. A. Bromley
	Afternoon (2:00 - 5:00)		
		Non-nucleonic, Hadronic Degrees of Freedom	E. Moniz
		Non-nucleonic, Quark Degrees of Freedom	G. T. Garvey
	Evening (7:30 --)		
		General Discussion (Budgets, Manpower)	

Wednesday	Morning (9:00 - 12:30)		
	Nuclear Matter and Equation of State: Quark Gluon Matter	G. A. Baym
	Strange Quarks (in nuclei)	C. B. Dover
	Afternoon (2:00 - 5:00)		
	Fundamental Symmetries and Interactions (in nuclei)	F. H. Boehm C. Baltay
	Societal Applications	K. A. Erb
	Evening (7:30 -)		
	General Discussion (International Aspects), Working Group Meetings	
Thursday	Morning (9:00 - 12:30)		
	Instrumentation	G. T. Garvey
	Ties to Other Scientific Disciplines	A. Schwarzschild
	Evening		
	General Discussion	
Friday	Discussion of Revised Drafts of Sections of the Long Range Plan	

Participants in Long Range Plan Workshop

E. G. Adelberger	University of Washington, Seattle
*S. M. Austin	Michigan State University
C. Baltay	Columbia University
*G. A. Baym	University of Illinois
W. Bertozzi	Massachusetts Institute of Technology
G. Bertsch	Michigan State University (Amer. Phys. Soc., Div. of Nucl. Phys.)
*F. H. Boehm	California Institute of Technology
*D. A. Bromley	Yale University
J. Cerny	Lawrence Berkeley Laboratory
*H. H. Chen	University of California, Irvine
*D. Cline	University of Rochester
P. T. Debevec	University of Illinois, Urbana
R. M. Diamond	Lawrence Berkeley Laboratory
C. B. Dover	Brookhaven National Laboratory
*K. A. Erb	Oak Ridge National Laboratory
G. T. Garvey	Argonne National Laboratory
D. F. Geesaman	Argonne National Laboratory
F. L. Gross	College of Wm. and Mary
*H. A. Grunder	Lawrence Berkeley Laboratory
M. Gyulassy	Lawrence Berkeley Laboratory
P. E. Haustein	Brookhaven National Laboratory (Am. Chem. Soc., Div. of Nucl. Sci.)
J. Heisenberg	University of New Hampshire
P. Herczeg	Los Alamos National Laboratory
*C. M. Hoffman	Los Alamos National Laboratory
F. Iachello	Yale University
G. J. Igo	University of California, Los Angeles
*A. K. Kerman	Massachusetts Institute of Technology
N. B. Koller	Rutgers University
S. E. Koonin	California Institute of Technology
T. W. Ludlum	Brookhaven National Laboratory
*M. H. Macfarlane	Indiana University
M. J. Martin	Oak Ridge National Laboratory
R. D. McKeown	California Institute of Technology
L. D. McLerran	University of Washington, Seattle
E. Moniz	Massachusetts Institute of Technology
P. D. Parker	Yale University
R. P. Redwine	Massachusetts Institute of Technology
R. G. H. Robertson	Los Alamos National Laboratory
*P. G. Roos	University of Maryland
*J. P. Schiffer	Argonne National Laboratory, Chairman
L. S. Schroeder	Lawrence Berkeley Laboratory
*A. Z. Schwarzschild	Brookhaven National Laboratory
*I. Sick	University of Basel
S. Vigdor	Indiana University
*E. W. Vogt	University of British Columbia

*Member of Nuclear Science Advisory Committee

Agency Representatives:

H. C. Britt	Department of Energy
H. L. Crannell	National Science Foundation
J. R. Erskine	Department of Energy
J. B. McGrory	Department of Energy
C. R. Richardson	Department of Energy
E. T. Ritter	Department of Energy
W. S. Rodney	National Science Foundation
H. B. Willard	National Science Foundation

Chairmen of Working Groups:

Nucleons in Nuclei	S. Vigdor
Non-nucleonic, Hadronic Aspects	E. Moniz
Non-nucleonic, Quark Aspects	G. T. Garvey
Nuclear Matter and Equation of State	G. A. Baym
Elementary Excitations	S. M. Austin
High Angular Momenta	R. M. Diamond
Nuclear Symmetries	F. Iachello
Macroscopic Aspects	D. A. Bromley
Fundamental Symmetries	F. H. Boehm
Strange Quarks in Nuclei	C. B. Dover
Nuclear Astrophysics	P. D. Parker
Connections with Other Sciences	A. Z. Schwarzschild
Societal Applications	K. A. Erb
Accelerator Facilities	M. J. Martin
Instrumentation	G. T. Garvey
International Aspects	E. W. Vogt

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