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PHYSICS THROUGH THE 1990s

Nuclear Physics

Nuclear Physics Panel
Physics Survey Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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Preface

This volume is the report of the Panel on Nuclear Physics of the Physics Survey Committee, established by the National Research Council in 1983. The report presents many of the major advances in nuclear physics during the past decade, sketches the impacts of nuclear physics on other sciences and on society, and describes the current frontiers of the field. It concludes with a chapter on the recommended priorities for this discipline.

The Panel on Nuclear Physics developed this report through its meetings in May 1983 and January 1984 and through extensive correspondence. We also joined with the Nuclear Science Advisory Committee (NSAC) of the Department of Energy and the National Science Foundation during its week-long Workshop in July 1983, when the major draft of its 1983 Long Range Plan was formulated. Appendix B lists those who attended the Workshop, which included broad participation beyond the members of NSAC or our Panel.

Most of the comments from 11 reviewers (see Appendix B), chosen to provide a representative viewpoint from the nuclear-science community, were incorporated into the manuscript, which was submitted to the National Research Council in May 1984 for further review. Additional comments were subsequently incorporated, and the final manuscript was submitted in August 1984.

Clearly, a comprehensive coverage of the field of nuclear physics would be impossible in a report of this size. Of necessity, only an

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overview of selected topics can be given, and the Panel has attempted to maintain a reasonable balance throughout. Although no explicit reference to nuclear chemistry per se is made in this report, we wish to note that nuclear chemists and nuclear physicists are working toward the same goal of understanding the nucleus. They thus have many interests in common and share the same experimental facilities.

The Panel wishes to thank the reviewers as well as the members of the Physics Survey Committee, the Board on Physics and Astronomy of the National Research Council, and a number of other individuals for their help in this task. We wish particularly to thank Fred Raab for his outstanding and invaluable assistance in the technical rewriting and editing of this report.

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Executive Summary

NUCLEAR PHYSICS TODAY

Nuclear physics deals with the properties of atomic nuclei, their structure and interactions, and the laws governing the forces between their constituents. The interactions in nuclei have their roots in the interactions of elementary particles, the quarks and gluons that together constitute nuclear matter. But additional dynamical forces, long known to exist in nuclei, cannot be understood with elementary particles alone, just as new cooperative interactions, not recognizable in nuclei or atoms, are known to exist in macroscopic materials.

The basic questions facing nuclear physics today span a broad range, including strong and electroweak interactions, and cover the properties of the physical world from the microscopic scale of nuclear forces to the large-scale structure of the universe. Nuclear physics deals with many-body aspects of the strong interaction. It also deals with tests of fundamental theories and symmetries. Furthermore, nuclear physics plays an important role in the fields of astrophysics and cosmology.

Our understanding of nuclear structure and nuclear dynamics continues to evolve. New simple modes of excitation have emerged, new symmetries are appearing, and some completely new phenomena are being discovered.

In the 1970s, for example, several new modes of vibration of nuclei were discovered, using the technique of inelastic scattering of charged particles from target nuclei. One of these vibrations, the giant mono-

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pole, is particularly significant because of its direct relation to the heretofore unmeasured compressibility of nuclear matter. In similar studies using pions as projectiles, important information on the relative roles of protons and neutrons in nuclear vibrations has been gained, as well as that of nucleon excited states called deltas.

The use of high-energy electron scattering from nuclei has revealed unprecedented levels of detail of nuclear structure, in terms not only of the nucleons but also of the mesons present in nuclei and, to a rudimentary degree, of the quarks that compose all of these particles. Such studies represent one of the major frontiers of nuclear physics today.

At the opposite extreme of projectile size, heavy ions have come into increasingly widespread use, particularly as versatile probes of nuclear dynamics. Their massive impact on target nuclei can cause a great variety of excitations and reactions, analyses of which are invaluable for understanding different kinds of motions of the nucleons within a nucleus. Heavy-ion collisions have also been indispensable for producing many exotic nuclear species, including four new chemical elements (numbers 106 through 109) during the past decade.

It is noteworthy that almost all nuclear-physics research to date has been possible only within the very limited domain of nuclei under conditions of low nuclear temperature and normal nuclear density. The vastly greater domain of high-temperature, high-density nuclear physics has just recently begun to be explored, using heavy-ion projectiles at relativistic energies. This too is currently a major frontier of the field.

Inevitably, fundamental new problems arise to challenge our understanding of nuclear physics. For example, although we now know how to explain certain nuclear phenomena in terms of the presence, within nuclei, of mesons in addition to protons and neutrons, we are not yet able to solve the corresponding equations of quantum chromodynamics (the quantum field theory that is believed to govern the manner in which these particles interact) to describe the effects in question.

Current efforts to solve this problem are particularly important because they hold the promise of new insights into one of the fundamental forces of nature, the so-called strong force. Indeed, the nucleus in general represents a uniquely endowed laboratory for investigating the relationships among the fundamental forces as well as the symmetry principles underlying all physical phenomena. Its key role in shaping our view of the cosmos is evident in the field of nuclear astrophysics, which provides information vital to our understanding of the origin and evolution of stars and of the universe itself. On the Earth, meanwhile, nuclear medicine (including the development and use of specifically tailored radioisotopes and accelerator beams for

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both diagnostic and therapeutic procedures), nuclear power (both fission and fusion), materials modification and analysis (for example, ion implantation and the fabrication of semiconductor microcircuits), radioactive tracers (used in a number of research areas ranging from geophysics to medical physics), as well as many routine industrial applications (including, for example, well-logging in test bores using miniaturized nuclear accelerators, food preservation by irradiation, and die hardening by ion implantation to reduce wear), and even the analysis of art objects are just a few examples of how the fruits of nuclear-physics research have found a multitude of useful and sometimes surprising applications in other basic sciences and in modern technologies, many of which have direct and significant impacts on society at large.

Much of this research is done with particle accelerators of various kinds. Some studies require large teams of investigators and high-energy accelerators, typically operated by national laboratories, while other, lower-energy studies continue to be performed at colleges and universities—typically by a professor and a few graduate students—using smaller accelerators or laboratory-scale equipment. Both produce fundamental advances in nuclear physics.

This very wide range of facilities and manpower requirements is among the unusual characteristics of nuclear physics. Maintaining the proper balance between the research programs of large and small groups is essential for overall progress in the field. Equally important is the balance between experimental and theoretical research, as well as the availability of state-of-the-art instrumentation and computers for the respective programs.

The major advances of the past decade of nuclear-physics research and the exciting prospects for its future—as well as some of the myriad ways in which nuclear physics has an impact on the other sciences and on society at large—constitute the subject of this nuclear-physics survey.

RECOMMENDATIONS FOR THE FUTURE OF NUCLEAR PHYSICS

In formulating the recommendations for the future of nuclear physics, as presented below, the Panel on Nuclear Physics has profited from extensive interactions between its members and the participants in the 1983 Long Range Planning Workshop of the Nuclear Science Advisory Committee (NSAC) of the U.S. Department of Energy and the National Science Foundation.

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Accelerators are the basic tools of nuclear-physics research. The planning, design, and construction of first-rate accelerators and their associated experimental facilities have become increasingly important to the nuclear-physics community at large. Designs must be optimized to support those programs most likely to produce new results in critical research areas and to satisfy the needs of the largest number of users. There are currently two major accelerators, of complementary natures, whose construction has been recommended by NSAC.

The Planned Continuous Electron Beam Accelerator Facility

In April 1983, NSAC recommended the construction of a 100-percent-duty-factor, 4-GeV linear-accelerator/stretcher-ring complex now called the *Continuous Electron Beam Accelerator Facility* (CEBAF), which was proposed by the Southeastern Universities Research Association. The research and development funding for this machine began in FY 1984, and construction funding is proposed for FY 1987. A total accelerator cost of $225 million (in actual-year dollars) is projected; this includes $40 million for the initial experimental equipment. The Panel on Nuclear Physics endorses the construction of CEBAF.

A major focus of nuclear-physics research at CEBAF will be investigations of the microscopic quark-gluon aspects of nuclear matter (the regime of high energies, high momentum transfers, and small distances), using the electron beam to probe the detailed particle dynamics within an entire nucleus with surgical precision. Of great importance also, however, will be investigations of baryon-meson aspects of nuclear matter (the regime of lower energies, lower momentum transfers, and larger distances). In particular, it will be most valuable to study the nature of the transition from the low-energy regime of nucleon-nucleon interactions (best described by independent-particle models of nuclear structure) to the intermediate-energy regime of baryon resonances and meson-exchange currents (described by quantum field theories of hadronic interactions in nuclei) and the ensuing transition to the high-energy regime of quarks and gluons (described by quantum chromodynamics).

For these and other studies, the variable beam energy of CEBAF, from 0.5 to 4.0 GeV, is necessary. Also necessary is its 100 percent duty factor (continuous-wave operation), so that coincidence measurements can be made; these are vital for isolating particular channels and variables for study. The unique capabilities of CEBAF will thus provide unprecedented opportunities for examining nuclear matter at different levels of structure in great detail.

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The Next Major Initiative: The Relativistic Nuclear Collider

In NSAC's 1983 Long Range Plan (*A Long Range Plan for Nuclear Science: A Report by the DOE/NSF Nuclear Science Advisory Committee*, December 1983), the construction of a variable-energy, relativistic heavy-ion colliding-beam accelerator is recommended. Such a machine is seen by NSAC as the highest-priority major new initiative in nuclear science after the completion of CEBAF. The recommendation is for a collider with an energy of about 30 GeV per nucleon in each beam; its estimated cost would be roughly $250 million (in FY 1983 dollars).

A major scientific imperative for such an accelerator derives from one of the most striking predictions of quantum chromodynamics: that under conditions of sufficiently high temperature and density in nuclear matter, a transition will occur from excited hadronic matter to a quark-gluon plasma, in which the quarks, antiquarks, and gluons of which hadrons are composed become "deconfined" and are able to move about freely. The quark-gluon plasma is believed to have existed in the first few microseconds after the big bang, and it may exist today in the cores of neutron stars, but it has never been observed on Earth. Producing it in the laboratory will thus be a major scientific achievement, bringing together various elements of nuclear physics, particle physics, astrophysics, and cosmology.

The only conceivable way at present of producing the conditions necessary for achieving quark deconfinement is to collide the very heaviest nuclei head-on at relativistic energies, thereby creating enormous nuclear temperatures and energy densities throughout the relatively large volume of the two nuclei. The ability of quarks and gluons to move about within this volume will enable fundamental aspects of quantum chromodynamics at large distances to be tested. It is believed that various exotic features of deconfined quark matter, such as the production of many "strange" particles and antibaryons, may be observed.

In addition to colliding-beam experiments, operation of such a relativistic nuclear collider (RNC) in a fixed-target mode with a variable-energy beam would provide a diversity of important research programs in high-energy nuclear physics, nuclear astrophysics, and atomic physics. Among the most valuable of these would be studies aimed at providing new information on the fundamentally important nuclear matter equation of state at high temperature and density.

The Panel endorses the NSAC 1983 Long Range Plan in recommending the planning for construction of this accelerator. Construction should begin as soon as possible, consistent with that of the 4-GeV

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electron accelerator discussed above. Since current funding levels are barely adequate to respond, with the *present* facilities, to the exciting scientific opportunities confronting the field, we recommend an increase in nuclear-physics operating funds sufficient to support the necessary accelerator research and development as well as the operations and research programs at these two new facilities as they come into being.

Additional Facility Opportunities

The major questions currently facing nuclear physics, including nuclear astrophysics, point to a number of important scientific opportunities that are beyond the reach of the experimental facilities either in existence or under construction. Many of these opportunities might be realized through a variety of upgrades and additions to the research capabilities of existing facilities, and it appears that a reasonable fraction of them could be achieved within the base program envisioned at present. Decisions regarding the relative priorities must be made at the appropriate later times.

It should be noted that a number of these important research opportunities could be encompassed by another major new multiuser accelerator, comprising a synchrotron that would produce very intense proton beams at energies of up to tens of GeV, followed by a stretcher ring to produce a nearly continuous spill of protons that would yield secondary beams of pions, kaons, muons, neutrinos, and antinucleons. The intensities of these beams could be typically 50 to 100 times greater than those available anywhere else, allowing a substantial improvement in the precision and sensitivity of a large class of important experiments at the interface between nuclear physics and particle physics.

Although funding for such an accelerator was not recommended by NSAC, given its commitments to the electron and heavy-ion facilities discussed above, the accelerator remains an important option for future consideration because of the unique scientific opportunities that it would address.

Nuclear Instrumentation

A serious national problem exists in the area of appropriate continued support for nuclear-physics instrumentation. The NSAC 1983 Long Range Plan notes that the amount spent by the United States for basic nuclear-physics research relative to its Gross National Product is

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less than half of that spent in Western Europe or Canada. The effects of this disparity can readily be seen in the quality and sophistication of European instrumentation, which in many instances far surpasses that found in American universities and national laboratories. An increase in dedicated funding for instrumentation at both large and small facilities is therefore deemed essential.

Nuclear Theory

The closer the link between theory and experiment, and the better the balance in the effort, the more effective they both become in synthesizing a coherent and elegant body of knowledge. Although the NSAC 1979 Long Range Plan stressed the need for increased support of nuclear theory, a comparison of the FY 1984 budget for nuclear physics with the FY 1979 budget shows that during the intervening 5 years, funding for nuclear theory has remained essentially constant as a percentage of the whole (5.8 percent in FY 1984 versus 6.0 percent in FY 1979). We believe that there is still a clear need for a substantial relative increase in the support of nuclear theory, especially in light of the new and challenging frontiers that are opening up in nuclear physics.

Progress in current theoretical research depends on substantial access to first-class computational facilities. Extensive calculations based on the complex models describing today's experiments require the large memories and rapid processing capabilities of Class VI computers. Access by nuclear theorists to a major fraction of the time available on a central, well-implemented Class VI computer could initially meet this need.

Accelerator Research and Development

Accelerator research and development continues to be vital in making progress toward new advanced facilities, and it must be appropriately supported. Among the important new accelerator technologies that are deserving of such support are superconducting materials for various accelerator structures (including main-field magnets), the radio-frequency quadrupole pre-accelerator for low-velocity ions, beam coolers for reducing the energy spread of accelerated beams, beams of short-lived radioactive nuclides with intensities that are adequate for nuclear-physics and astrophysics experiments, and a variety of advanced ion sources.

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Training New Scientists

Nuclear physics is among the most fundamental of sciences. The applications of its principles and techniques are vital to such diverse areas of the national interest as energy technology, military preparedness, health care, environmental monitoring, and materials engineering. To meet these needs and to continue to explore the basic research opportunities in nuclear physics, a steady influx of first-rate young scientists to our universities, national laboratories, and industries is essential.

The Panel is concerned about the continuing decline in the number of students pursuing graduate courses in physics, and nuclear physics in particular. The decline has various causes. Its remedy must lie in large measure in the vigorous support of nuclear-physics education—from undergraduate to postdoctoral—by the federal government.

Enriched Stable Isotopes

The Calutron facility at Oak Ridge National Laboratory is the major U.S. source of stable isotopes, which are used both in scientific research and in the production of radioactive isotopes needed for biomedical research and clinical medicine. Acute shortages of stable isotopes now exist (some 50 are currently unavailable), and severe funding insufficiencies forecast rapid deterioration in the supply.

The worsening shortages could have disastrous consequences in many areas of scientific research as well as in clinical medicine, where stable isotopes are indispensable tools. An important priority is therefore to replenish the supply of separated isotopes before much nuclear-physics research is crippled. To ensure that the problem is solved, corrective steps must continue to be vigorously pursued, both by the scientific communities affected and by the funding agencies.

Nuclear-Data Compilation

For more than 40 years, compilers and evaluators have attempted to keep scientists abreast of detailed nuclear data as they become available. With the rapid experimental advances of the last two decades, however, nuclear-data compilations have begun to fall behind. Because the costs of this program are relatively small, a modest increase in funding would greatly enhance the ability to maintain a thorough compilation/evaluation effort and to ensure the timely publication of these results in the various formats required both by nuclear physicists and by applied users of radioactive isotopes.

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1

Introduction to Nuclear Physics

All phenomena in the universe are believed to arise from the actions of just three fundamental forces: *gravitation* and the less familiar *strong force* and *electroweak force*. The complex interplay between these last two forces defines the structure of matter, and nowhere are the myriad manifestations of this interplay more evident than in the nucleus of the atom. Much of the substance of the universe exists in the form of atomic nuclei arranged in different ways. Within ordinary nuclei, the weak gravitational attraction between the constituent particles is overwhelmed by the incomparably more powerful strong nuclear force, but gravitation's effect is large indeed in neutron stars—bizarre astrophysical objects whose properties are very much like those of gigantic nuclei.

Studies of the nucleus can thus be viewed as a link between the worlds of the infinitesimal and the astronomical. Collectively, the various nuclei can be regarded as a laboratory for investigating the fundamental forces that have governed our universe since its origin in the big bang. Indeed, as this report illustrates, the study of nuclear physics is becoming ever more deeply connected with that of cosmology as well as elementary-particle physics.

Before venturing into these exciting realms, we will quickly survey the field of nuclear physics at an elementary level in order to learn the language. Although nuclear physics has the reputation of being a difficult subject, the basic concepts are relatively few and simple.

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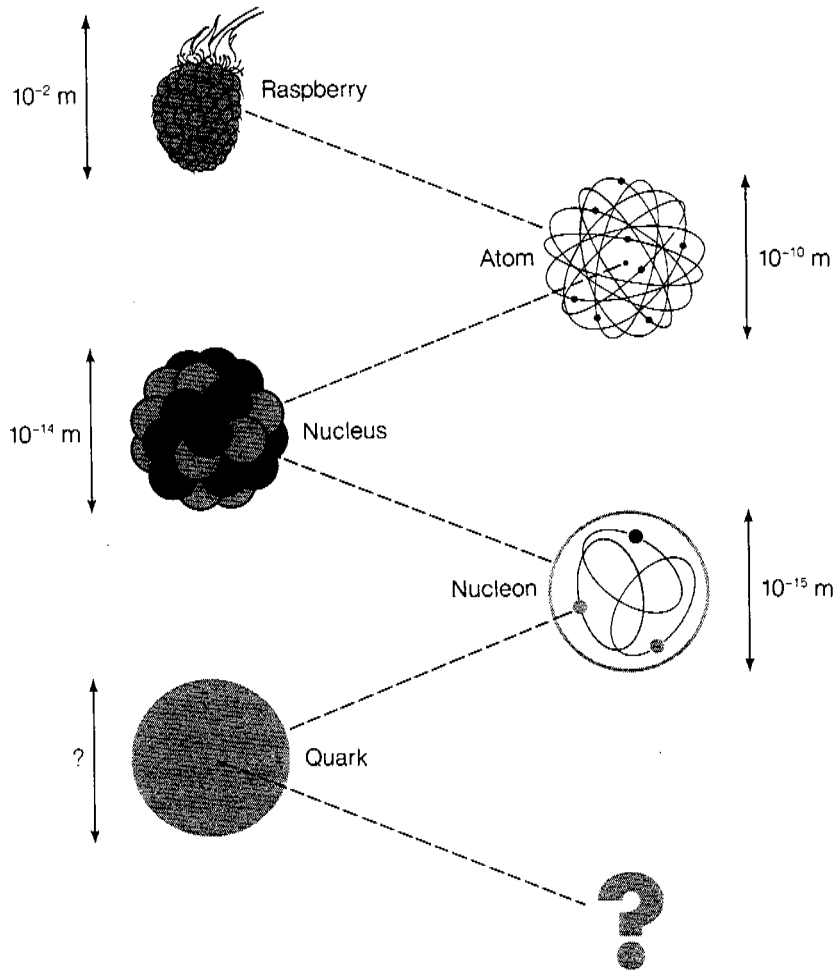


FIGURE 1.1 Approximate dimensions for the structure of matter from raspberries to quarks (the cellular and molecular levels of structure have been omitted).

THE ATOMIC NUCLEUS

The atomic nucleus is an extremely dense, roughly spherical object consisting primarily of *protons* and *neutrons* packed fairly closely together (see Figure 1.1). Protons and neutrons are collectively called *nucleons*, and for many years it was thought that nucleons were truly elementary particles. We now know, however, that they are not elementary but have an internal structure consisting of smaller parti-

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cles and that there are other particles in the atomic nucleus along with them. These aspects of the nucleus are discussed below. Protons and neutrons are very similar, having almost identical physical properties. An important difference, however, lies in their electric charge: protons have a unit positive charge, and neutrons have no charge. They are otherwise so similar that their interconversion in the decay of radioactive nuclei is a common occurrence.

The character of the nucleus provides the diversity of the chemical elements, of which 109 are now known, including a number of man-made ones. (The cosmic origin of the elements is a different question—one that is addressed by the specialized field of nuclear astrophysics.) Each element has a unique *proton number*, Z. This defines its chemical identity, because the proton number (equal to the number of unit electric charges in the nucleus) is balanced, in a neutral atom, by the electron number, and the chemical properties of any element depend exclusively on its orbital electrons. The smallest and lightest atom, hydrogen, has one proton and therefore one electron; the largest and heaviest naturally occurring atom, uranium, has 92 protons and 92 electrons. In a rough sense, this is all there is to the diversity of the chemical elements and the fantastic variety of forms—inanimate and animate—that they give rise to through the interactions of their electron clouds.

To explain the *stability* of the elements, however, and to study nuclear physics, we must also take into account the *neutron number*, N, of each nucleus. This number can vary considerably for the nuclei of a given element. The nucleus of ordinary hydrogen, for example, has one proton and *no* neutrons, the latter fact making it unique among all nuclei. But a hydrogen nucleus can also exist in a form that has one proton and one neutron ($Z = 1$, $N = 1$); this nucleus is called a *deuteron*, and the atom, with its one electron, is called *deuterium*. Chemically, however, it is still hydrogen, as is the even heavier, radioactive form *tritium*, which has one proton and two neutrons ($Z = 1$, $N = 2$); a tritium nucleus is called a *triton*.

These separate nuclei of a single chemical element, differing only in neutron number, are the *isotopes* of that element. Every element has at least several isotopes—stable and unstable (radioactive)—and some of the heavier elements have already been shown to have more than 35. Although the chemical properties of the isotopes of a given element are the same, their nuclear properties can be so different that it is important to identify every known or possible isotope of the element unambiguously. The simplest way is to use the name of the element and its *mass number*, A, which is just the sum of its proton and neutron numbers:

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$A = Z + N$. Because different combinations of Z and N can give the same value of A, nuclei of different elements can have the same mass number (chlorine-37 and argon-37, for example). To emphasize the uniqueness of every such separately identifiable type of nucleus, scientists refer to them as *nuclides*.

There are about 300 naturally occurring stable nuclides of the chemical elements and about 2400 *radioactive* (i.e., spontaneously decaying) ones. Of the latter, the great majority do not exist naturally but have been made artificially in particle accelerators or nuclear reactors. These machines of modern physics can also create experimental conditions that are drastically unlike those ordinarily existing on Earth but that are similar, perhaps, to those characteristic of less hospitable corners of the universe. Thus they enable us, in our efforts to understand the laws of nature, to extend our intellectual grasp into domains that would otherwise be inaccessible.

Experimental and theoretical investigations of the broad range of nuclides available to us represent the scope of nuclear physics. In the study of *nuclear spectroscopy*, for example, experimentalists perform many kinds of measurements in order to characterize the behavior of the nuclides in detail and to find patterns and symmetries that will allow the huge amounts of information to be ordered and interpreted in terms of unifying principles. The theorists, on the other hand, search for these unifying principles through calculations based on the available facts and the fundamental laws of nature. Their aim is not only to explain all the known facts of nuclear physics but to predict new ones whose experimental verification will confirm the correctness of the theory and extend the bounds of its applicability.

A similar approach applies to the study of *nuclear reactions*, in which experimentalists and theorists seek to understand the changing nature and mechanisms of collisions between projectile and target nuclei at the ever-increasing energies provided by modern accelerators. The many ways in which target nuclei can respond to the perturbations produced by energetic projectile beams provide a rich fund of experimental data from which new insights into nuclear structure and the laws of nature can be gained. In extreme cases, new states of nuclear matter may be found.

THE NUCLEAR MANY-BODY PROBLEM

The essential challenge of nuclear physics is to explain the nucleus as a *many-body system of strongly interacting particles*. In physics, three or more mutually interacting objects—whether nucleons or stars—are

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considered to be "many" because of the tremendous mathematical difficulties associated with solving the equations that describe their motions. With each object affecting the motions of all the others through the interactions that exist among them, and with all the motions and hence all the interactions changing constantly, the problem very quickly assumes staggering proportions. In fact, this *many-body problem* is now just barely soluble, with the largest computers, for three bodies. For four or more, however, it remains generally insoluble, in practice, except by methods relying on various approximations that simplify the mathematics.

What nuclear physicists try to do—within the constraints imposed by the many-body problem—is to understand the structure of nuclei in terms of their constituent particles, the dynamics of nuclei in terms of the motions of these particles, and the fundamental interactions among particles that govern these motions. Experimentally, they study these concepts through nuclear spectroscopy and the analysis of nuclear reactions of many kinds. Theoretically, they construct simplifying mathematical models to make the many-body problem tractable.

These nuclear models are of different kinds. *Independent-particle models* allow the motion of a single nucleon to be examined in terms of a steady, average force field produced by all the other nucleons. The best-known independent-particle model is the *shell model*, so called because it entails the construction of "shells" of nucleons analogous to those of the electrons in the theory of atomic structure. At the other extreme, *collective models* view the nucleons in a nucleus as moving in concert (collectively) in ways that may be simple or complex—just as the molecules in a flowing liquid may move smoothly or turbulently. In fact, the best-known collective model, the *liquid-drop model*, is based on analogies with the behavior of an ordinary drop of liquid.

The above descriptions are necessarily oversimplified. The actual models in question, as well as related ones, are very sophisticated, and their success in explaining most of what we know about nuclear structure and dynamics is remarkable. As we try to push this knowledge to ever deeper levels, however, we must take increasingly detailed account of specific nucleon-nucleon interactions. Doing so brings out the other half of the essential challenge of nuclear physics: that nucleons are *strongly interacting* particles.

THE FUNDAMENTAL FORCES

In nature, the so-called *strong force* holds atomic nuclei together despite the very substantial electrostatic repulsion between all the

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positively charged protons. The distance over which the strong force is exerted, however, is extremely short: about 10^{-15} meter, or 1 femtometer—commonly called 1 *fermi* (fm) after the great nuclear physicist Enrico Fermi. A fermi is short indeed, being roughly the diameter of a single nucleon. The time required for light to traverse this incredibly short distance is itself infinitesimal: only 3×10^{-24} second. As we will see, the characteristic duration of many events taking place in the nucleus is not much longer than that: about 10^{-23} to 10^{-22} second, corresponding to a distance traveled, at the speed of light, of only about 3 to 30 fm.

This is the domain—incomprehensibly remote from our everyday experience—of the strong force, which dominates the nucleus. Nucleons within the nucleus are strongly attracted to one another by the strong force as they move about within the confines of the nuclear volume. If they try to approach each other too closely, however, the strong force suddenly becomes repulsive and prevents this from happening. It is as though each nucleon had an impenetrable shield around it, preventing direct contact with another nucleon. The behavior of the strong force is thus very complex, and this makes the analysis of multiple nucleon-nucleon interactions (the nuclear many-body problem) much more challenging.

At the opposite extreme of the fundamental forces is *gravitation*, a long-range force whose inherent strength is only about 10^{-38} times that of the strong force. Since the gravitational force between any two objects depends on their masses, and since the mass of a nucleon is extremely small (about 10^{-24} g), the effects of gravitation in atomic nuclei are not even close to being measurable. Nonetheless, the universe as a whole contains so many atoms, in the form of hugely massive objects (stars, quasars, galaxies), that gravitation is the dominant force in its structure and evolution. And because gravitation is extremely important in neutron stars, as mentioned earlier, these supermassive nuclei are all the more interesting to nuclear astrophysicists.

Lying between gravitation and the strong force, but much closer to the latter in inherent strength, is the *electroweak force*. This rather complex force manifests itself in two ways that are so different that until the late 1960s they were believed to be separate fundamental forces—just as electricity and magnetism, a century ago, were thought to be separate forces rather than two aspects of the one force, *electromagnetism*. Now we know that electromagnetism itself is but a part of the electroweak force; it is therefore no longer considered to be a separate fundamental force of nature.

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Electromagnetism is the force that exists between any two electrically charged or magnetized objects. Like gravitation, its influence can extend over great distances, and it decreases rapidly in strength as the distance between the objects increases. Its inherent strength is relatively large, however, being about 0.7 percent of that of the strong force at separation distances of about 1 fm. Electromagnetism is the basis of light and all similar forms of radiation (x rays, ultraviolet and infrared radiation, and radio waves, for example). All such radiation propagates through space via oscillating electric and magnetic fields and is emitted and absorbed by objects in the form of tiny bundles of energy called *photons*. In some radioactive decay processes, extremely energetic photons called *gamma rays* are emitted by the nuclei as they change to states of lower total energy. A photon is considered to be the fundamental unit of electromagnetic radiation: a *quantum*. This profound idea—revolutionary in its time but now commonplace—lies at the heart of *quantum mechanics*, the physical theory that underlies all phenomena at the submicroscopic level of molecules, atoms, nuclei, and elementary particles.

The other manifestation of the electroweak force is the *weak force*, which is responsible for the decay of many radioactive nuclides and of many unstable particles, as well as for all interactions involving the particles called *neutrinos*, which we discuss below. The weak force in nuclei is feeble compared with the electromagnetic and strong forces, being only about 10^{-5} times as strong as the latter, but it is still extremely strong compared with gravitation. The distance over which it is effective is even shorter than that of the strong force: about 10^{-18} m, or 0.001 fm—roughly 1/1000 the diameter of a nucleon. The weak force governs processes that are relatively slow on the nuclear time scale, taking about 10^{-10} second or more to occur. As short as this time may seem, it is about one trillion times longer than the time required for processes governed by the strong force.

The prediction in 1967—and its subsequent experimental confirmation—that the electromagnetic and weak forces are but two aspects of a single, more fundamental force, the electroweak force, were triumphs of physics that greatly expanded our understanding of the laws of nature. However, because these two component forces are so different in the ways in which they are revealed to us (their essential similarities start to become clear only at extremely high energies, far beyond those of conventional nuclear physics), it is usually convenient to discuss them separately, just as we often discuss electricity and magnetism separately. Thus they are still often described as though each were fundamental. In this book, we will let the circumstances

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decide how they should be discussed: as electromagnetic and weak, or as electroweak. For the remainder of this chapter, we will discuss them separately.

The fundamental forces are often called fundamental *interactions*, because the forces exist only by virtue of interactions that occur between particles. These interactions, in turn, are mediated by the exchange of *other* particles between the interacting particles. This may seem like Chinese boxes, but as far as we know, it stops right there: in the realm of elementary-particle physics, which we must now briefly introduce in order to see where the foundations of nuclear physics lie.

THE ELEMENTARY PARTICLES

The experimental study of elementary-particle physics—also known by the inexact name high-energy physics—diverged from that of nuclear physics around 1950, when developing accelerator technology made it relatively easy to search for other—and ultimately more basic—"elementary" particles than the proton or the neutron. An enormous variety of subnuclear particles has by now been discovered and characterized, some of which are truly elementary (as far as we can tell in 1984), but most of which are not.

Along with the discovery of these particles came major theoretical advances, such as the electroweak synthesis mentioned above, and mathematical theories attempting to classify and explain the seemingly arbitrary proliferation of particles (several hundred by now) as accelerator energies were pushed ever higher. Chief among these theories, because of their great power and generality, are the *quantum field theories* of the fundamental interactions. All such theories are relativistic, i.e., they incorporate *relativity* into a quantum-mechanical framework suitable to the problem at hand. They thus represent the deepest level of understanding of which we are currently capable.

We will return to these theories shortly, but first let us see what classes of particles have emerged from the seeming chaos. This is essential for two reasons. First, the nucleus as we now perceive it does *not* consist of just protons and neutrons, and these are not even elementary particles to begin with. To understand the atomic nucleus properly, therefore, we must take into account all the other particles that exist there under various conditions, as well as the compositions of the nucleons and of these other particles. Second, the theoretical framework for much of nuclear physics is now deeply rooted in the quantum field theories of the fundamental interactions, which are the domain of particle physics. Aspects of the two fields are rapidly

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converging, after their long separation, and it is no longer possible to investigate many fundamental problems of nuclear physics except in the context of the elementary particles. Much of the material in this book, in fact, deals with the ways in which this new view of nuclear physics has come about and the ways in which it will accelerate in the future.

Physicists now believe that there are three classes of elementary particles—*leptons*, *quarks*, and *elementary vector bosons*—and that every particle, elementary or not, has a corresponding *antiparticle*. Here we must make a short digression into the subject of *antimatter*. An antiparticle differs from its ordinary particle only in having some opposite elementary properties, such as electric charge. Thus, the antiparticle of the electron is the positively charged *positron*; the antinucleons are the negatively charged *antiproton* and the neutral *antineutron*. The antiparticle of an antiparticle is the original particle; some neutral particles, such as the photon, are considered to be their own antiparticles. In general, when a particle and its corresponding antiparticle meet, they can annihilate each other (vanish completely) in a burst of pure energy, in accord with the Einstein *mass-energy equivalence* formula, $E = mc^2$. Antiparticles are routinely observed and used in many kinds of nuclear- and particle-physics experiments, so they are by no means hypothetical. In the ensuing discussions of the various classes of particles, it should be remembered that for every particle mentioned there is also an antiparticle.

Leptons

Leptons are weakly interacting particles, i.e., they experience the weak interaction but not the strong interaction; they are considered to be pointlike, structureless entities. The most familiar lepton is the *electron*, a very light particle (about 1/1800 the mass of a nucleon) with unit negative charge; it therefore also experiences the electromagnetic interaction. The *muon* is identical to the electron, as far as we know, except for being about 200 times heavier.* The tau particle, or *tauon*, is a recently discovered lepton that is also identical to the electron except for being about 3500 times heavier (making it almost twice as

*The muon is still occasionally called a mu meson—its original name—which can be confusing because the term "meson" is now restricted to a very different kind of particle; thus a "mu meson" is *not* a meson in the modern sense.

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heavy as a nucleon). The very existence of these "heavy electrons" and "very heavy electrons" is a major puzzle for physicists.

Associated with each of the three charged leptons is a lepton called a *neutrino*: thus there is an electron neutrino, a muon neutrino, and a tauon neutrino. Neutrinos are electrically neutral and therefore do not experience the electromagnetic interaction. They have generally been assumed to have zero rest mass (see page 31 for an explanation of this term) and must therefore move at the speed of light, according to relativity, but the question of their mass is currently controversial. If the electron neutrino, in particular, does have any mass, it is very slight indeed. The possible existence of such a mass, however, has great cosmological significance: because there are so *many* neutrinos in the universe, left over from the big bang, their combined mass might exert a gravitational effect great enough to slow down and perhaps halt the present outward expansion of the universe.

Neutrinos and antineutrinos are commonly produced in the radioactive process called *beta decay* (a weak-interaction process). Here a neutron in a nucleus emits an electron (often called a *beta particle*) and an antineutrino, becoming a proton in the process. Similarly, a proton in a nucleus may beta-decay to emit a positron and a neutrino, becoming a neutron in the process. Neutrinos and antineutrinos thus play an important role in nuclear physics. Unfortunately, they are extremely difficult to detect, because in addition to being neutral, they have the capability of passing through immense distances of solid matter without being stopped. With extremely large detectors and much patience, however, it is possible to observe small numbers of them.

We have now seen that there are three pairs, or families, of charged and neutral weakly interacting leptons, for a total of six; there are therefore also six antileptons. Let us next look at the quarks, of which there are also three pairs—but there the similarity ends.

Quarks

Quarks are particles that interact both strongly and weakly. They were postulated theoretically in 1964 in an effort to unscramble the profusion of known particles, but experimental confirmation of their existence was relatively slow in coming. This difficulty was due to the quarks' most striking single characteristic: they apparently cannot be produced as free particles under any ordinary conditions. They seem instead always to exist as bound combinations of three quarks, three antiquarks, or a quark-antiquark pair. Thus, although they are believed

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to be truly elementary particles, they can be studied—so far—only within the confines of composite particles (which are themselves often inside a nucleus). This apparent inability of quarks, under ordinary conditions, to escape from their bound state is called *quark confinement*.

There are six basic kinds of quarks, classified in three pairs, or families; their names are *up* and *down*, *strange* and *charm*, and *top* and *bottom*. Only the top quark has not yet been shown to exist, but preliminary evidence for it was reported in the summer of 1984. The six varieties named above are called the quark *flavors*, and each flavor is believed to exist in any of three possible states called *colors*. (None of these names have any connection with their usual meanings in everyday life; they are all fanciful and arbitrary.) Flavor is a property similar to that which distinguishes the three families of leptons (electron, muon, and tauon), whereas color is a property more analogous to electric charge.

Another odd property of quarks is that they have fractional electric charge; unlike all other charged particles, which have an integral value of charge, quarks have a charge of either $-1/3$ or $+2/3$. Because free quarks have never been observed, these fractional charges have never been observed either—only inferred. They are consistent, however, with everything we know about quarks and the composite particles they constitute. These relatively large composite particles are the *hadrons*, all of which experience the strong interaction as well as the weak interaction. Although all quarks are charged, not all hadrons are charged; some are neutral, owing to cancellation of quark charges.

There are two distinctly different classes of hadrons: baryons and mesons. *Baryons*—which represent by far the largest single category of subnuclear particles—consist of three quarks (antibaryons consist of three antiquarks) bound together inside what is referred to as a *bag*. This is just a simple model (not a real explanation) to account for the not yet understood phenomenon of quark confinement: the quarks are assumed to be "trapped" in the bag and cannot get out.

Now, finally, we can say what nucleons really are: they are baryons, and they consist of up (u) and down (d) quarks. Protons have the quark structure *uud*, and neutrons have the quark structure *udd*. A larger class of baryons is that of the *hyperons*, unstable particles whose distinguishing characteristic is *strangeness*, i.e., they all contain at least one strange (s) quark. In addition, there are dozens of *baryon resonances*, which are massive, extremely unstable baryons with lifetimes so short (about 10^{-23} second) that they are not considered to be true particles.

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The other class of hadrons is the *mesons*, of which there are also many kinds. These are unstable particles consisting of a quark-antiquark pair, to which the bag model can also be applied. Like the baryons, all mesons experience the strong and weak interactions, and the charged ones also experience the electromagnetic interaction. The most commonly encountered mesons are pi mesons (*pions*) and *K* mesons (*kaons*); the latter are strange (in the quark sense) particles.

All hadrons are subject to the strong force. But the strong force, as it turns out, is merely a vestige of the much stronger force that governs the interactions among the quarks themselves: the *color force*. The two forces are actually the same force being manifested in different ways, at different levels of strength.

These two manifestations of the force that holds nuclei together are of great importance, because they underlie two distinctly different levels of understanding of nuclear phenomena, beyond the simple view that encompasses only nucleons as constituents of the nucleus. The strong force is related to the presence of large numbers of mesons (especially pions) in the nucleus, and many concepts of nuclear physics cannot be understood unless the nucleus is viewed as consisting of baryons and mesons. The color force, on the other hand, is related to the presence of particles called *gluons* inside the baryons and mesons themselves; this represents a different and much deeper view of nuclear phenomena—one that is not nearly so well understood, from either theoretical arguments or experimental evidence. Gluons belong to the third class of elementary particles, the elementary vector bosons, which we will examine shortly, after a brief introduction to the concept of spin.

In addition to their mass and charge, all subatomic particles (including nuclei themselves) possess an intrinsic quality called *spin*, which can be viewed naively in terms of an object spinning about an axis. The values of spin that particles can have are *quantized*: that is, they are restricted to integral values (0, 1, 2, . . .) or half-integral values (1/2, 3/2, 5/2, . . .) of a basic quantum-mechanical unit of measure. All particles that have integral values of spin are called *bosons*, and all particles that have half-integral values are *fermions*. Thus, all particles, regardless of what else they may be called, are also either bosons or fermions. Following the sequence of particles that we have discussed thus far, the classification is as follows: all leptons are fermions; all quarks are fermions; hadrons are divided—all baryons are fermions, but all mesons are bosons. In broad terms, fermions are the building-block particles that comprise nuclei and atoms, and bosons are the particles that mediate the fundamental interactions.

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The significance of the fermion-boson classification lies in a quantum-mechanical law called the *Pauli exclusion principle*, which is obeyed by fermions but not by bosons. The exclusion principle states that in any system of particles, such as a nucleus, no two fermions are allowed to coexist in the identical quantum state (i.e., they cannot have identical values of every physical property). This means that all the protons and all the neutrons in a nucleus must be in different quantum states, which places restrictions on the kinds of motions that they are able to experience. No such restrictions apply to mesons, however, because they are bosons. This situation has profound consequences in the study of nuclear physics.

Most of the bosons to be discussed in the next section are elementary particles—unlike mesons—and are called *vector bosons* (because they have spin 1).

Elementary Vector Bosons

Earlier it was mentioned that the fundamental interactions are mediated by the exchange of certain particles between the interacting particles. These *exchange particles* are the elementary vector bosons (and some mesons, as mentioned below), whose existence is predicted by the quantum field theories of the respective interactions. For example, the theory of the electromagnetic interaction, called *quantum electrodynamics* (QED), predicts the photon to be the carrier of the electromagnetic force. A photon acting as an exchange particle is an example of a *virtual particle*, a general term used for particles whose ephemeral existence serves no purpose other than to mediate a force between two material particles: in a sense, the virtual particles moving from one material particle to the other *are* the force between them (see Figure 1.2).

The virtual particle appears spontaneously near one of the particles and disappears near the other particle. This is a purely quantum-mechanical effect allowed by a fundamental law of nature called the *Heisenberg uncertainty principle*.* According to this principle, a virtual particle is allowed to exist for a time that is inversely proportional to its mass as a material particle. (Under certain conditions, a

*Strictly speaking, the Heisenberg uncertainty principle refers to the impossibility of measuring simultaneously and with arbitrarily great precision physical quantities such as the position and momentum of a particle, but the structure of quantum mechanics leads to an analogous statement for energy and time.

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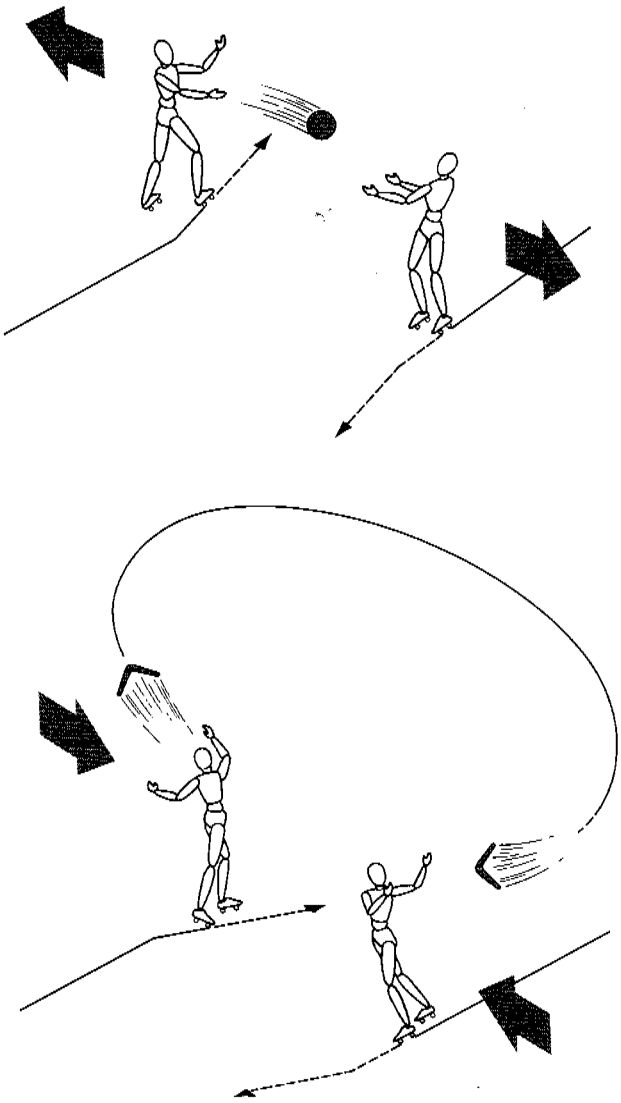


FIGURE 1.2 The way in which force is transmitted from one particle to another can be visualized (crudely) through the example of two roller skaters playing different games of catch as they pass each other. Throwing and catching a ball tends to push the skaters apart, but using a boomerang tends to push them together. (After D. Wilkinson, in *The Nature of Matter*, J. H. Mulvey, ed., Oxford University Press, Oxford, 1981.)

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virtual particle can become a material particle.) The allowed lifetime of a virtual particle determines the maximum distance that it can travel and, therefore, the maximum range of the force that it mediates. Hence, the greater the mass of the material particle, the shorter the distance it can travel as a virtual particle, and vice versa. Photons have zero mass, so the range of the electromagnetic force is infinite.

By contrast with QED, the theory of the weak interaction (the electroweak theory, actually) predicts the existence of three different carriers of the weak force, all of them extremely massive: about 90 to 100 times the mass of a nucleon. These elementary particles are the W^+, W^-, and Z^0 bosons, collectively called the *intermediate vector bosons*. Their discovery in 1983 dramatically confirmed the validity of the electroweak theory. Because of their great mass, these particles are restricted by the uncertainty principle to lifetimes so short that they can travel only about 10^{-18} m before disappearing. This explains the extremely short range of the weak force.

The strong force exists in two guises, as we have seen. Here the fundamental quantum field theory, called *quantum chromodynamics* (QCD), predicts the existence of no less than eight vector bosons—the *gluons*—to mediate the color force between quarks. Experimental evidence for the gluons has been obtained. Gluons are massless, like photons, but because of quark confinement, the range of the color force does not extend beyond the confines of the hadrons (the quark bags).

In its second, vestigial guise, the strong force is experienced by hadrons (baryons and mesons) and is mediated by mesons—by pions at the largest distances. Here we have a type of particle, the meson (which is a boson, but not an elementary one and not necessarily of the vector kind), that can act as its own exchange particle, i.e., material mesons can interact through the exchange of virtual mesons. (This is not a unique case, however, because the gluons, which themselves possess an intrinsic color, are also self-interacting particles.) The range of the strong force—very short, yet much longer than that of the weak force—is explained by the mesons' moderate masses, which are typically less than that of a nucleon and very much less than that of an intermediate vector boson. What is most significant for nuclear physics is that the nucleons interact via the exchange of virtual mesons, so the nucleus is believed always to contain swarms of these particles among its nucleons.

Thus the traditional picture of the nucleus as consisting simply of protons and neutrons has given way to a more complex picture in which the strong nucleon-nucleon interactions must be viewed in terms of *meson-exchange* effects. And even this view is just an approach to

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the deeper understanding of nuclear structure and dynamics that can come about only through detailed considerations of the *quark-gluon* nature of the nucleons and mesons themselves. Ultimately, the nucleus must be explainable in terms of a very complex many-body system of interacting quarks and gluons. The experimental and theoretical challenges posed by this goal are enormous, but so are the potential rewards in terms of our understanding of the nature of nuclear matter.

CONSERVATION LAWS AND SYMMETRIES

The total amounts of certain quantities in the universe, such as electric charge, appear to be immutable. Physicists say that these quantities are conserved, and they express this idea in the form of a *conservation law*. The law of the conservation of charge, for example, states that the total charge of the universe is a constant—or, simply, "charge is conserved." This means that no process occurring in any isolated system can cause a *net* change in its charge. Individual charges may be created or destroyed, but the algebraic sum of all such changes in charge must be zero, thus conserving the original charge, whatever it might have been.

Another important quantity that is conserved is mass-energy. Before Einstein, it was thought that mass and energy were always conserved separately, but we now know that this is not strictly true: mass and energy are interconvertible, so it is their *sum* that is conserved. Mass, in the form of elementary or composite particles, can be created out of pure energy, or it can be destroyed (annihilated) to yield pure energy; both of these processes are commonplace in nuclear and particle physics. This example illustrates the important point that although any conserved quantity may change its form, the conservation law is not invalidated. Energy itself, for instance, can exist in many different forms—chemical, electrical, mechanical, and nuclear, for example—all of which are interconvertible in one way or another without any net gain or loss, provided one accounts for any mass-energy conversion effects. Such effects are significant only in subatomic processes and are, in fact, the basis of nuclear energy.

Two other conserved quantities, linear momentum and angular momentum, are related to the linear and rotational motions, respectively, of any object. Conservation laws for these quantities and the others mentioned above apply to all processes, at every level of the structure of matter. However, there are also conservation laws that have meaning only at the subatomic level of nuclei and particles. One such law is the conservation of baryon number, which states that

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baryons can be created or destroyed only as baryon-antibaryon pairs. All baryons have baryon number +1, and all antibaryons have baryon number −1; these numbers cancel each other in the same way that opposite electric charges cancel. Thus, a given *allowed* process may create or destroy a number of baryons, but it must also create or destroy the same number of antibaryons, thereby conserving baryon number. Processes that violate this law are assumed to be *forbidden*—none has ever been observed to occur. There is no conservation law for meson number, so mesons, as well as other bosons, can proliferate without such restrictions.

A law of nature that predicts which processes are allowed and which are forbidden—with virtual certainty and great generality, and without having to take into account the detailed mechanism by which the processes might occur—represents a tool of immeasurable value in the physicist's effort to understand the subtleties and complexities of the universe. Conservation laws are therefore often regarded as the most fundamental of the laws of nature. Like all such laws, however, they are only as good as the experimental evidence that supports them. Even a single proved example of a violation of a conservation law is enough to invalidate the law—for that class of processes, at least—and to undermine its theoretical foundation. We will see that violations of certain conservation laws do occur, but first let us examine another important aspect of conservation laws: their connections with the symmetries of nature.

Symmetry of physical form is so common in everything we see around us—and in our own bodies—that we take it for granted as a basic (though clearly not universal) feature of the natural world. An example of some geometrical symmetries is shown in Figure 1.3. Underlying these obvious manifestations of symmetry, however, are much deeper symmetries. For example, the fundamental symmetry of space and time with respect to the linear motions and rotations of objects leads directly to the laws of the conservation of linear and angular momentum. Similarly, the mathematical foundations of the quantum field theories imply certain symmetries of nature that are manifest as various conservation laws in the subatomic domain.

One such symmetry, called *parity*, has to do with the way in which physical laws should behave if every particle in the system in question were converted to its mirror image in all three spatial senses (i.e., if right were exchanged for left, front for back, and up for down). Conservation of parity would require that any kind of experiment conducted on any kind of system should produce identical results when performed on the kind of mirror-image system described above. For

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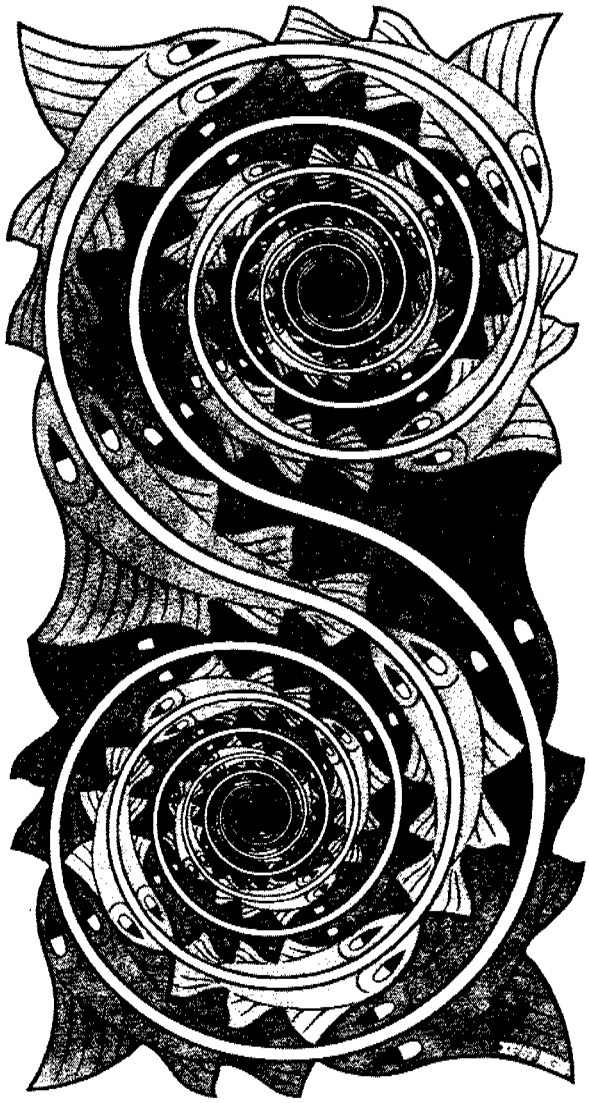


FIGURE 1.3 *Whirlpools*, a woodcut by M. C. Escher, provides an example of complex geometrical symmetries, which underlie many aspects of nuclear structure. Equally important are dynamical symmetries found in the physical laws governing all natural phenomena. (By permission of the Escher Foundation, Haags Gemeentemuseum, The Hague. Reproduction rights arranged courtesy of the Vorpal Galleries, New York, San Francisco, and Laguna Beach.)

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many years, it was believed that parity was an exact (universal) symmetry of nature. In 1956, however, it was discovered by nuclear and particle physicists that this is not so; parity is not conserved in weak interactions, such as beta decay. However, it is conserved, as far as we know, in all the other fundamental interactions and thus represents a simplifying principle of great value in constructing mathematical theories of nature.

A similar, albeit isolated, example of symmetry violation has been found for the equally fundamental and useful principle called *time-reversal invariance*, which is analogous to parity except that it entails a mirror imaging with respect to the direction of time rather than to the orientation of particles in space. This symmetry has been found to be violated in the decays of the neutral kaon. No other instances of the breakdown of time-reversal invariance are known—yet—but physicists are searching carefully for other cases in the hope of gaining a better insight into the underlying reason for this astonishing flaw in an otherwise perfect symmetry of nature.

The implications of such discoveries extend far beyond nuclear or particle physics; they are connected to basic questions of cosmology, such as the ways in which the primordial symmetry that is believed to have existed among the fundamental interactions at the instant of the big bang was then "broken" to yield the dramatically different interactions as we know them now. The efforts of theoretical physicists to construct *Grand Unified Theories* of the fundamental interactions, in which these interactions are seen merely as different manifestations of a single unifying force of nature, depend strongly on experimental observations pertaining to symmetries, conservation laws, and their violations.

A most important observation in this regard would be any evidence of a violation of the conservation of baryon number, which may not be a universal law after all. Certain of the proposed Grand Unified Theories predict, in fact, that such a violation should occur, in the form of spontaneous proton decay—not in the sense of a radioactive beta decay, in which a proton would be converted to a neutron (thus conserving baryon number) but rather as an outright disappearance of a baryon (the proton) as such. Extensive searches have been mounted to find evidence for proton decay, so far without success.

Also of great importance would be any violation of the conservation of lepton number. This law, which is also obeyed in all currently known cases, is analogous to the conservation of baryon number, but with an added twist: lepton number ($+1$ for leptons, -1 for antileptons) appears to be conserved not only for leptons as a class but also for each

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of the three families of leptons individually (the electron, muon, and tauon, with their respective neutrinos). Any violation of lepton-number conservation would mean that neutrinos are not, in fact, massless and that they can *oscillate* (change from one family to another) during their flight through space. Exactly these properties are also predicted by certain of the proposed Grand Unified Theories, and this provides the impetus for searching for them in various types of nuclear processes. Such searches for violations of conservation laws represent an important current frontier of nuclear physics as well as of particle physics.

ACCELERATORS AND DETECTORS

The principal research tools used in nuclear physics are *accelerators*—complex machines that act as powerful microscopes with which to probe the structure of nuclear matter. Equally indispensable are the sophisticated *detectors* that record and measure the many kinds of particles and the gamma rays emerging from the nuclear collisions produced by the accelerator beams.

There are several different kinds of accelerators, differing mainly in the ways in which they provide energy to the particles, in the energy ranges that they can span, and in the trajectories followed by the accelerated particles. The most common kinds are Van de Graaff electrostatic accelerators, linear accelerators, cyclotrons, and synchrotrons; an example of a modern cyclotron is shown in Figure 1.4. Most of the details of these machines need not concern us here, but a survey of some basic ideas is necessary for an appreciation of how nuclear physics research is actually done. Additional information on accelerators in general and on several important accelerators of the future can be found in Chapter 10, and a survey of the major operating accelerators in the United States is given in Appendix A.

Projectiles and Targets

The basic principle of all accelerators is the same: a beam of electrically charged *projectile* particles is given a number of pulses of energy—in the form of an electric or electromagnetic field—to boost the particles' velocity (and hence kinetic energy) to some desired value before they collide with a specified *target*. Typically, the projectiles are electrons, protons, or nuclei. The latter are often called *ions*, because they are generally not bare nuclei, i.e., they still retain one or more of the orbital electrons from the atoms from which they came. Nuclei of the two lightest elements, hydrogen and helium, are called the *light*

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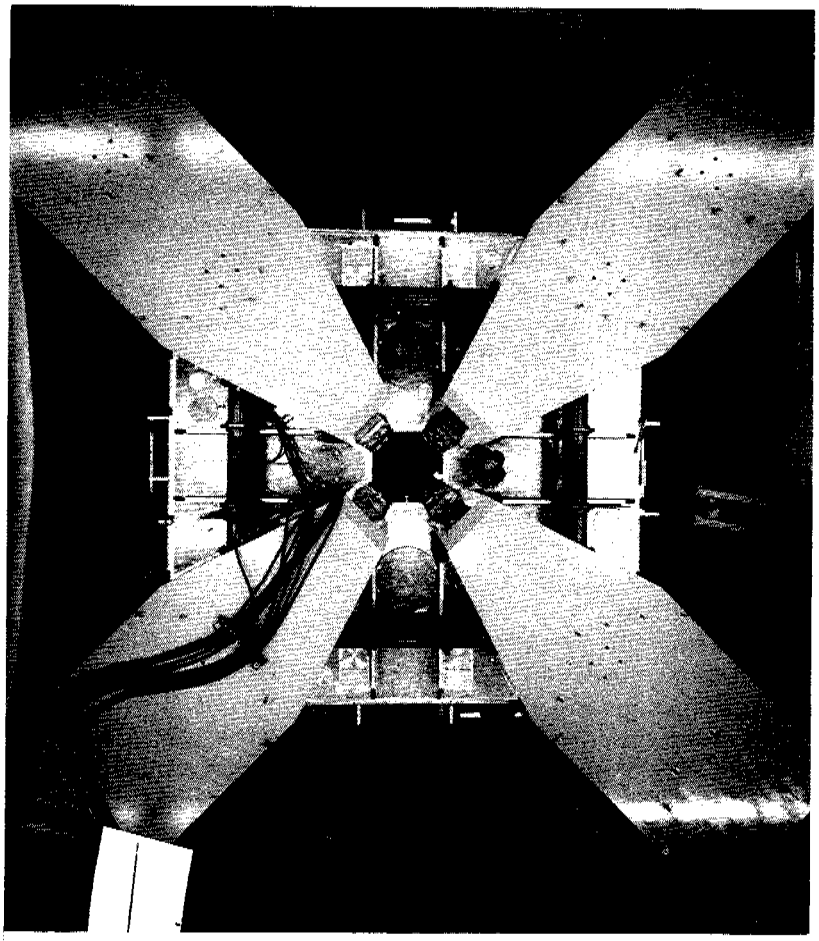


FIGURE 1.4 Top view of the main cyclotron of the Indiana University Cyclotron Facility, a modern accelerator used for basic nuclear-physics research. The field produced by the four large magnets (note the physicist standing between two of them) confines the projectile particles—light ions up to mass number 7—to a series of roughly circular orbits of ever-increasing size as they are accelerated to energies in the range of 40 to 210 MeV. After about 300 orbits, the beam is extracted and directed at targets in nearby experimental areas. (Courtesy of the Indiana University Cyclotron Facility.)

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ions; they include the often-used *alpha particle*, which is just the nuclide helium-4 ($Z = 2$, $N = 2$). Nuclei from those of lithium ($A = 6$ or 7) to those with a mass number of about 40 can be called *medium ions*, and those with a mass number from about 40 on up through the rest of the periodic table are called *heavy ions*. (This classification is useful but necessarily somewhat arbitrary; the definition of heavy ion, for example, is sometimes extended all the way down to lithium.)

Accelerators can also produce beams of exotic or unstable charged projectiles such as muons, mesons, antiprotons, and radioactive nuclides. These are made in reactions occurring at the target of a primary beam and are then focused into a secondary beam. Even neutral particles, such as neutrons and neutrinos, can be produced and used as secondary beams.

The target struck by the accelerated projectile in a typical nuclear-physics experiment is a small piece of some solid chemical element of particular interest, although liquid and gaseous targets can also be used. The objective may be to use the projectiles to raise nuclei in the target substance from their lowest-energy *ground state* to higher-energy *excited states* in order to gain insight into the structures and dynamics of intact nuclei; in this way one studies nuclear spectroscopy. Alternatively, the objective may be to bombard the target nuclei in such a way that they undergo a nuclear reaction of some kind, possibly disintegrating in the process.

The above descriptions pertain to the traditional *fixed-target* machines (a stationary target being bombarded by a projectile beam), but accelerators can also be constructed as *colliding-beam* machines, or *colliders*. Here two beams collide violently with each other, nearly head-on, in a reaction zone where the beams intersect. Colliders have been pioneered by elementary-particle physicists because of the huge amounts of energy that can be deposited in the collision zone when both beams have been accelerated to high velocities. Their use is becoming increasingly important to nuclear physicists for the same reason, as described in Chapter 7.

Energies

The kinetic energies to which particles or nuclei are accelerated are expressed in terms of large multiples of a unit called the *electron volt* (eV), which is the amount of energy acquired by a single electron (or any other particle with unit electric charge, such as a proton) when it is accelerated through a potential difference of 1 volt (V) as in a 1-V

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battery. The characteristic particle beam energies in modern nuclear-physics accelerators are of the order of mega-electron volts (1 MeV = 10^6 eV) and giga-electron volts (1 GeV = 10^9 eV). When dealing with accelerated nuclei, which contain more than one nucleon, it is customary to give the energy per nucleon rather than the total energy of the nucleus.

For convenience, not only the energies of particles but also their masses are customarily given in terms of electron volts. Any mass can be expressed in terms of an equivalent energy, in accord with $E = mc^2$. Thus the mass of an electron is 0.511 MeV, and the mass of a proton is 938 MeV. These are the *rest masses* of these particles, i.e., the masses that they have when they are not moving with respect to some frame of reference (such as the laboratory). When they are moving, however, their kinetic energy is equivalent to additional mass. This effect becomes significant only when their velocity is very close to the speed of light; then their kinetic energy becomes comparable to or greater than their rest mass, and they are said to be *relativistic* particles (or nuclei), because the dynamics of their reactions cannot be accurately described without invoking relativity theory.

It is convenient to classify nuclear processes in terms of different energy regimes of the projectiles, although any such classification, like that of the projectile masses, is somewhat arbitrary and not likely to find universal acceptance. Bombarding energies of less than about 10 MeV per nucleon, for example, produce a rich variety of *low-energy* phenomena. It is in this regime (at about 5 MeV per nucleon) that the effects due to the *Coulomb barrier* are particularly important; the Coulomb barrier is a manifestation of the electrostatic repulsive force between the positively charged target nucleus and any positively charged projectile. For a collision involving the effects of the strong force to occur, the projectile must be energetic enough to overcome the Coulomb barrier and approach the target closely.

Between about 10 and 100 MeV per nucleon is the *medium-energy* regime, where many studies of nuclear spectroscopy and nuclear reactions are carried out; these are the energies characteristic of the motions of nucleons within a nucleus. In the *high-energy* regime, between about 100 MeV per nucleon and 1 GeV per nucleon, high temperatures are produced in the interacting nuclei; also, some of the collision energy is converted to mass, usually in the form of created pions, which have a rest mass of 140 MeV. Above about 1 GeV per nucleon is the *relativistic* regime, where extreme conditions, such as the formation of exotic states of nuclear matter, are explored. [It is worth noting here that for electrons the transition to relativistic

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behavior occurs at much lower energies (about 0.5 MeV), owing to the electron's small rest mass.]

Nuclear Interactions

The principal kinds of nuclear interactions in collisions are *scattering*, in which the projectile and target nuclei are unchanged except for their energy states; *transfer*, in which nucleons pass from one nucleus to the other; *fusion*, in which the two nuclei coalesce to form a compound nucleus; *spallation*, in which nucleons or nucleon clusters are knocked out of the target nucleus; and *disintegration*, in which one or both nuclei are essentially completely torn apart.

Not all interactions that occur in collisions are equally probable, so it is important to know what does occur to an appreciable extent and what does not—and why. The probability of occurrence of a given interaction is expressed by a quantity called its *cross section*, which can be measured experimentally and compared with theoretical predictions.

Another quantity whose experimental measurement is important is the *half-life* of a radioactive species—the time it takes for half of all the nuclei of this nuclide in a sample to decay to some other form or state. Normally, this decay is by the emission of alpha or beta particles or gamma rays; less commonly, it is by *spontaneous fission*, in which a nucleus simply splits in two, with the emission of one or more neutrons. After half of the nuclei have decayed, it will take the *same* length of time for half of the remaining nuclei to decay, and so on. The characteristic half-lives of radioactive nuclides vary over an enormous range of values: from a small fraction of a second to billions of years.

Particle Detectors

Accelerators would be useless if there were no way to record and measure the particles and gamma rays produced in nuclear interactions. The detectors that have been invented for this purpose represent a dazzling array of ingenious devices, many of which have pushed high technology to new limits. Some are designed to detect only a specific particle whose presence may constitute a *signature* of a particular kind of event in the experiment in question. They may be designed to detect this particle only within a certain limited range of angles of emission with respect to the beam direction or over all possible angles of emission.

Other detectors are designed to detect as many kinds of particles as

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possible, simultaneously—again either for limited angles or for all angles. This kind of detector is necessarily complex, owing to the many kinds of particles that must be observed and to the number of particles actually produced. This latter number, called the *multiplicity*, is as small as one or two for many kinds of events, but in the catastrophic collisions of relativistic heavy ions, it may be several hundred. Yet another consideration in the design of detectors is whether they are to be used at a fixed-target accelerator or a collider; the requirements are often very different.

Among the simplest detectors are those in which a visible track is left in some medium by the passage of a particle. Examples of such visual detectors are the streamer chamber (in which the medium is a gas), the bubble chamber (liquid), and photographic emulsions (solid). Most detectors, however, rely on indirect means for recording the particles, whose properties must be inferred from the data. The operating principles of the great majority of such detectors are based on the interactions of charged particles with externally applied magnetic fields or on the ionization phenomena resulting from their interactions with the materials in the detectors themselves. The largest of these detector systems may consist of thousands of individual modules and are used in the study of very complex events. Sophisticated, dedicated computers are required to store and analyze the torrents of data from such instruments.

At the largest accelerators, the efforts of many physicists, engineers, and technicians may be required for many months to plan and execute one major experiment, and months more of intensive effort may be required to process and analyze the data and interpret their meaning. This is the "big-science" approach to nuclear-physics research. A highly noteworthy feature of nuclear physics, however, is that much research of outstanding value is still done by individuals or small groups working with more modest but nonetheless state-of-the-art facilities in many universities and laboratories throughout the world. It is the cumulative effort of all these scientists and their colleagues working at the accelerators—together with that of the nuclear theorists—that advances our knowledge of nuclear physics.

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I

Major Advances in Nuclear Physics

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2

Nuclear Structure and Dynamics

The modern era of nuclear physics began with the surprising revelation that, despite the violent forces that are present in the nucleus, the nucleons can for the most part be considered to be moving independently in a single, smoothly varying force field. This is the conceptual basis of the *shell model*, which is the foundation for much of our quantitative understanding of nuclear energy levels and their properties. In this model, individual nucleons are considered to fill energy states successively, forming a series of nuclear shells that are analogous to the shells formed by electrons in the atom.

At the simplest level, the shell model predicts that nuclei having closed (completely occupied) shells of protons or neutrons should be unusually stable—as is, in fact, observed. (The chemical analogy is the noble gases, in which all the electrons are in closed shells.) If a nucleus has one nucleon beyond the closed shells, many of the properties of the nucleus can be attributed to that one nucleon—just as the chemistry of sodium can be explained largely in terms of the sodium atom's single valence electron.

The shell model has been developed to incorporate the residual forces among the nucleons that are not included in the smooth field. This has evolved to a valuable tool for understanding and predicting many of the energy levels and their properties, such as electromagnetic interactions and decay rates. However, the shell model with interactions can be computationally difficult or impossible, depending on the

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number of nucleons and the number of shells that the nucleons move in.

Under such circumstances, or when a simpler description is needed, other models have enjoyed considerable success. The *liquid-drop model* depicts the nucleus as a drop of liquid having such familiar properties as pressure and surface tension. This model has been useful in systematizing the data on binding energies and in providing useful qualitative pictures of vibrations and the process of nuclear fission. An important feature of the liquid-drop model is the collective motion of many particles, which is often observed in the properties of nuclear levels.

Another simplified model is the *interacting boson model.* Here nucleons spanning many shells are thought to combine to form even-numbered nucleon clusters (which have integral values of spin and can therefore be regarded as bosons), which can be studied by the application of symmetry principles. For many of these models, it is possible to make the connection with the more fundamental but more complicated shell-model description.

Experimentalists study nuclear structure by determining what energy states appear in a given nucleus and what states play a role in particular nuclear reactions. In the early days of nuclear physics, experiments were restricted to the states involved in the decay of naturally occurring radioactive nuclides or in a few low-energy reactions that could be carried out with alpha particles emitted by radioactive minerals. The advent of accelerators greatly increased the number of nuclear states that could be excited, by making available new projectile species having a wide range of precisely controllable bombarding energies. Electrons, protons, light ions, and heavy ions can be supplied by acceleration acting on the projectile's electric charge. Furthermore, secondary beams of neutral (uncharged) projectiles—for instance, photons and neutrons—can be produced in primary reactions, a technique that can also supply exotic projectiles such as pions and even neutrinos. In fact, intense pion beams have become a standard tool of nuclear-physics research during the past decade.

A great many nuclear states have thus become accessible, partly because the number of excited states increases with increasing energy above the ground state and partly because the interactions of different projectiles cause different types of internal nuclear motions to be excited. For example, highly charged heavy-ion projectiles can exert powerful Coulomb (electric) forces on the protons of a target nucleus (a process called *Coulomb excitation*) while remaining well outside the

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range of nuclear forces. Thus, the effects of Coulomb excitation can be studied with no interference from unwanted nuclear interactions.

The ability to excite certain types of nuclear motion selectively has become an even more important tool in nuclear-structure studies over the past decade. The following sections discuss some excitation modes of current interest and the kinds of information that they provide on nuclear structure and dynamics.

ELEMENTARY MODES OF EXCITATION

Extreme limiting cases, in which one type of behavior overshadows all competing effects, are often the easiest to deal with in physics. Nuclear physicists have therefore concentrated much of their attention on excited states corresponding either to the shell model, at one extreme, or to the liquid-drop model, at the other. In the first case, the excitation is designed to alter the motion of only one nucleon, while the remaining core nucleons remain essentially unaffected, so that the excited states generated can be related to the motion of just the one nucleon. In the second case, the excitation requires all the nucleons to "forget" their individual motions and to participate in an overall coherent motion, much as a milling school of fish, when frightened, suddenly darts away in a single direction. Both of these modes of excitation are amenable to experiment and theory and give unique views of the behavior of the nuclear many-body system.

The collective motions of nuclei include rotations and internal vibrations. Collective rotations occur only in deformed, nonspherical nuclei and entail the coherent swirling of some nucleons around a motionless inner core. Collective vibrations can occur in any nucleus and are somewhat akin to the complex bulgings of a water-filled balloon that is being shaken.

The motion of nucleons in three-dimensional space, however, is not the only way collective modes can arise. The direction of the spin axes of several nucleons may flip back and forth in concert after an excitation. Because a nucleon's magnetic field lies parallel to its spin axis (similar to the alignment of the Earth's magnetic field with the polar axis), a *spin-flip* collective mode gives the nucleus an oscillating spin direction and therefore an oscillating magnetic field. In a related collective mode called the *Gamow-Teller resonance*, the excitation flips the *isospin* (causing a proton to change to a neutron, or vice versa) as well as the spin. These spin-flipping and isospin-flipping modes have both recently been observed unambiguously in actual nuclei, as discussed later in this chapter. These modes make up a new class of

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excited states that gives some insight into how the interaction between two nucleons is modified by the presence of neighboring nucleons. The discovery of these modes has stimulated the development of nuclear-structure theory.

Giant Electric Resonances

In the late 1940s, physicists studying neutron-emission reactions caused by bombarding nuclei with gamma rays were startled to find a large peak—a *resonance*—in the curve of the reaction cross section (the probability of reaction) when it was measured over a wide range of gamma-ray energies. This peak represented a value typically 50 to 100 times greater than those of the cross sections for neighboring energies—truly a giant resonance. The gamma-ray energy of the peak was found to decrease systematically with increasing mass number, from 23 MeV in carbon to 14 MeV in lead.

The giant resonance is a general characteristic of the nuclear many-body system and does not depend on the detailed structure of a particular nuclide. It is now recognized as a *giant electric dipole* vibration caused by collective motion in the nucleus: the oscillating electric field associated with the gamma ray induces the protons in the nucleus to oscillate. The neutrons, being uncharged, do not respond to an electric field, so a vibration is set up in which the center of electric charge (due to the protons) oscillates with respect to the center of mass, as shown schematically in Figure 2.1. Classically, this type of linear charge oscillation is described as an oscillating electric dipole—hence the name of the phenomenon. The peak in the cross-sectional curve is caused by an amplifying resonance between the oscillation frequency of the gamma ray's electric field and the natural frequency of the dipole oscillation in the target nucleus.

The maximum possible probability for a nucleus to absorb a gamma ray can be calculated from very general considerations and is expressed as a *sum rule* involving a sum over all the nuclear charges and masses. The observed probability for absorption of the gamma rays at resonance energies is nearly equal to the theoretical maximum from the sum rule for electric dipole oscillations—strong evidence that essentially all of the protons take part in the collective motion.

The giant electric dipole resonance peak extends over a width of 3 to 7 MeV in energy, depending on the nucleus. This is a relatively wide peak, and wide peaks generally correspond to short lifetimes. The giant electric dipole oscillation is estimated to go through only a few

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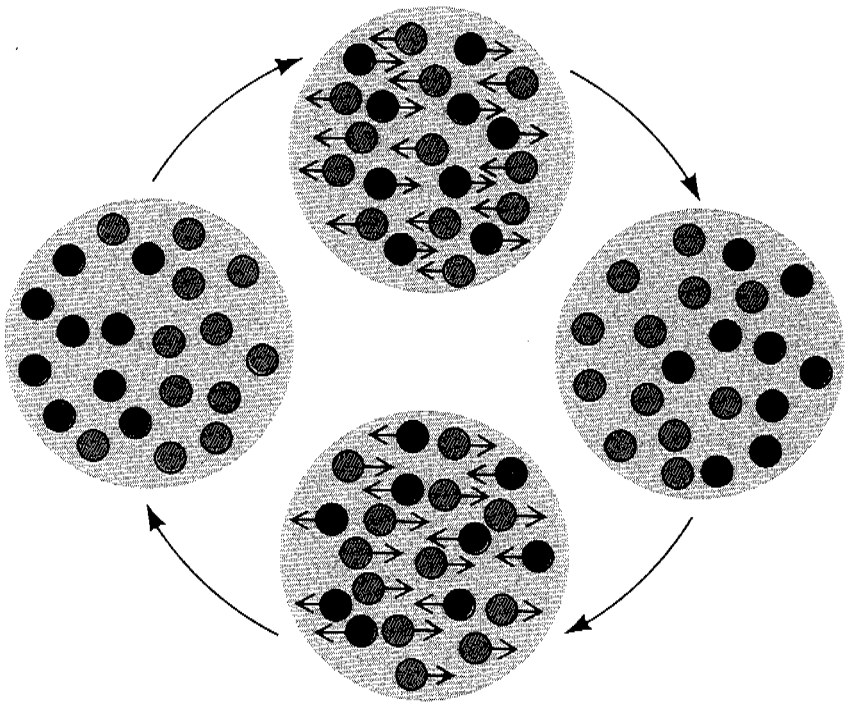


FIGURE 2.1 The giant electric dipole vibration, as described in the text. The relative motions of the protons (dark circles) and neutrons (light circles) during the intermediate stages of the vibration are indicated by the arrows. (After G. F. Bertsch, *Scientific American*, May 1983, p. 62.)

complete cycles before it dissipates, corresponding to a lifetime of roughly 10^{-21} second.

For about 25 years, the electric dipole resonance remained the only known giant vibrational mode. As the above description implies, gamma rays are efficient at exciting only linear dipole vibrations; vibrations corresponding to more complex patterns (multipoles) are best studied with other means of excitation. Experimentalists therefore turned to the inelastic scattering of charged particles from nuclei, in which the projectile retains its identity but deposits some of its energy in the target. In the early 1970s, a group in Darmstadt, West Germany, using inelastic electron scattering, and a group at Oak Ridge National Laboratory, using inelastic proton scattering, both found clear evidence for a giant electric *quadrupole* resonance. Here the protons and neutrons move together in a quadrupole vibration, in which the center

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of charge and the center of mass do not move, but the distributions of charge and mass change rhythmically as the nucleus oscillates between a prolate (football) shape and an oblate (doorknob) shape.

Later, the inelastic scattering of alpha particles was found to be particularly efficient at exciting the giant quadrupole vibration. This technique provides a particularly handy tool, because the necessary 100- to 150-MeV alpha-particle beams are available at many cyclotrons and because the scattered alpha particles are easy to detect. Use of the alpha-particle excitation has established the energy peak, the energy width, the strength, and some of the decay modes of the giant electric quadrupole resonance for a wide range of nuclei. The resonance tends to appear at 10 to 20 MeV above the ground state and has a width between 2 and 8 MeV, depending on the nuclide. The sum rule appropriate to quadrupole vibrations indicates that nearly all of the nucleons in heavy nuclei take part in the collective motion.

Unlike gamma-ray absorption, which excites dipole vibrations selectively, the inelastic scattering of charged particles can excite several vibrational modes. To disentangle the individual vibrational patterns from the measured angular intensities of the scattered particles, physicists exploit the fact that each multipole is associated with a definite integer value L of angular momentum ($L = 1$ for dipole, $L = 2$ for quadrupole). Thus, the particles scattered during the excitation of a particular multipole vibration show an angular pattern characteristic of the L value; the experimental data usually have to be analyzed as a sum of several different angular patterns from different resonances.

The giant *monopole* vibration $L = 0$ is a *breathing mode* in which the nuclear volume expands and contracts symmetrically, as Figure 2.2 illustrates. Discovering the giant monopole resonance experimentally was not easy. It is generally masked by the quadrupole resonance except at very small scattering angles, where the detector system must be carefully designed to avoid false counts from the intense beam of undeflected projectiles. In 1977, a group at Texas A&M University identified the giant monopole resonance with certainty by studying inelastic alpha scattering at angles as small as 3° from the projectile beam direction. The monopole mode was recognized by its unique small-angle scattering pattern. Further evidence came from the monopole sum rule, which was satisfied essentially fully by the observed scattering intensity, as would be expected for a collective mode in which all the nucleons are taking part.

The monopole vibration is particularly important because its frequency is directly related to the compressibility of nuclear matter, a heretofore unmeasured property. The value for the compressibility

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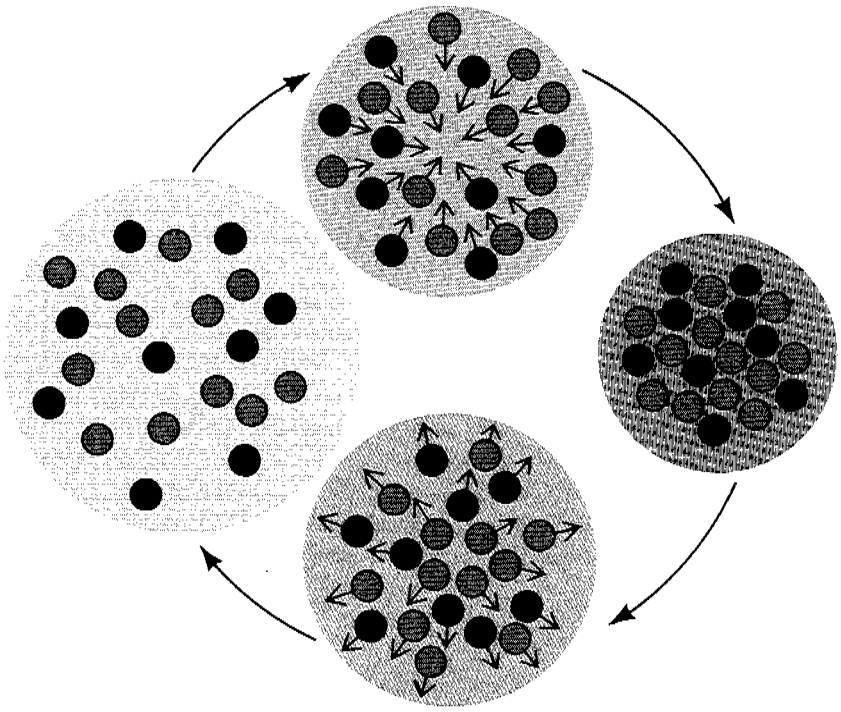


FIGURE 2.2 The giant monopole vibration, as described in the text. As the protons (dark circles) and neutrons (light circles) move in and out from their equilibrium positions, the nucleus "breathes," and its density oscillates. (After G. F. Bertsch, *Scientific American*, May 1983, p. 62.)

derived from measured monopole vibration frequencies turns out to be in good agreement with values predicted by various theoretical models. To gain an appreciation of the extraordinary differences between nuclear matter and ordinary atomic matter, it is worth noting that the latter is about 10^{22} times more compressible, i.e., all ordinary matter is almost infinitely soft by comparison.

Preliminary experimental evidence exists for giant multipole resonances of higher L values, such as the pear-shaped *octupole* vibration $L = 3$. Heavy ions might be especially suitable projectiles for exciting vibrations with large L values, because such massive ions can transfer a large amount of angular momentum to a target nucleus. Also, variations on monopole or quadrupole vibrations are possible in which the neutrons and protons move in opposition rather than together. Such out-of-phase vibrations have not yet been explored systemati-

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cally, but there is recent evidence that the monopole mode is selectively excited in reactions that transfer charge between a projectile pion and the target nucleus.

In fact, the pion has turned out to be an efficient indicator of the relative roles of protons and neutrons in nuclear excitations. Both positive and negative pion beams can be focused on a target. Positive pions in a certain energy range interact with target protons almost ten times more strongly than with target neutrons; the reverse is true for negative pions, which interact much more strongly with target neutrons. Direct comparison of the results obtained with these two probes thus yields a measure of the relative importance of the protons and neutrons in a particular nuclear vibration. Some excited states in light nuclei, for example, have been shown to be essentially pure proton or pure neutron excitations. Even when the differences between the target protons and neutrons are much smaller, as in the giant quadrupole vibrations in heavy nuclei, they can be detected through positive and negative pion scattering. This technique thus provides a sensitive test of the microscopic theory of nuclear vibrations.

Giant Spin Vibrations

In addition to vibrations involving the motion of nucleons, nucleon spins can also exhibit collective behavior. A nucleon has a built-in "bar magnet" along its spin axis, so a collective mode for spin is also a collective mode for magnetism. Nucleons have spin 1/2, and, according to quantum mechanics, the nucleon spin measured along a coordinate axis can be only $+1/2$ (spin oriented parallel to the axis) or $-1/2$ (spin antiparallel). Under certain conditions, the spin of a nucleon can flip between $+1/2$ and $-1/2$, simultaneously reversing the direction of the magnetic field that it produces.

Researchers at the Indiana University Cyclotron Facility, using proton beams of 100 to 200 MeV, were recently able to flip the spin and isospin of nucleons in the nucleus without upsetting the spatial arrangements of the nucleons. Thus, they were able to excite Gamow-Teller resonances without obscuring them with other forms of excitation. The trick is to observe a neutron coming out of the nucleus in exactly the same direction in which the proton entered. The neutron has nearly the same velocity as the proton, so the law of conservation of momentum tells us that hardly any momentum was transferred to the nucleus. Hence, the only change inside the nucleus is that a neutron changed to a proton, and possibly its spin flipped. In experiments now

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being carried out, the spins of the proton and the neutron are actually measured.

It is a simple matter to count the number of neutrons that are available to be changed into protons in the nucleus. Then the total probability of the Gamow-Teller process for a nucleus relative to the process for a free neutron can be calculated with great accuracy. A surprising result of the measurements is that the actual total probability is only 50 to 75 percent of the calculated probability. One possible explanation for the strength shortfall is that the transition from a neutron to a proton is not the elementary process. Rather, we should consider that the nucleons are made of quarks and that the elementary Gamow-Teller process is a spin-isospin flip of one of the constituent quarks. The quark flip can indeed change a neutron into a proton, but it can also change a neutron to a higher-energy configuration called a *delta resonance* (which is a baryon resonance). In this model, the delta states must also be counted in the total transition probability. Then, possibly, the strength will come out right. Complete calculations on this model have not yet been done, and the missing strength problem has not been resolved.

A Michigan State University-Orsay collaboration working at Orsay, France, has identified a component of the Gamow-Teller excitation in which the charge of the nucleus remains the same; according to isospin symmetry arguments, such an excitation should exist. The measurement had to be made as close to the beam direction as possible, with the best possible discrimination between the beam and the scattered particles, which had similar energies. The experimental solution was to use an extremely precise magnetic spectrometer that could identify the scattered protons and operate close to the beam.

Deltas in Nuclei

One interesting aspect of the Gamow-Teller resonance arises from the possible importance of the delta resonance in this low-energy phenomenon. Deltas are high-energy excited states of the baryon. The first (lowest-level) such state has a mass of 1.23 GeV, compared with 0.94 GeV for a nucleon, and this great excess of mass-energy causes it to decay (into a pion and a nucleon) even before it has traversed the diameter of the nucleus. With such a short lifetime, the delta is not regarded as a true particle, and yet it can play a crucial role in nuclear phenomena.

The importance of the delta in nuclear physics has become clear during the last decade, mostly in experiments with pions. When a pion

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with an energy of several hundred MeV collides with a nucleus, one of the nucleons may absorb the pion to become a delta. This transformation creates a vacancy, or *hole*, in the energy state originally occupied by the nucleon. The progress of the reaction is then determined by the dynamics of the delta-hole system as it propagates through the nucleus. A comparison of predictions based on this mechanism with experiments on pion-nucleus reactions (carried out at *meson factories* such as the Los Alamos Meson Physics Facility) casts light on several phenomena of current interest, e.g., modification of the delta lifetime and mass by the nuclear environment, the nature of pion absorption by nucleons, and the nature of the delta-nucleon interaction. It is surprising that one can even think about the average potential seen by such a short-lived particle inside the nucleus. And yet experiments can be interpreted to show that the delta is substantially less bound than a nucleon in the center of a nucleus, whereas the effective spin-dependent potential for a delta is comparable with that for the nucleon. Study of the propagation of other baryon resonances in nuclei is just beginning.

Electron-Scattering Results

There are several reasons why the scattering of high-energy electrons is a powerful tool for studying nuclear structure. First, the interaction is electromagnetic and thus more readily understood. (The weak part of the electroweak interaction plays a significant role only if one looks directly at its unique effects, for example, in an experiment that exhibits parity violation.) This implies that the experimental results have a direct interpretation in terms of the quantum-mechanical structure of the nuclear target. (By contrast, it is often difficult to separate the reaction mechanism from the target structure in hadronic scattering of strongly interacting particles.) Of course, these comments also apply to photon scattering, but a second great advantage of electron scattering is that, for a *fixed* nuclear excitation energy, one can vary the momentum transferred by the scattered electron to the nucleus and map out the charge and current densities, even in the deep interior of the nucleus. Thus an electron accelerator is, in effect, a huge microscope for studying the spatial distributions of charges and currents inside a nucleus, which has a typical diameter of 10^{-13} cm. To see smaller and smaller distances, we require higher and higher momentum transfer, which implies higher and higher electron energies.

The charge density in the nucleus arises from the proton distribution. One part of the current arises because of the motion of the protons.

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Both the neutron and proton have a small magnetic moment, and hence each behaves like a small magnet. This intrinsic magnetization also contributes to the electromagnetic interaction of electrons with the nucleus. In addition, there are *exchange currents* present in the nucleus due to the fleeting presence of virtual pions and other charged mesons.

Another feature of electron scattering allows us to obtain a nuclear excitation *energy profile* by varying the momentum transferred to the target. At low momentum transfer, the spectrum is dominated by electric dipole transitions. At high momentum transfer, however, transitions that require a high angular momentum may take place, and it becomes possible to investigate high-spin states. Furthermore, because the interaction of the electron with the intrinsic magnetization is enhanced at high momentum transfer and large electron scattering angles, it is possible to examine high-spin states of a magnetic character.

Finally, at the very high energy and momentum transfers that are obtainable at the Stanford Linear Accelerator Center (SLAC), it has been possible to study small distances in the nuclear system and to see the pointlike quarks inside the protons and neutrons.

We clearly cannot touch on all the recent advances in electron scattering from nuclei. Instead, we will briefly discuss two examples.

Elastic charge scattering of electrons from nuclei makes it possible to measure the detailed spatial distribution of the charge inside the nucleus in its ground state. Our most precise knowledge of the sizes and shapes of nuclei comes from such experiments. The basic process is analogous to what is observed when light passes through a small circular aperture: the wavelets from each part of the aperture interfere with each other and produce a diffraction pattern consisting of rings of varying light intensity that can be observed on a screen. Since a basic hypothesis of quantum mechanics is that electrons also possess wave properties, a diffraction pattern (of a somewhat different kind) is observed when an electron is scattered by a nuclear charge distribution.

To see the details of this charge density due to nuclear orbits and shells requires measuring the scattered electron energies to better than 1 part in 20,000, a precision unattainable 10 years ago. Today, spectrometers with the necessary energy discrimination are in use, notably at CEN Saclay (France) and at the MIT Bates Accelerator Laboratory. In Figure 2.3 we show an example of a diffraction pattern of scattered electrons obtained with a calcium-40 target. Such data can be used to make accurate maps of the spatial distributions of charge in

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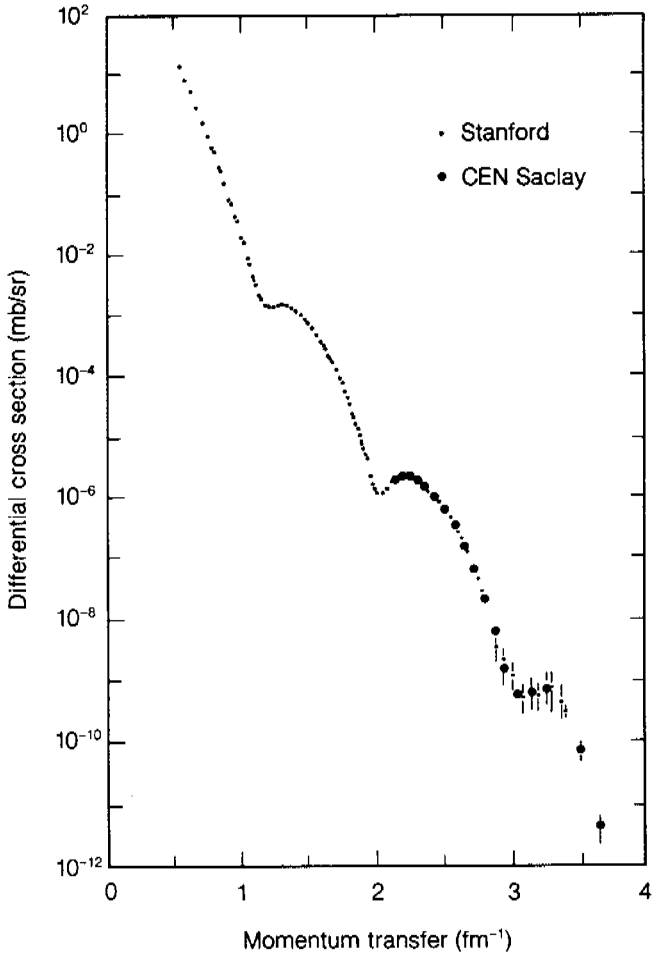


FIGURE 2.3 A nuclear diffraction pattern obtained by the elastic scattering of 500-MeV electrons from calcium-40 nuclei. Note that the measurements were made over the enormous range of about 12 orders of magnitude. (From B. Frois, in *Nuclear Physics with Electromagnetic Interactions*, H. Arenhövel and D. Drechsel, eds., Vol. 108 of *Lecture Notes in Physics*, Springer-Verlag, Berlin, 1979.)

nuclei. In the rare-earth nuclei, these shapes are deformed from spherical, owing to the tidal forces of outer-shell nucleons orbiting around a central core (see Figure 2.4). In a recent experiment, the charge distributions of two neighboring nuclei were compared; the charge difference was concentrated in peaks at various distances from

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the center of the nucleus. This could be attributed to the extra proton's occupying a particular shell, as was expected from the shell model. However, the peaks were smaller than expected, showing that additional effects beyond those incorporated in the shell model must be present.

We now turn to the related topic of *elastic magnetic scattering*. Each nucleus, if it has some angular momentum in its ground state, is also a small magnet. Just as the total charge of the nucleus receives contributions from spatially varying elements of the charge density, the total magnetic moment receives contributions from the spatially varying elements of the magnetization density. By measuring the diffraction pattern of electrons elastically scattered from a nucleus in the *backward direction*, one can measure the spatial distribution of this magnetization density. Because the individual proton and neutron spins and angular momenta pair off in a nucleus, the total nuclear magnetization typically comes from the last valence nucleon. Since neutrons possess a small intrinsic magnetic moment, they will also contribute to elastic magnetic scattering. By measuring the scattered electrons' diffraction pattern to high values of momentum transfer, one can see the spatial distribution of the last valence particle—proton or

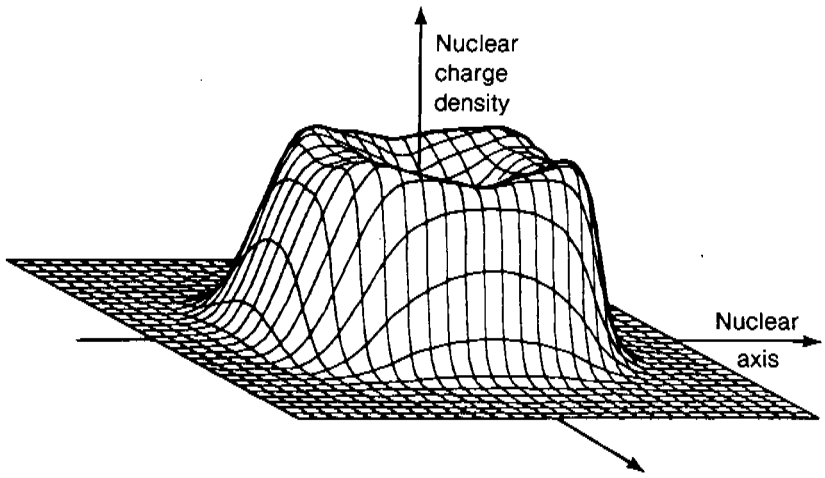


FIGURE 2.4 A perspective view of the electric charge distribution in the nucleus of ytterbium-174. This nucleus is seen to be somewhat elongated, with its maximum charge density in regions away from the center. (From J. Heisenberg, in *Advances in Nuclear Physics*, Vol. 12, J. W. Negele and E. Vogt, eds., Plenum Press, New York, 1981.)

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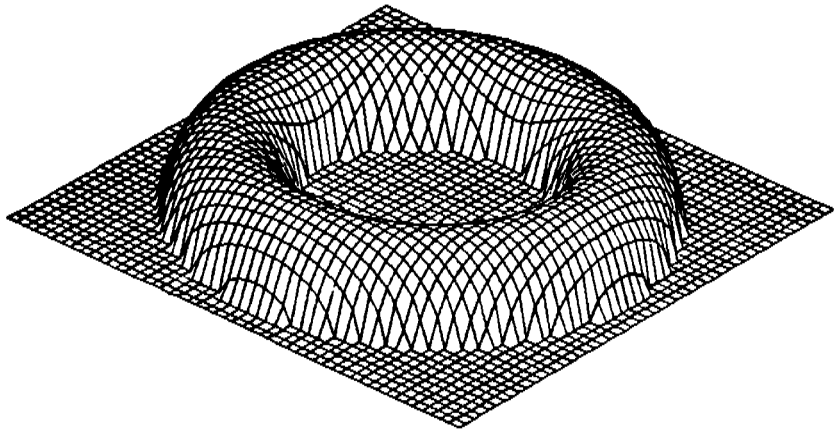


FIGURE 2.5 A perspective view of the surface of half-maximum magnetization density in the nucleus of vanadium-51. The diagram, computed from data obtained by the elastic scattering of electrons, reveals the circular orbit of the last valence nucleon in this nucleus. [From T. W. Donnelly and J. D. Walecka, *Nuclear Physics A201*, 81 (1973).]

neutron—in the nucleus. Figure 2.5 shows the spatial distribution of this nuclear magnetization, determined from electron scattering in vanadium-51. Note how the spatial orbit of the last nucleon is clearly defined.

Finally, we observe that electron scattering plays a crucial role in interpreting the results of experiments using other projectiles, such as protons and pions, that have been done at new accelerators and experimental facilities developed during the past decade. All of these particles are now used as precision probes, bringing together complementary interactions with which the whole of nuclear matter can be mapped.

The Interacting Boson Model

Geometrical symmetries are used to describe special, simple properties of otherwise complex structures. Examples of geometrical symmetries, such as those related to reflections and rotations, can be easily recognized in many objects, including nuclei. Dynamical symmetries are related to a similarly simple order that can sometimes be found in the laws governing the behavior of physical systems. Because of the complexity of the nuclear many-body problem, it was not expected that such symmetries would play a major role in nuclear physics.

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Recently, however, it has been found that the locations and decay properties of the excited states of a wide range of even-even nuclei (those with an even number of protons and an even number of neutrons) can be accurately calculated by making use of a symmetry in which the valence neutrons and valence protons (those outside the closed-shell, inert core) are paired to form spin-0 and spin-2 bosons (particles with integer spin). This *interacting boson model* is characterized by a particular pattern of nuclear energy levels (and their decays) that depend only on the number of available bosons. The pattern was first recognized in platinum-196 in 1978. This symmetry has already provided a unification of several different nuclear collective modes of motion (for example, rotation, vibration, and the transitional behavior that falls between these limiting cases). All of these modes can be described in a uniform way by the symmetry associated with the interacting boson model, depending simply on the number of valence (interacting) bosons present in each nucleus. Because of the way in which this model makes use of shell-model properties in describing the collective properties of nuclei, it is hoped that it will be able to provide a unification between the shell model and the collective model of nuclei.

The most recent development has been the extension of this model to nuclei with an odd number of neutrons and protons. This extension involves a coupling between the unpaired nucleons (fermions) and the paired nucleons (bosons) in neighboring nuclei, which allows the calculation of the properties of nuclear states in *both* odd-mass and even-mass nuclei, using a single formula. This coupling is characterized by a *supersymmetry*. A good example of such behavior has now been found in the comparison between iridium-193 and osmium-192 and in a few neighboring nuclei, such as iridium-191. However, unlike the interacting boson model, which has had striking success over a wide range of even-even nuclei, there are so far only a few successful examples of supersymmetry, with substantial breakdown of the supersymmetry predictions occurring for nuclei just a little removed from this region. At present, it is not clear whether this is caused by problems in the supersymmetric model and its calculations or whether it points to an inability on our part to analyze and organize the experimental results properly so as to see the expected supersymmetric pattern.

Given a highly complex and seemingly random pattern, it is not always obvious where to look or how to orient one's perspective in order to see the underlying symmetry. However, given even the hint that such an important supersymmetry may exist in the present case

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(the first fermion-boson supersymmetry found in nature), this area of nuclear spectroscopy will receive much attention in the near future. The result should be a clarification of our interpretation and understanding of the connection between odd-mass nuclei and even-mass nuclei and the more general connection between fermions and bosons.

MACROSCOPIC NUCLEAR DYNAMICS

A high-energy proton colliding with a nucleus may simply punch straight through, interacting strongly with only a few of the nucleons. But if the projectile is itself a nucleus (heavy ion), a collision involves the interaction of two many-nucleon systems. The large number (as many as several hundred) of strongly interacting nucleons in a heavy-ion collision can drastically alter the shapes, neutron-to-proton ratios, or internal excitation energies of the collision partners. A major program effort in heavy-ion physics is to utilize these effects to study macroscopic nuclear properties involving the cooperative motion of many nucleons.

Heavy-ion collisions can give rise to new phenomena not seen when the projectile is a single particle: they can split off chunks of nuclear matter, they can completely disintegrate nuclei in a burst of nucleons, and they can transfer large amounts of angular momentum, leading to instability and breakup. An added source of interest is the wide variety of projectiles available, all the way to the heaviest natural element, uranium. Some experiments have been done at energies of up to several GeV per nucleon, but the most extensive studies have been in the energy range below 20 MeV per nucleon.

A useful perspective on the meaning of the term "low energy" in heavy-ion physics comes from the example of a calcium-40 nucleus at 10 MeV per nucleon, which has a total kinetic energy of 400 MeV. Heavy-ion physics, in fact, demands substantial energies to allow the projectile nucleus to overcome the powerful repulsive Coulomb force exerted by the target nucleus. The short-range nuclear forces between two nuclei, which cause the interesting phenomena in heavy-ion reactions, cannot act effectively unless the nuclei are at least close enough to touch.

A characteristic feature of a low-energy heavy ion is its short wavelength compared to the dimensions of the collision region around the target nucleus. Its quantum-mechanical wave nature is thus suppressed, and it can be viewed as a classical particle having a well-defined trajectory. According to the classical trajectory picture, low-energy heavy-ion collisions can be classified according to their *impact*

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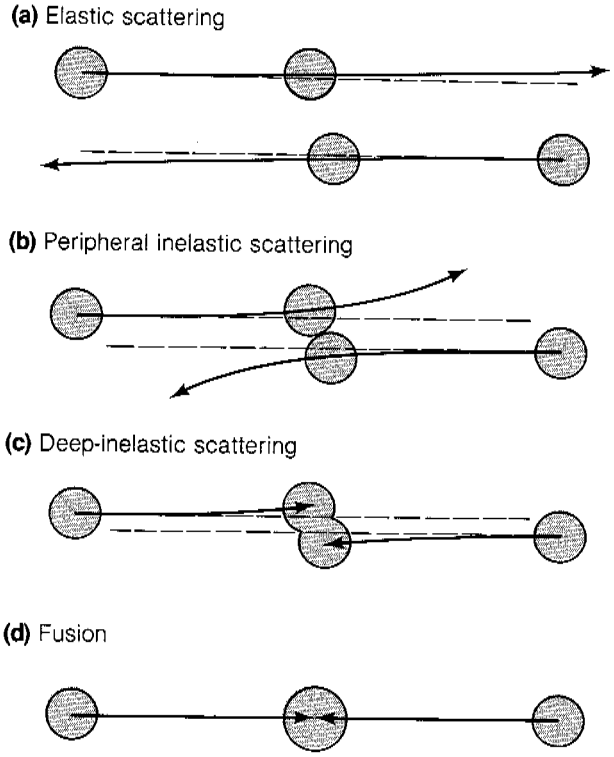


FIGURE 2.6 Examples of some of the kinds of nuclear interactions that occur in collisions (shown here in the colliding-beam mode rather than the fixed-target mode) at different values of the impact parameter. At large values (a), the nuclei do not touch at all. At values approaching zero (d), the collision can result in fusion of the two nuclei.

parameter (see Figure 2.6), which is a number describing how close to being central (head-on) the collision is. At large values of the impact parameter, the projectile and target nuclei never come close enough to touch, and their trajectories are governed by the repulsive Coulomb force between them.

At intermediate impact parameters, the nuclei graze just closely enough to bring the nuclear forces into play. A likely event during a grazing collision is the transfer of one or more nucleons between the collision partners, or perhaps the excitation of collective modes. At relatively small impact parameters, a substantial part of the projectile hits part of the target. Amazingly, the nuclei typically emerge from the welter of nucleon interactions with their original identities intact, give or take a few nucleons, but with a substantial conversion of energy into

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heating of the nuclei. This type of event, called a *deep-inelastic collision*, has been a major focus of study during the last decade and is discussed in detail later.

Finally, an approximately head-on collision (very small impact parameter) can cause the colliding nuclei to fuse, forming a single *compound nucleus* that lives long enough for the nucleons to reach a degree of equilibrium in shared energy and angular momentum. The compound nucleus is typically unstable, however, and decays after 10^{-19} second or so. One decay mode is by the emission of several low-mass particles, such as nucleons and alpha particles. Another possibility is that of fission into two smaller fragments. During fission, the compound nucleus behaves much like a drop of liquid, "necking off" as the two portions separate. On rare occasions, the neck coalesces to form a third small partner in the fission (typically an alpha particle), a phenomenon that has a known analogy in the breakup of real liquid drops.

Fusion reactions such as those described (not to be confused with the thermonuclear fusion of light nuclei) have been useful in producing exotic nuclear species, in determining the maximum angular momentum that nuclei can sustain, and in illuminating the dynamics of the fission process. These reactions are largely a feature of the low-energy regime; at high or relativistic energies, head-on collisions deliver so much energy that the collision partners are shattered into smaller fragments.

When a beam of heavy ions is directed against a target, all impact parameters are possible among the chance collisions; the smaller impact parameters (nearly head-on collisions) occur with lower probability, however, because of the smaller cross-sectional area presented. Given sufficient projectile energy to overcome the repulsive Coulomb forces, all the reaction types described above can occur, and great skill is needed to single out the particular reaction of interest.

Our present understanding of low-energy, heavy-ion reactions spans a rich phenomenology with a corresponding theoretical framework. The full scope of progress made during the last decade cannot be described adequately in this volume. Instead, we will focus on just two broad topics that give something of the flavor and issues of the field.

Resonances in Heavy-Ion Systems

The widely successful shell model of the nucleus views an individual nucleon as moving in an average force field produced by all the other nucleons. The success of this model stems from the Pauli exclusion

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principle, which states that no two nucleons can have identical states of motion. The strong nuclear force causes free nucleons (those not bound inside a nucleus) to scatter markedly in a collision, but for nucleons in a nucleus, the Pauli principle greatly decreases the nucleon-nucleon interaction by forbidding many of the final states that would normally result from scattering.

In the nuclear shell model, the energy of a bound nucleon is restricted to certain discrete (quantized) values, just as the sound from a plucked guitar string is restricted to a fundamental tone and certain overtones. The shell model describes the energy levels of a nucleus as the promotion (raising) of one or a few nucleons from the normally occupied ground level to normally unoccupied excited levels.

A general result from the quantum mechanics of many-body systems is that the energy levels allowed for the nucleus become more closely spaced as the energy above the ground level increases. The first few low-lying levels are rather widely spaced, on the average, and they can be selectively excited for study in collisions if the projectile has the proper narrowly defined energy. At higher excitation energies, however, the energy levels are so close together that the spread of energies in a projectile beam overlaps many levels, blurring the details. Another factor contributing to the blurring is the short lifetime of most excited states; as a consequence of the Heisenberg uncertainty principle, the energy levels of such states are broadened.

In some heavy-ion experiments, pronounced peaks (*resonances*) appear unexpectedly in the observed cross sections as the bombarding energy is varied. For example, when oxygen-16 projectiles scatter elastically from oxygen-16 target nuclei, the cross-sectional curve exhibits broad, irregular peaks as the projectile energy is increased. For the reaction of oxygen-18 with oxygen-18, however, only a smooth variation with energy is observed. The explanation is related to the fact that in oxygen-16 the proton and neutron shells are both closed, whereas in oxygen-18, with two additional neutrons outside the closed shells, there are numerous low-lying excited levels. Because oxygen-16 has only a few states through which the interaction can proceed, the wave-mechanical interference effects are not smeared out beyond recognition.

When a carbon-12 projectile reacts with a carbon-12 target nucleus, the cross-sectional curve displays narrow, jagged peaks that give strong evidence for the formation of relatively long-lived *nuclear molecules*. A bound system, such as a chemical molecule, exists because the attractive forces predominate over the repulsive forces. Two nuclei could possibly form a bound "molecule" if the attractive

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FIGURE 2.7 Artist's rendering of the computed nuclear density during two different collisions of an oxygen-16 nucleus with a calcium-40 nucleus at a laboratory bombarding energy of 315 MeV. For simplicity, the events are visualized here in the colliding-beam mode rather than the fixed-target mode. *Top:* At a large impact parameter, a very high angular momentum is produced in the reacting system; the highly excited compound nucleus formed (nickel-56) holds together temporarily before dissipating its energy by evaporating nucleons. *Bottom:* At a smaller impact parameter, a lower angular momentum of the compound nucleus is produced, but the nucleus breaks apart almost immediately because most of the kinetic energy of this deep-inelastic collision has been transformed into internal excitation energy. (Courtesy of M. Weiss, Lawrence Livermore National Laboratory.)

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outer part of the nuclear force just balanced the repulsive inner part of the nuclear force, the repulsive Coulomb force, and the repulsive centrifugal force that arises when two nuclei revolve around each other. Because of the way the forces vary with distance, such a balance may not be possible for most nuclei, and even if it were achieved, it would not be expected to last long. If the attractive force outweighed the repulsive forces, the nuclei would crash together; if the attractive force were too weak, they would fly apart.

According to the uncertainty principle, the narrowness of the resonances in the reaction of two carbon-12 nuclei suggests lifetimes between 10^{-21} and 10^{-22} second for these states. Although this is unimaginably brief on the macroscopic time scale of the everyday world, it is several times longer than the interaction time in ordinary nuclear reactions—long enough for a nuclear molecule to make many rotations about its center of mass.

Deep-Inelastic Collisions

The compound-nucleus picture of reactions has been used successfully in nuclear physics for a long time, because compound-nucleus formation is a common mode of reaction when the projectiles are low-energy nucleons or alpha particles. The approximately head-on collision of heavy ions at low energy is also liable to produce a compound nucleus. But when the impact parameter lies between the grazing and head-on limits, the interaction between low-energy heavy ions is likely to result in a *deep-inelastic collision* instead (see Figure 2.7).

Deep-inelastic collisions display surprising new phenomena not seen in compound-nucleus reactions, and they have therefore received much attention in heavy-ion physics. They involve some of the same reaction mechanisms that occur in fission, but in deep-inelastic collisions, these can be studied in a controlled way by the suitable choice of projectile, target, and energy, for example.

In a deep-inelastic collision, the projectile nucleus can lose most of its energy as it plows into the target nucleus; the energy loss is often so great that the emerging reaction fragments are initially nearly at rest, and they fly apart mainly because of the repulsive Coulomb force between them. But unlike reactions that proceed by compound-nucleus formation, a deep-inelastic collision retains a "memory" of the initial conditions, so that the reaction fragments are closely related to the original colliding nuclei.

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A deep-inelastic collision presents seemingly contradictory properties: the substantial energy loss might appear to indicate a violent collision, yet the retention of identity of the products suggests a relatively gentle collision. The most successful approach to understanding this paradox views the original nuclei as starting with values of the basic parameters, such as neutron-to-proton ratio, energy, angular momentum, and mass, that are suited only to the stable equilibrium of two nuclei far apart. The new stable equilibrium in the collision environment requires different values of these parameters, however, and during the collision, each of the properties begins to shift toward the new values.

The value of a property cannot change, however, without some driving mechanism. In general, the mechanisms for different properties operate at different rates, so some properties move more rapidly than others toward their new equilibrium values. The pertinent rates in a deep-inelastic collision can be sorted out experimentally by using a built-in "clock" for the reaction. The off-center nature of the collision starts the system rotating, so that the angle of rotation increases with time; fragments given off at small rotation angles therefore correspond to an early stage in the reaction. Analysis of the reaction fragments shows that the neutron-to-proton ratio reaches its equilibrium value very quickly, in 10^{-22} second or so. Energy equilibrates next, followed by angular momentum. The masses of the fragments take so long to reach equilibrium (roughly 50 times longer than for the neutron-to-proton ratio) that the collision is over before the masses are able to change much from their original values. Providing accurate models for the various driving mechanisms has been a challenge to nuclear theorists—combining, as it does, collective motion with the statistical nature of the approach to equilibrium.

The nuclear matter in a low-energy, deep-inelastic collision is not highly excited, and relatively few excited states are accessible to the nucleons. Under these conditions, the Pauli exclusion principle still diminishes the effects of the nuclear force, and a given nucleon can move fairly freely through the nuclear interiors. Interactions among nucleons occur mainly near the nuclear surface, where the average force on a nucleon is no longer constant. Simple models therefore describe deep-inelastic collisions as the exchange of freely moving nucleons between two nuclei, including the effects of surface "friction" at the contact region between the fragments. Such models have had considerable success in describing the experimental data. A more fundamental description is based on a time-dependent generalization of the shell model, where now the average potential experienced by each

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nucleon changes rapidly as the colliding system evolves toward a new equilibrium.

Despite the progress that has been made in understanding deep-inelastic, heavy-ion collisions, much remains to be done, such as identifying the mechanism responsible for dissipating excess energy. On the theoretical side, the successful models need to be related to more fundamental theories, and the time-dependent average potential calculations need to be extended to higher bombarding energies. Experimentally, many questions need to be answered. How is angular momentum transferred in the colliding system? What is the mechanism for ejecting prompt light particles? How does the behavior of the reacting system change as the bombarding energy becomes comparable with the internal energy of nucleons in a nucleus? Can collisions just on the border between fusion and deep-inelastic collisions be used to probe the long-term dynamics of nearly unstable nuclear systems?

THE NUCLEAR MANY-BODY PROBLEM

A long-standing goal of nuclear physics has been to develop a microscopic many-body theory that can account quantitatively for the structure and interactions of nuclei in terms of the cumulative effects of individual nucleon-nucleon (NN) forces. There are many roadblocks on the way toward achieving this ambitious goal. First, the NN force itself is not known in sufficient detail. The scattering of nucleons provides much information, but only for a situation characterized by a constant total energy of the two colliding nucleons; in a nucleus, where nearby nucleons can transfer energy, other aspects of the NN force can come into play. Furthermore, even if the NN force were completely understood, available mathematical techniques cannot readily handle the complexities of many closely spaced, strongly interacting nucleons in a nucleus.

Great progress has nevertheless been made in microscopic nuclear theory during the past decade, thanks to the steadily increasing knowledge of the NN force, improved calculational techniques, and more precise data on nuclear structure and interactions. A broad conclusion from this work is that the traditional picture of interacting nucleons alone cannot explain the detailed behavior of nuclear matter. Necessary corrections appear to involve many-body forces, the relativistic description of nucleon motion, the presence of virtual mesons in nuclei, and, ultimately, the nucleon's internal quark-gluon structure. Progress in incorporating these corrections into many-body calcula-

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tions will be hastened if experiments can be devised with specific sensitivity to the effects in question.

The following sections summarize the status, successes, and shortcomings of the traditional nucleon picture of nuclear matter and discuss briefly the seemingly essential corrections to that picture.

The Three-Nucleon Nucleus and Infinite Nuclear Matter

Advances in many-body calculations are usually tested first on two limiting cases, to see if an extension to more complicated systems is warranted. Two such cases often employed are the three-nucleon nucleus and an infinite nuclear matter consisting of neutrons and protons filling all space uniformly at a given density. For simplicity, the neutron and proton masses are taken to be equal in infinite nuclear matter; the Coulomb repulsion between protons is assumed to be inoperative, so that only the strong interaction is operative.

The *three-nucleon nucleus* is the simplest possible many-nucleon system. Nature provides two actual examples: hydrogen-3 (tritium; one proton, two neutrons) and helium-3 (two protons, one neutron). A wealth of experimental data for testing theories is available, including the binding energy (the minimum energy required to separate the three nucleons completely), the charge and mass distribution (nuclear radius), the nuclear magnetism, and the ways in which the nuclei react with photons, nucleons, muons, and pions. With the aid of a new mathematical technique, the properties of hydrogen-3 and helium-3 can now be calculated numerically in great detail, once the form of the NN force is chosen.

In practice, popular choices assume that the force acts only between pairs of nucleons (two-body forces). Various parameters specifying the force are adjusted to give good agreement with measured nucleon-nucleon scattering and with the properties of the bound neutron-proton system (the deuteron). A number of admissible forms satisfy these mild constraints, but in general, all admissible two-body forces give a three-body binding energy that is too small by 1 to 2 MeV (out of 8 MeV) and a nuclear radius too large by 9 percent or so. The accuracy of the binding-energy prediction is better than might at first appear, however, because binding energy is the relatively small difference between two large, nearly equal terms: the energy of motion of the nucleons and the energy content of the NN forces. Nevertheless, the discrepancies appear to be greater than the accuracy of the calculations, and they must be taken seriously as indicative of shortcomings in the assumed interactions.

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Infinite nuclear matter exists in nature in neutron stars. It is a useful system to consider because it avoids the complications that arise from having to take into account the properties of a nuclear surface. Although it does not exist on Earth, its supposed properties can be inferred from measurements on real nuclei. Of particular interest are the nucleon density of nuclear matter, 0.16 nucleon per cubic fermi, and the average binding energy per nucleon, inferred to be 15.8 MeV per nucleon. A third property, the compressibility, has recently been derived from giant monopole resonances in real nuclei, as described earlier; the compressibility tells how the binding energy per nucleon changes when the nucleon density is varied.

During the 1970s, major advances in mathematical techniques and in the development of powerful computers spurred a vast amount of theoretical work that largely eliminated earlier inconsistencies among various techniques for calculating the properties of nuclear matter. The discrepancies between theoretical predictions and experimental facts still remain, however. A major long-term challenge for nuclear physicists is to expand the traditional many-body theory of nuclear matter in ways that will remove these discrepancies. How this goal might be achieved is discussed at the end of this chapter.

Properties of Finite Nuclei

Although more effective computational techniques are under development, most calculations of the properties of real nuclei are carried out at present using a modification of the *Hartree-Fock method*, which was originally invented to calculate the electronic structures of atoms and molecules. In this method, each nucleon is assumed to move according to the average force exerted by the other nucleons. But the average force itself depends on how the nucleons move, so the calculations are carried out iteratively until the computed nucleon motion and the assumed average force are consistent with each other. Part of the success of the Hartree-Fock method stems from the exclusion principle, which inhibits strong short-range nucleon collisions in a nucleus, thus allowing two-body interactions to be replaced by a smoothly varying average force through the nuclear interior.

An important recent advance in the theoretical treatment of finite nuclei has been the *density-dependent Hartree-Fock* (DDHF) method, which takes into account the effect of the density of surrounding nucleons on the NN force. The DDHF method is well adapted for calculating charge and matter distributions in nuclei, because self-consistency is achieved only when the nucleon motion, average force,

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and local density are in accord. The repulsive short-distance part of the NN force is particularly important in finite nucleus calculations, to keep the nucleons the correct distance apart. To obtain agreement of theory with experiment, the NN interaction in the DDHF method must be augmented by suitable empirical terms.

Electron-scattering experiments have provided exquisitely detailed pictures of nuclear charge distributions, all the way to the centers of nuclei and over the full range of the chemical elements. The detail of the measurements is sufficient to show the varying proton densities associated with the nuclear shell structure, providing a good test of DDHF methods. The general agreement with theoretical predictions is good, but some small systematic discrepancies remain.

Electron-scattering experiments do not yield the distribution of matter in a nucleus, however, because electrons interact primarily with the electric charge of the protons and do not "see" the neutrons. Protons interact with all nucleons, and many of the data on matter distributions come from the elastic scattering of protons on nuclei. When the projectile's energy is much higher than the energies of the bound nucleons (800-MeV protons are available at the Los Alamos Meson Physics Facility, for instance), the effects of the binding become less important, and the NN force derived from the scattering of free nucleons becomes a good approximation. The proton-nucleus scattering data can then be understood with the help of these factors to derive the unknown neutron distribution. DDHF calculations generally reproduce the measured distributions quite well, but they are more accurate for the differences among neighboring nuclear species than for absolute neutron densities.

Calculations of finite nuclei can now also be tested in favorable cases by the measured distribution of an individual nucleon in a nucleus—a major advance in the field during the past decade. One method makes use of electron scattering to measure the proton distributions in nuclei differing by only one proton—for example, thallium-205 (81 protons, 124 neutrons) and lead-206 (82 protons, 124 neutrons); the comparison yields a one-proton distribution. Neutrons in a nucleus associate in pairs with their spins antiparallel, effectively canceling their intrinsic magnetism. If a nucleus has an odd (unpaired) neutron, this neutron's magnetism—and hence its distribution in the nucleus—can be seen by electron scattering, especially for scattering at large angles in collisions that transfer a large amount of momentum from the electron projectile.

DDHF calculations also generally reproduce the measured single-nucleon distributions well, as in the case of overall charge and matter distributions. The remaining discrepancies, however, seem to indicate

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the need for small but significant corrections arising, for example, from relativistic effects or electromagnetic contributions due to meson exchange between nucleons in the nucleus.

The Effective NN Interaction at Intermediate Energies

For the properties of finite nuclei to be calculated properly, many-body theory must evaluate how the interaction between two given nucleons in a nucleus is modified by the presence of the other nucleons. The attractive gravitational force between a planet and the Sun, or the repulsive Coulomb force between two electrons in an atom, can be described in terms of the separation distance alone. The effective nucleon-nucleon force is more complicated, depending not only on distance but also on momentum, spin, and isospin—and all of these factors are modified in a nucleus by the inhibiting effect of the Pauli principle.

With so many factors involved at once, it would obviously benefit the development of nuclear theory to have experiments that significantly test only one specific factor at a time. A suitable type of experiment for this purpose is the reaction that involves the interaction of a projectile nucleon with only one nucleon in the target nucleus. A typical example is the charge-exchange reaction of a fast proton with carbon-14, in which the projectile proton changes to a neutron while a target neutron becomes a proton, leaving a nitrogen-14 nucleus as the reaction product. This type of reaction (discussed earlier from another perspective) involves the transfer of a charged pion from the proton to the target neutron and is of special interest because of its sensitivity to the pion field inside a nucleus. The target, bombarding energy, reaction type, and especially the specific state in which the product nucleus is left can be chosen so as to make a particular factor in the NN interaction dominant. Progress in developing such selective filters has been rapid in recent years, with the availability of high-quality proton (and electron) beams at intermediate energies.

Intermediate projectile energies from 100 to 400 MeV are employed because it is at these energies that the NN interaction is weakest; this makes it more likely that the projectile nucleon will interact mainly with only one target nucleon. Also, modifications of the NN force induced by other nucleons are not too large at intermediate energies, thus simplifying the interpretation of the data. Further information on the properties of the target-nucleon state can sometimes be obtained from electron inelastic scattering or from other nuclear processes, such as beta decay.

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Complementary proton and electron inelastic-scattering experiments have been carried out with narrow energy resolution (smaller than one part per thousand) for a number of nuclei. The results have demonstrated for the first time the real possibility of attaining a quantitative microscopic understanding of nucleon-nucleus collisions. The density of surrounding nucleons seems to have an especially important effect on the part of the NN interaction that is independent of spin or isospin. Some small discrepancies between theory and experiment remain in the study of the spin-independent interactions, but their relationship to the known shortcomings of nuclear theory is not yet clear.

The spin-dependent parts of the NN interaction are currently a subject of great experimental and theoretical interest. As an example of how nucleon-induced reactions can act as a selective filter, consider the proton/carbon-14 charge-exchange reaction described earlier, which flips the isospin of a target neutron, changing it to a proton. If the reaction does not simultaneously flip the spin, the nitrogen-14 product nucleus is left in an excited state with the same spin as the target nucleus. If, however, the reaction also flips the neutron's spin (this is the Gamow-Teller transition described earlier), the product nucleus is left in an even higher excited state. Experimental results show that as the bombarding energy is increased from 60 to 200 MeV, the isospin-flipping reaction (without spin flip) diminishes in importance while the Gamow-Teller reaction increases; this implies different energy dependences for the spin-dependent and spin-independent parts of the NN interaction. The NN force between free nucleons displays a similar trend in the relative strengths, but predictions based on it are not in quantitative agreement with these experiments; the nuclear environment can dramatically modify pion-exchange processes, as various many-body calculations have suggested.

The results to date have demonstrated that nucleon-induced transitions at intermediate bombarding energies can indeed act as a selective filter for various components of the nucleon-nucleon force in nuclei. This program is likely to have its real payoff in the future, with a more systematic application of state-of-the-art many-body techniques to a wider variety of reactions, nuclear excitations, bombarding energies, and measured properties (especially spin-dependent observables).

Expanding the Traditional Many-Body Theory

Traditional nuclear theory considers only structureless, nonrelativistic nucleons interacting through two-body forces. The persistent discrepancies between the best traditional calculations and exper-

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iment are widely attributed to the oversimplifications of the traditional picture, and serious efforts have been made recently to improve the theory by including some of our modern understanding of strong interactions.

The main direction of the effort is to incorporate mathematically the effects of additional hadrons beyond the traditional proton and neutron—an approach that might descriptively be called quantum hadrodynamics (QHD). (Hadrons interact through the strong force and encompass all the baryons and all the mesons.) Much as the electromagnetic force between charged particles can be viewed as arising from the exchange of virtual photons, the strong force between hadrons can be viewed as arising from the exchange of virtual mesons (which are themselves hadrons). Pions are the mesons of lightest mass, and since the mass of the virtual particle is inversely related to the range of the force, single-pion exchange is responsible for the longest-range part of the nuclear force. The shorter-range part is due to multipion exchange and to the exchange of heavier mesons, such as the sigma, rho, and omega mesons.

The existence of baryon resonances in nuclei leads to the possibility of new phenomena omitted in traditional theory. For instance, one nucleon could excite a second nucleon to the delta state, and the delta could then interact with a third nucleon. Invoking such three-body forces may enable theorists to remove the discrepancies that currently exist between experiment and the theories of three-nucleon systems and of nuclear matter, as discussed above. For example, this approach has been suggested in an attempt to explain the unexpected dip in the central region of the charge distribution of the helium-3 nucleus inferred from electron-scattering measurements. However, three-body forces have not yet been fully incorporated into many-body calculations, nor have their effects been clearly identified experimentally.

A quantum field theory of the hadronic interactions in nuclei combines relativity and quantum mechanics. These are essential features of any reliable extrapolation of the properties of nuclear matter to extreme conditions of temperature (average nuclear energy) and density. One advantage of relativistic theories is that spin interactions are naturally present in the fundamental equations and need not be included as additional terms. Such theories also predict that the apparent mass of a nucleon in a nucleus is altered, a possibly significant influence on the origin of the repulsive forces that keep the nucleus from collapsing. Although there are as yet few experiments or calculations bearing on a fully relativistic field theory of hadronic interactions in nuclei, the description of nuclei within such a framework will

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be a major future objective. One recent attempt at constructing a meson-baryon field theory starts from only a few mesons (pi, rho, sigma, omega) and a few baryons (proton, neutron), but it has already had significant success in treating both nuclear structure and nucleon-nucleus reactions.

Although mesons and baryons represent an efficient and appropriate language for describing much of nuclear structure, we know that these hadrons are themselves made up of quarks and gluons, whose behavior is described by quantum chromodynamics (QCD). Ultimately, QCD must reproduce the known meson-exchange currents between any two baryons at large internucleon separation. The central issues for understanding the nuclear many-body problem are thus to identify unambiguously the quark and color contributions to the description of nuclear systems, to establish the theoretical relationship between the quantum chromodynamic and quantum hadrodynamic pictures of nuclear structure, and to develop a description of nuclei entirely within the framework of quantum chromodynamics.

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3

Fundamental Forces in the Nucleus

Since the early days of nuclear physics, researchers have had considerable success in accounting for the measured properties of nuclei by assuming that the only constituents of nuclei are protons and neutrons. The effects of the other constituents, such as virtual mesons, are present in the strong forces that act between nucleons. However, the mesons and more fundamental constituents are usually hidden from view in experimental measurements. The situation is analogous to the role of the core electrons in the chemical bonding of atoms. The core electrons certainly affect the chemical bonding forces but can for the most part be ignored in describing the chemical bond. In the same way, nucleons are viewed as composite objects made up of quarks, but only a few kinds of experiments are decisive in revealing this underlying structure.

Experiments measuring the electromagnetic properties of nuclei are particularly informative. Many of the constituents are charged and thus produce measurable electromagnetic currents. Another kind of experiment is to measure violations of symmetry in nuclear transitions. Nuclear states have symmetries that are easy to classify and measure, and any violations can be attributed to fundamental particles that mediate the nuclear forces. In the next two sections, some of the studies that connect nuclear properties with the fundamental particles and interactions are described in more detail.

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NONNUCLEONIC CONSTITUENTS OF NUCLEI

The lightest hadron, the pion, has a prominent role in both nuclear and elementary-particle physics. In nuclear physics, the strong interaction is mediated at large internucleon distances by virtual pions. The charged virtual pions found in the nucleus make their presence known by the magnetic effects of their currents. The pionic aspects of nuclear states can be studied in many other ways as well, such as the scattering of high-energy nucleons from nuclei. In a grazing collision, the projectile nucleon hardly disturbs the target except for the fleeting effect of the pionic cloud of the projectile, as well as the effects of the other forces. Measurement of the scattering and absorption of pions by nuclei has provided knowledge of the hadronic interactions, supporting the idea that the symmetries embodied in the quark physics apply to the pions in the nuclear medium.

The realization that the nucleus contains virtual mesons suggests that it may contain other virtual particles as well. To complicate even further this sharp departure from the simple proton-neutron model of the nucleus, it is now widely accepted that nucleons and mesons are themselves composite objects made up of quarks. The quarks that constitute a nucleon interact strongly by exchanging gluons among themselves. The quarks are strongly bound in the nucleon and have a spectrum of energy states analogous to those of bound electrons in an atom. From this viewpoint, a particular nucleon is only one possible quark state; other excited states correspond to more massive, nonnucleonic members of the baryon family, so that a nucleon changes to a different kind of baryon when the quarks change state. In the five decades since the discovery of the neutron, the picture of the nucleus has changed from a simple cluster of proton and neutron "billiard balls" to a seething mass of nucleons, other baryons, and mesons, all consisting of quarks and gluons.

It is natural to ask whether the new, nonnucleonic features in the present model of the nucleus have observable consequences. The success of the proton-neutron model of the nucleus at low to moderate energies implies that nonnucleonic contributions must be looked for in higher energy ranges or in interactions different from the nucleon-nucleon scattering used so widely in the past. In recent years, experimenters have probed nonnucleonic effects in nuclei by going to higher energies, by deliberately creating nonnucleonic constituents in nuclei, and by studying directly the interactions of more exotic particles.

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Scientists have long known that an object is difficult to see unless the wavelength of light is small compared with the object's dimensions; this fundamental wave property limits the useful magnification of optical microscopes, for example. It is one of the stranger aspects of quantum mechanics (also called wave mechanics) that any particle of atomic dimensions or smaller exhibits distinctly wavelike as well as particlelike behavior and has a definite wavelength that is inversely proportional to the particle's momentum. Exploring small structures in the nucleus therefore requires a particle probe with high momentum (and correspondingly high energy) to give a wavelength small enough to enable inner structures to be distinguished clearly. High-energy electrons are a good choice for this type of experiment, because they interact with nuclei through the well-understood electromagnetic force and because they seem to be pointlike particles having no dimensions or inner structure themselves.

Another recent approach is to implant nonnucleonic baryon impurities into a nucleus and to study the subsequent response of the system. Using advanced experimental techniques, one can replace a single nucleon in a nucleus by a strange lambda or sigma hyperon (a baryon that differs from nucleons in having a strange quark rather than up and down quarks only) with hardly any disturbance of the nucleon orbits. The result is a *hypernucleus*, in which a nucleon-nucleon interaction is replaced by the somewhat different hyperon-nucleon interaction. Because the internal motions in the hypernucleus are closely related to known motions in the original nucleus, properties of the nucleon-hyperon interactions can be inferred from the measured hypernuclear structure.

A new class of experiments still being developed uses proton-antiproton collisions at moderate energies to bridge the gap between nuclear physics and particle physics. On the one hand, the proton-antiproton system represents a familiar interaction mediated by the exchange of mesons, but from the viewpoint of the quark model it is a system of three quarks and three antiquarks whose interactions are mediated by the exchange of gluons. These experiments should provide challenging tests of both meson-exchange theories and quark models.

The three types of experiments outlined here are discussed in further detail below, to bring out the kinds of information that they can provide and to mention some of the exciting surprises that have already been found.

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Probing Quark Structure with Leptons

Leptons—electrons, muons, tauons, and their associated neutrinos—interact with nucleons through the electroweak force rather than the strong force. Thus a lepton interacting with a nucleus does not usually exert enough force on the nucleons to perturb them significantly from their internal motions, even if the lepton passes directly through the nuclear matter. Leptons are therefore excellent probes for observing the nucleus essentially in its natural state. Moreover, because the electromagnetic force is well understood, the measured scattering of leptons from nuclei can be related to the properties of the scatterers without much uncertainty.

Over the past three decades, the scattering of high-energy electrons by nuclei has been the most successful method for providing detailed information on the distribution of electric charge, and also of magnetism, in nuclei. This charge does not reside in the protons alone, however. Many of the virtual mesons existing momentarily in a nucleus are electrically charged, and even the neutrons and neutral mesons can exert magnetic forces. The technique of high-energy electron scattering is therefore a natural choice in looking for the effects of these mesonic constituents.

Relatively high bombarding energies (in the GeV range) are needed to make the electron's wavelength short enough to be able to "see" the fine details inside a nucleus. The experimental results of scattering high-energy electrons from the very light nucleus helium-3 cannot be explained satisfactorily using theoretical models that take into account only the effects of the charge and magnetism of the two protons and one neutron; one must also include the electromagnetic effects arising from the exchange of a pion or rho meson between nucleons. The *meson-exchange model* gives a strikingly better account of the data (see Figure 3.1). Such tantalizing results obtained over the past decade have created intense scientific interest. The 4-GeV Continuous Electron Beam Accelerator Facility (CEBAF) proposed for construction by the Southeastern Universities Research Association (SURA) would allow much-improved investigation of meson-exchange contributions in experiments of the kind described above.

Electrons, muons, and neutrinos have all been used to investigate the quark structure of hadrons (baryons and mesons). The usual method of studying new particles—bombarding a target with sufficient energy to create or release the desired particle—does not apply here, however. Because of the phenomenon of *quark confinement*, it is

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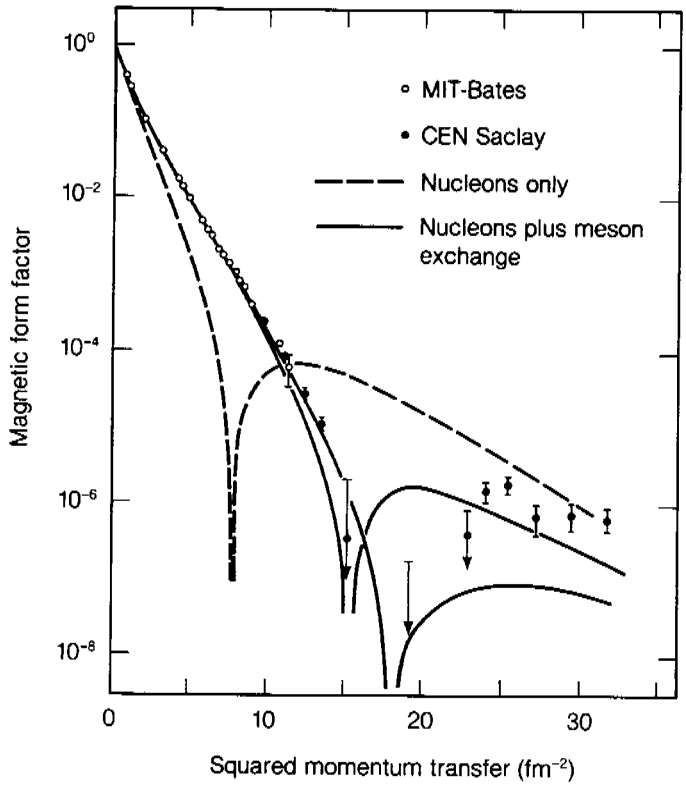


FIGURE 3.1 Data obtained by the high-energy elastic scattering of electrons from the helium-3 nucleus reveal the superiority of the meson-exchange model in describing the distribution of magnetism in nuclei, compared with the model that considers only the nucleons. All three curves represent theoretical calculations; the two solid ones are based on somewhat different assumptions. [From J. M. Cavedon *et al.*, *Physical Review Letters 49*, 986 (1982).]

apparently impossible to liberate quarks from their hadrons with the means currently at hand.

To describe this unique situation, quark models are based on the assumption that the constituent quarks of a hadron are confined in an impenetrable *bag* or tied together by unbreakable *strings*, so that they cannot escape. This aspect of quark behavior is based on an astonishing characteristic of the strength of their color interaction: it is nearly zero when they are very close together (a condition called *asymptotic freedom*) and grows stronger as they move apart! This is just the opposite of the gravitational, electromagnetic, and strong interactions

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between hadrons, all of which grow weaker as the interacting particles move apart. The size of a quark bag (i.e., the size of a hadron) represents the limit beyond which the quarks are unable to move apart.

The standard quark model was developed in order to account concisely for the variety of known hadrons. The model requires quarks to have the spin quantum number 1/2 so that their spins can combine properly to yield the observed spins of the hadrons. Electron-scattering and muon-scattering experiments have yielded results consistent with this requirement. These experiments make use of the magnetism that spinning charged particles inherently possess. Comparison of the fraction of projectiles scattered through small angles with the fraction scattered through large angles allows the effect of electric forces to be eliminated, leaving only the scattering due to magnetism. At the energies where the theoretical model is most accurate, the magnetic effects are consistent with the scattering from pointlike particles (the quarks) having spin 1/2.

The standard quark model also assumes that quarks have fractional electric charge (compared with the unit charge of the electron), to make the net charge of a given combination of quarks equal to the observed charge of the hadron that they constitute. The existence of a free fractional electric charge has never been convincingly demonstrated for any macroscopic object; this is explained on the basis of quark confinement. However, electron scattering from hydrogen and deuterium at the Stanford Linear Accelerator Center and neutrino scattering from a fluorinated hydrocarbon at CERN in Geneva have both produced results consistent with those predicted by a quark model based on pointlike particles having charges of $-1/3$ and $+2/3$ (in units of the electron charge). Furthermore, the experimental results are in excellent agreement with each other. Taken as a whole, the lepton-scattering experiments provide strong support for the quark model.

Nuclei provide the only available system for hunting for complex multiquark states, in which more than three quarks are confined in the same bag. Finding multiquark states would be of great interest in developing our understanding of quark confinement. The European Muon Collaboration at CERN has recently obtained exciting results in collisions between muon projectiles and deuterium or iron targets. The experiments have been interpreted to show that the distribution of quarks in iron nuclei is slightly, but significantly, different from the distribution in isolated nucleons (see Figure 3.2). (The deuteron is so loosely bound as to be essentially two free nucleons.)

Possible explanations based on the notion that quarks are less strongly confined within the environment of a nucleus have been

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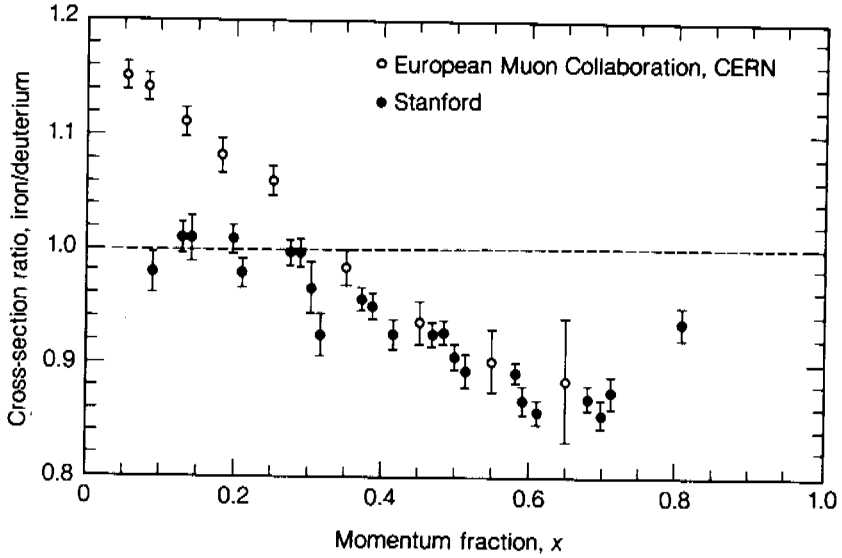


FIGURE 3.2 Inelastic scattering data from experiments with high-energy muons and electrons can be interpreted as showing that the distributions of quarks in iron nuclei and deuterium nuclei are substantially different, as discussed in the text. If they were not different, the data points would be expected to fall along the dashed line. (New electron data courtesy of R. G. Arnold, American University, Washington, D.C.)

advanced. The nucleons may expand as a result of their mutual interactions, or the quarks may "percolate" from one nucleon to another. An alternative explanation is that the additional quarks are part of the virtual pions in the nucleus; the lepton scattering, in effect, provides a "snapshot" of the nuclear constituents. The progress of these experiments is being closely watched by nuclear physicists and elementary-particle physicists, all of whom have much to gain from a deeper understanding of the role of quarks in nuclear structure.

The Physics of Hypernuclei

The presence of surrounding nuclear matter can drastically modify the properties of a particle. A free neutron, for example, has a half-life of about 10 minutes for decaying into a proton, but the neutrons in ordinary atomic nuclei have existed throughout the age of the universe. In turn, the interactions of an embedded particle can modify the properties of nuclear matter. The possibility of studying nonnucleonic particles and nuclear matter in the same system has stimulated both

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experimenters and theorists alike since the discovery of the first hypernucleus about three decades ago.

For several reasons, much of the work in hypernuclear physics has concentrated on the lambda-nucleus interaction. A lambda hyperon implanted in a nucleus does not modify the nucleus drastically, because a lambda is very much like a neutron: it has zero charge, about 20 percent greater mass, and only somewhat weaker interactions with nucleons. Thus a lambda hypernucleus is different from the original nucleus, but not so different as to preclude understanding. Another useful property of this hyperon is that, compared with other unstable particles, it has the enormously long lifetime (on the nuclear time scale) of about 10^{-10} second. The lambda's lifetime is long enough for the details of its interaction with nucleons to be studied precisely.

The general technique for making hypernuclei is to produce the hyperon in situ by allowing a suitable projectile to react with a nucleon in the target nucleus. The usual projectile is the negative kaon, which is produced in accelerators at such institutions as CERN (Switzerland), Brookhaven National Laboratory, and KEK (Japan). The kaon reacts with a neutron to produce a lambda and a negative pion; the pion is ejected from the system and provides a signal that a hypernucleus has been formed.

For the cleanest experiments, the nonnucleonic baryon should be created nearly at rest in the nucleus, to avoid depositing a burst of energy that could boil nucleons out of their orbits or even out of the nucleus entirely. With the appropriate choice of experimental parameters, this condition can be achieved in the kaon-induced reactions, and the created baryon will be moving not much more rapidly than the nucleons already present in the target nucleus. The baryon will be left in essentially the same state as the nucleon it replaced; this is called a *substitutional state* of the nucleus. Experimentally, substitutional states can be studied by programming the measuring equipment to accumulate data only when the detectors spot an exiting pion moving nearly parallel to the projectile beam direction.

The kaon beams required for producing substitutional states are difficult to produce with high quality. Kaons, which are unstable, are generated as a secondary beam in a multi-GeV proton accelerator. The kaons produced in the initial proton reaction with a selected target have a wide spread in energy and angle and are mixed with a large proportion of pions. Considerable sorting is necessary before the kaons can be isolated for the production of substitutional states in hypernuclei. The research is greatly hampered at present by the lack of intense kaon beams having a narrow energy spread.

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About two dozen distinct types of lambda hypernuclei have been produced, mainly from among the light elements (up to oxygen). Analysis of the binding energy data of the lambda in the nuclear ground state (i.e., the amount of energy required to break the lambda free) shows that the spin-independent part of the lambda-nucleon interaction is only about two thirds as strong as the nucleon-nucleon interaction and that the spin-dependent interaction is much weaker for the lambda.

If an excited state of a lambda hypernucleus is produced, it may decay to a lower state by emitting a gamma ray. Measurement of the gamma-ray energy therefore gives the energy spacing between the states—the same method commonly used to study the energy levels of ordinary nuclei and thereby to test theories of nuclear structure. Researchers at Brookhaven National Laboratory have been especially active in this field, and they are currently performing experiments with high-resolution gamma-ray detectors to measure the energies more precisely.

The sigma hypernucleus has also been studied to a small extent. The sigma is a hyperon that decays to the lambda—a process that is expected to be very fast. Workers at CERN and at Brookhaven were therefore surprised recently to discover quite long-lived substitutional states in sigma hypernuclei. The data are sparse, and it is not yet known whether the slow decay of a sigma to a lambda in hypernuclei represents a special inhibiting effect limited to light nuclei or a general property of nuclear matter.

Quantum Chromodynamics at Low Energies

It is now widely believed that quantum chromodynamics will become established as the correct theory of the strong interaction. For the region of asymptotic freedom, where the quarks are close together and interact very weakly, QCD calculations produce results in good agreement with experiment. At larger distances, however, where the confined quarks interact strongly, the calculations become so complicated that reliable results are difficult to obtain, although considerable progress is being made through the use of lattice gauge theory (see page 142 for an explanation of this term). Because the region of asymptotic freedom can be probed in the laboratory only in experiments at very high energies, theory and high energy have gone hand in hand in the development of QCD. At lower energies, however, the experiments performed so far do not seem to bear on QCD in a way that would facilitate extending the theory to the domain of strong quark interac-

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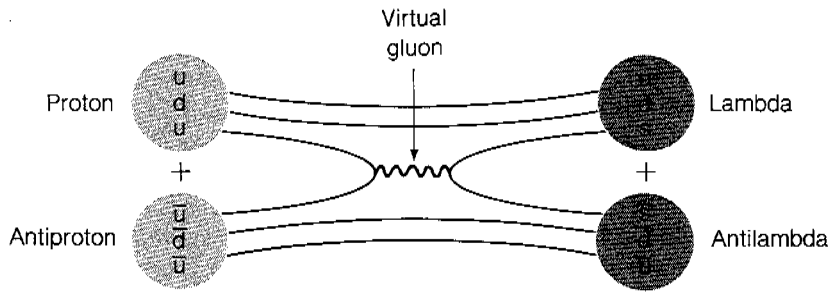


FIGURE 3.3 Annihilation of a u quark and a u antiquark in a proton-antiproton collision. The annihilation produces a high-energy virtual gluon, which disappears with the creation of an s quark and an s antiquark in the respective nuclei, which have thus become a lambda hyperon and an antilambda hyperon.

tions. Physicists have therefore tried to conceive lower-energy experiments directly relevant to QCD.

Prime candidates for studying quark properties at lower energies (less than 1 GeV) are the proton-antiproton interaction or the proton-kaon interaction. According to the quark model, a proton has the quark structure uud (two up quarks and one down quark). An antiproton has the analogous structure $\bar{u}\bar{u}\bar{d}$, made with antiquarks instead of quarks. During a proton-antiproton collision, one u quark may annihilate its antiquark $\bar{u}$ to form, for example, the strange quark s and its antiquark $\bar{s}$ (see Figure 3.3). After the collision, the system separates into two three-quark hyperons: uds (a lambda) and $\bar{u}\bar{d}\bar{s}$ (an antilambda). The precise study of such processes over a range of energies is expected to provide important data for guiding the development of QCD.

Studies of proton-antiproton interactions are already under way at CERN's new Low-Energy Antiproton Ring (LEAR), an accelerator facility that is a nearly ideal source of low-energy antiprotons. It provides a copious, essentially pure beam of antiprotons over a wide energy range, with a very small energy spread. Although it could profit from the additional ability to produce polarized (spin-aligned) antiprotons for the investigation of spin-dependent forces, the LEAR facility offers opportunities for exciting research that make it singularly attractive to many user groups from the United States.

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THE NUCLEUS AS A LABORATORY FOR FUNDAMENTAL SYMMETRIES

Much of our physical understanding of nature is embodied in conservation laws and in the symmetry principles from which they stem. Conservation laws make powerful statements of great generality that apply even if the details of a system are unknown. The classical laws of electric-charge conservation, energy conservation, and momentum conservation are routinely applied to the analysis of nuclear reactions because of their complete reliability. From the opposite viewpoint, the fact that conservation laws inferred from everyday physics can be applied to nuclear systems represents a great extension of these laws to new realms of size and energy. The study of nuclear systems has also revealed new symmetries and conservation laws not apparent in the behavior of macroscopic objects. As theory pushes on to examine the nature of the fundamental forces at energies far beyond the reach of the largest manmade accelerators, searches for symmetry violations in the precisely calibrated environment of the nucleus may be the only viable approach for seeing the subtle residual effects predicted to occur at energies that *are* accessible.

There are several reasons why the nucleus is an excellent laboratory for the study of fundamental symmetries. The nucleus readily displays the effects of both the strong and electroweak forces, and the dimensions of the nucleus place it only one or two steps away from what we believe is the ultimate structure of matter. Furthermore, the wide range of proton and neutron numbers available in nuclei helps to illuminate differences and distinguish the general from the specific. Strange particles such as the lambda hyperon can be implanted to form hypernuclei, thereby extending the variety of nuclei even further. Finally, nuclei have definite quantum states, so that the systems studied have well-defined properties. An added advantage is the large amplification of small effects that can occur when two nuclear states with specific properties happen to have nearly the same energy; as physics has advanced to more and more comprehensive theories, experimental sensitivity to small effects has become increasingly important.

The weak force has been an extraordinarily fruitful source of information about the underlying symmetries of nature. It is exposed for convenient study in the more than 2000 known nuclei that undergo beta decay—a manifestation of this force. The attention of physicists was refocused on the question of symmetry laws by a famous experiment carried out in 1956 at the National Bureau of Standards. The beta

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decay of parallel-spin (magnetically oriented) cobalt-60 nuclei was shown not to give the same result as the corresponding mirror-image experiment—a most astounding result at the time. In terms of symmetry, this result is described by saying that the weak force does not behave symmetrically under reflection; in terms of conservation laws, it is described by saying that weak-force interactions do not conserve parity. The strong, electromagnetic, and gravitational forces do not appear to violate parity; why the weak force does is not understood.

In familiar examples of the phenomena of classical physics—colliding billiard balls, for example—the physical laws that govern the interactions of objects appear always to be the same, regardless of whether one considers time to be running forward or backward. This independence of the direction of time's arrow is a symmetry principle called *time-reversal invariance*, which was long thought to be absolutely valid in all physical systems. In 1964, however, a violation of time-reversal invariance was discovered in a decay process involving the weak force. The particle in question was the neutral K meson (kaon), which can undergo beta decay by two modes, to give in part either positive electrons (positrons) or negative electrons. If time-reversal invariance held, the two rates of decay would be exactly equal; instead, their ratio is found to be 1.0067.

Although the effect is small and occurs in an obscure submicroscopic system, it may have important cosmological implications: it may be related to the preponderance of matter over antimatter in the known universe or to the preponderance of radiation over matter. Along with other cases of symmetry-principle violations, time-reversal-invariance violation has forged unexpected links between nuclear physics and cosmology, connecting the unimaginably small with the unimaginably large.

Finding other examples of time-reversal-invariance violation in processes simpler than that of kaon decay would help greatly in understanding the origin of this surprising phenomenon. Theorists have therefore tried to predict observable effects of such a violation in nucleons and nuclei—for instance, a nonzero electric dipole moment (slight separation of internal positive and negative charges) for the neutron. Searches for such effects are being conducted in phenomenally precise studies that are a tribute to the ingenuity of experimentalists.

Because symmetry principles can apply even when the detailed interactions in a system are unknown, modern theory building often starts by postulating certain symmetries suggested either by experimental data or by beauty of design in the theory. Some symmetries can

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be readily visualized, such as the symmetries of space and time that underly the conservation laws for momentum, angular momentum, parity, and energy. But symmetries can also apply to abstract quantities such as the isospin concept that merges individual proton and neutron identities into the more general nucleon description.

Present-day theorists have set themselves the ambitious task of unifying the "fundamental" forces of nature into one comprehensive description from which everything else can be rigorously derived. Their achievements to date have been impressive. The theory showing that electromagnetism and the weak force both spring from a common *electroweak* force has been a triumph of successful predictions, including the existence of the charm quark and the recently discovered W^+, W^-, and Z^0 bosons. These last three particles are crucial because their exchange (as virtual particles) is at the origin of the weak force.

Despite these triumphs, the new electroweak theory—which, together with QCD, is now referred to as the *Standard Model*—is incomplete. It does not explain (but does allow) the violations of parity and time-reversal invariance, it does not unify the strong force or the gravitational force with the electroweak force, and it does not predict, a priori, the observed relative strengths of the electromagnetic and weak forces. Theorists are still striving for a *Grand Unified Theory* that would unite all the forces and that would include all the symmetry laws and their violations. The following sections give some examples of how nuclear physics is providing guideposts along the dimly outlined road to grand unification.

Right-Handed Bosons in Beta Decay

Parity is found to be violated to the maximum possible extent by nuclear beta decay; i.e., the mirror-image decays are never observed. Suppose that the neutrino emitted in a beta decay is represented by a partially closed left hand, with the thumb in the direction of the neutrino's motion. The curl of the fingers represents the direction of the classical rotation analogous to the neutrino's spin. If this model is viewed in a mirror parallel to the thumb, the direction of motion is unchanged, but the mirror-image spin is in the opposite direction. Mirror reflection changes a left hand to a right hand, a complete reversal of parity. The hypothesis that neutrinos are strictly left-handed therefore successfully accounts for parity violation.

The Standard Model assumes that the W^+ and W^- bosons are left-handed (strictly speaking, it is their interactions that are left-

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handed) and that the Z^0 boson is partly left-handed, which leads automatically to the left-handedness of neutrinos. Other theories consider the more symmetric possibility that there are right-handed as well as left-handed W and Z bosons. If the right-handed bosons were significantly more massive than the left-handed ones, their force would have a shorter range, and left-handed neutrinos would dominate in present experiments. The situation is somewhat like that of the electroweak force, where the constituent electromagnetic and weak forces are fundamentally the same yet manifest themselves to us with very different strengths.

Several different kinds of experiments have shown that if right-handed W and Z bosons do exist, they must be extremely massive. Some experiments have searched for small right-handed effects in muon decay or in the beta decay of neon-19 nuclei; other experiments infer the properties of neutrinos from the measured spin and motion of the much more easily observed decay electrons. It will be some time before accelerators large enough to permit a direct search for the massive right-handed bosons themselves can be constructed.

The Mass of the Neutrino

If an observer could overtake and pass a left-handed neutrino, the neutrino's direction of motion (but not its spin direction) would appear to reverse, the way cars seem to fall behind when we pass them. The observer's motion alone could thus change a left-handed neutrino into a right-handed one, so that left-handedness would no longer be an intrinsic property of the neutrino. The way out of this paradox is to assume that neutrinos move with the speed of light, too fast for any observer to overtake. The theory of relativity shows that particles moving with the speed of light must have zero mass. The Standard Model admits only massless neutrinos, but in most proposed Grand Unified Theories, electron neutrinos, for example, can have a very small mass, typically between 10^{-8} and 1 eV. (By comparison, the mass of the electron is 511,000 eV.)

Whether a neutrino has zero or nonzero mass bears directly on neutrino handedness and parity, and on the structure of Grand Unified Theories. The neutrino mass also has important implications for cosmology. The universe still contains so many neutrinos formed during the big bang that if the neutrinos have even a very small mass, their gravitational force could eventually brake and reverse the universe's current outward expansion. Because the density of observed stars and galaxies appears to be too low to accomplish this, the

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neutrinos could represent the additional "missing mass" needed to hold the universe together. Indeed, arguments from cosmology have set a rough upper limit of 30 eV on the electron neutrino mass, based on the observation that the universe is still expanding at present.

In 1980, researchers in the Soviet Union reported that the electron neutrino from nuclear beta decay probably has a mass between 15 and 50 eV, just within the interesting range for cosmology. Their experimental method was to study the beta decay of hydrogen-3. The decay electron and the neutrino (actually an antineutrino in this case) are emitted simultaneously and share the available decay energy between them, so that in different decays, the electron may receive anywhere from nearly zero energy to the maximum. The probability of the electron's receiving a particular energy within this range is a characteristic of the decay and is called the *shape* of the electron spectrum. The object of the Soviet experiment was to determine the shape (by measuring the energies of the decay electrons), because it depends on the neutrino mass in a known way.

The experiment is far from easy, and certain systematic effects can distort the shape in a way that mimics the effect due to neutrino mass. Conclusions from this experiment are not universally accepted, and refined versions are now being carried out in the United States and other countries.

Neutrino Oscillations

A mass hanging from a spring is a favorite demonstration in physics lectures. The system has two modes of oscillation: the mass can vibrate up and down, or the whole system can swing like a pendulum. With proper design, the system can pass alternately from one mode to the other, with swinging changing gradually to springing, and back again. A quantum-mechanical system may exhibit a similar alternation of mode, as a kind of swelling and ebbing "beat" of the quantum-mechanical wave oscillations. In some cases, the beats can even manifest themselves as alternations in the identity of a particle.

There are three apparently distinct neutrinos emitted during beta decays: a different neutrino is associated with electrons, muons (essentially, heavy electrons), and tauons (very heavy electrons). The Standard Model strictly maintains the separate identities of electron neutrinos, muon neutrinos, and tauon neutrinos, in accord with the currently accepted lepton-family-number conservation laws: the total number of electrons and electron neutrinos in the universe minus the total number of antielectrons (positrons) and electron antineutrinos is

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constant. Similar laws hold separately for the muon family and for the tauon family.

However, Grand Unified Theories generally allow a neutrino of one kind to transform gradually into another kind. An electron neutrino from a nuclear decay, for example, could gradually become a muon neutrino or a tauon neutrino as it sped along its way. The rate of change as the quantum-mechanical beats ebb and swell depends on the mass differences between the various neutrinos; equal-mass or zero-mass neutrinos retain their identities. If neutrino oscillations were observed experimentally, it would imply that at least one kind of neutrino has nonzero mass. Also, an observed change in identity would be the first known violation of the lepton-family-number conservation laws. The beta decay of fission products in a nuclear reactor produces a copious flux of antineutrinos, and experimenters at the Savannah River, Grenoble (France), and Gösgen (Switzerland) reactors have set up detectors to see if the number of electron antineutrinos diminishes along their flight path. The most sensitive experiments to date have produced no evidence of the disappearance of electron antineutrinos. Similarly, accelerator experiments at Fermilab, Brookhaven, and CERN have not revealed any oscillation of muon neutrinos to other kinds, or any oscillation of electron neutrinos or muon neutrinos to tauon neutrinos.

The sensitivity of the reactor experiments to small neutrino-mass differences increases as the flight path is lengthened; small mass differences make the oscillations very slow, so that neutrinos could travel great distances before undergoing observable transformations. The flight paths in the reactor experiments so far have extended up to 46 m, which sets an upper limit on the possible neutrino oscillations. Using neutrinos produced in the Sun would give a flight path of 1.5×10^8 km, increasing the sensitivity dramatically. As discussed in Chapter 5, the counting rate in present solar-neutrino detectors is roughly one fourth the theoretically expected value. One proposed solution to this vexing disparity is that oscillation decreases the number of solar-electron neutrinos arriving at the Earth. However, present neutrino detectors are sensitive only to the small fraction of the Sun's neutrinos that result from a rather minor nuclear-energy-generating process, so the theoretical uncertainties in the expected number may be large.

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Double Beta Decay

The energy for the decay of a radioactive nucleus comes from the mass difference between the initial nucleus and the decay products. Accurate mass data are available from many different experimental methods, so the energy available for decay can be predicted quite well. Study of these mass data shows that certain nuclides—for example, selenium-82 and tellurium-130—are stable against ordinary beta decay but are allowed by energy considerations to undergo *double beta decay*. In this process, the decaying nucleus simultaneously emits two electrons instead of one, thereby raising the proton number of the nucleus by 2; double beta decay would therefore change selenium to krypton, and tellurium to xenon.

In ordinary beta decay, the decaying nucleus emits an electron and an antineutrino, a process that conserves lepton family number, as discussed earlier. The analogous process for double beta decay would be the emission of two electrons and two antineutrinos, again conserving lepton family number. The more particles that are to be emitted in a given decay process, the smaller the probability that the decay will occur. Because four particles are emitted in this two-neutrino mode of double beta decay, the half-lives are expected to be extremely long, typically 10^{20} to 10^{25} years.

On the other hand, double beta decay might possibly proceed by emitting only the two electrons and no antineutrinos. This neutrinoless mode of double beta decay would be expected to have a shorter half-life than the two-neutrino mode, because only two particles need be emitted, instead of four. However, the neutrinoless mode is opposed by the conservation law for lepton number—it involves the creation of two leptons (the two electrons) uncompensated by antileptons (the two antineutrinos). If neutrinoless double beta decay were observed, it would imply a violation of lepton-number conservation.

Certain conditions in addition to the violation of lepton-number conservation must also be satisfied to allow neutrinoless double beta decay to occur. The neutrinoless mode is described as a two-step process: the decaying nucleus first emits one electron and a virtual antineutrino, a reaction analogous to ordinary beta decay. In the second step, the daughter nucleus instantaneously absorbs this antineutrino and emits the second electron. The second step is analogous to a known process, except that nuclei absorb neutrinos, rather than antineutrinos, to emit electrons. For neutrinoless double beta decay to occur, therefore, the antineutrino and the neutrino must in

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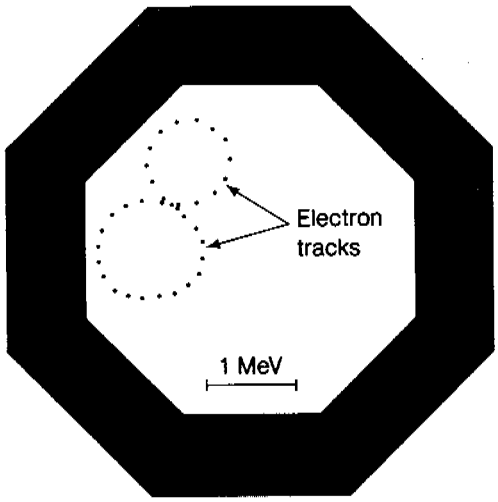


FIGURE 3.4 Computer simulation of the two-neutrino double beta decay of a selenium-82 nucleus in a particle detector called a time projection chamber. In this hypothetical event, the strong magnetic field in the detector causes the two emitted electrons to spiral away from the nucleus along separate paths. The computer-generated helical tracks of the electrons have been projected onto a plane in this cross-sectional view, producing a figure-8 pattern. (The energy scale gives the track diameter of a 1-MeV electron emitted in the plane of the figure.) Finding such a pattern in an actual experiment might signal the occurrence of this extremely rare event. (Courtesy of M. K. Moe, University of California, Irvine.)

fact be one and the same particle. Furthermore, the neutrinoless mode requires the virtual neutrino to be partially right-handed.

Although the necessary conditions described above stack the cards heavily against the neutrinoless mode, a single observed instance would shatter many currently held ideas. Meanwhile, considerable effort has been put into the search for two-neutrino double beta decay, despite the experimental difficulties imposed by the very long half-lives and the consequent low rates of decay. Such difficulties make the computer simulation of possible events a valuable design tool (see Figure 3.4).

The search for the presumably even rarer neutrinoless double beta decay is made extremely difficult by cosmic rays, which can create background effects in the experimental apparatus that mask the true signal. For increased sensitivity, therefore, the experiments must be moved deep into the Earth, under a thick shield of rock. The Soviet Union has recently completed a large underground laboratory at Baksan for physicists who require very high sensitivity in such

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experiments as the search for neutrinoless double beta decay, the search for decay of the proton, and the measurement of the solar-neutrino flux. A similar dedicated facility, the National Underground Science Facility, has been proposed in the United States. Several experiments are already under way in deep mines and mountain tunnels in the United States and Europe.

Parity Violation in Nuclei

According to the Standard Model, nucleons are made of two different combinations of three up and down quarks. In this picture, all the properties of nuclei spring ultimately from quark interactions, but only recently have the first attempts been made to relate nuclear properties to quark behavior. The strong quark interaction (and the resulting strong force) is believed to conserve parity strictly, but quarks also take part in the parity-nonconserving weak force, in which charged W^+ or W^- bosons or neutral Z^0 bosons are exchanged. The quark model predicts that the exchange of charged W^+ or W^- bosons will add to the nucleon-nucleon force a small weak-force component that does not conserve parity and that chiefly causes the isospin of a pair of interacting nucleons either to remain the same or to change by two units. The neutral Z^0 exchange gives rise to a weak-force component that also does not conserve parity and that changes the isospin of a pair of nucleons by zero, one, or two units. A great many states of different parities and isospins are available among the known nuclei, and careful selection of the test nuclei allows the two different weak-force components (from W and Z exchange) to be distinguished experimentally.

The strong force in nuclei conserves parity, so that each nuclear state can be assigned a definite parity value (even or odd). However, the parity-nonconserving weak force mixes the parities of the states, so that they are actually neither purely even nor purely odd. The nuclei fluorine-19 and neon-21 both exhibit the favorable circumstance of having two closely spaced energy levels of the same angular momentum but opposite parity; this close proximity increases the usually tiny effects of the weak force in mixing the parities of these states. Furthermore, the isospins of the states in question are such that both the charged and neutral boson-exchange components are able to influence the mixing in fluorine-19 and in neon-21.

Experimentally, the parity-nonconserving mixing is observed in fluorine-19, where the charged and neutral components add. However, it is not seen in neon-21, where the charged and neutral components

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tend to cancel. Higher sensitivity should soon allow the pure neutral-component contribution in a nearby nucleus, fluorine-18, to be measured. Comparing the experimental results with theory allows two important conclusions to be drawn. First, the Z^0 boson exchange between nucleons is definitely present (the Z^0 boson has recently been detected directly as a free particle). Second, the dynamic masses of the up and down quarks in a nucleon are very close to the values originally predicted.

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4

Nuclei Under Extreme Conditions

As accelerator technology has advanced, so has our ability to produce nuclei under highly unusual conditions. This has resulted in the discovery of exciting new phenomena and has given us a broader perspective on the properties of nuclei under more normal conditions. Increasingly, nuclear projectiles with heavier and heavier masses accelerated from medium to relativistic energies are being used in collisions with other nuclei to raise nuclear matter to high temperatures and densities, to create new elements and exotic isotopes, and to produce highly excited and deformed nuclear systems.

Some projectile fragments that are formed in relativistic nuclear collisions appear to exhibit totally unexpected behavior not explained by current theory. Called *anomalons*, they were first seen sporadically in cosmic-ray experiments but have now been reported in some laboratory experiments as well. Their appearance has stirred a spirited controversy worldwide, and vigorous efforts are under way to prove—or disprove—that they are what they seem to be.

As higher projectile energies become available, it may be possible to create from nuclear matter a state of such high temperature and density that it will undergo a transition to a *quark-gluon plasma*. In this exotic state of matter, individual nucleons will cease to exist, and conditions will be similar to those that existed briefly after the big bang. Recent research that is leading toward this ambitious goal is discussed in the following section.

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NUCLEI AT HIGH TEMPERATURE AND DENSITY

Some of the nuclear matter in the universe is much hotter and denser than the relatively cold atomic nuclei on Earth. In order to understand the origin and evolution of spectacular celestial objects such as supernovas and neutron stars, we must produce nuclear temperatures and densities comparable with theirs. To do this in the laboratory, a huge amount of energy (on the submicroscopic scale of nuclei) must be deposited instantaneously throughout a much larger volume than that of a single nucleon. As we will see below, this requires the violent collisions of very heavy nuclei in powerful accelerators.

Until 10 years ago, no such nuclear collisions could be produced systematically. Although tantalizing glimpses of extremely energetic heavy nuclei were caught in cosmic-ray experiments, these events were rare and uncontrollable. In 1974, however, the Bevalac accelerator at the Lawrence Berkeley Laboratory became capable of accelerating nuclei as heavy as iron to energies as high as 2.1 GeV per nucleon. This achievement marked the beginning of a dedicated research program of accelerator-based *relativistic heavy-ion physics*, in

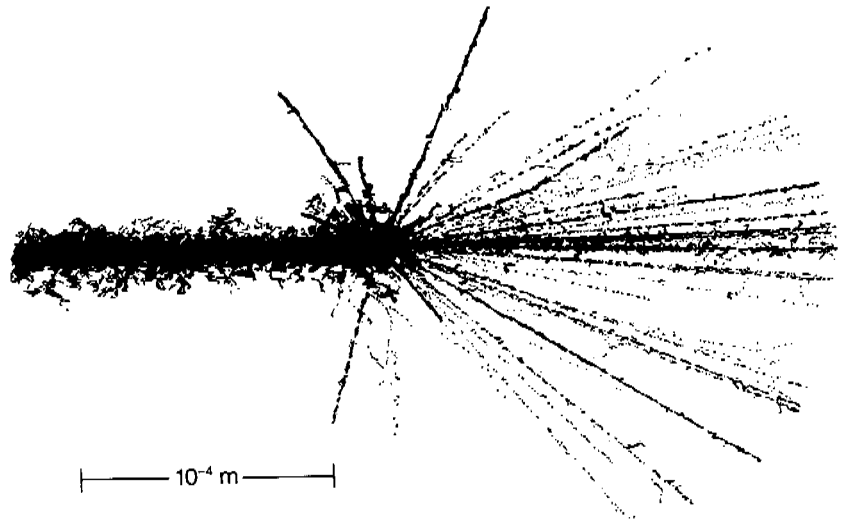


FIGURE 4.1 A microprojection drawing of the central collision of a relativistic uranium-238 nucleus, having an energy of 1 GeV per nucleon, with a heavy nucleus (either silver or bromine) in a photographic emulsion. In this event, the two nuclei were completely destroyed. (Courtesy of H. H. Heckman, Lawrence Berkeley Laboratory.)

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which a massive projectile (heavy ion) is accelerated to a speed so close to that of light that its kinetic energy becomes comparable with or greater than its own rest energy. At such enormous energies, the effects of special relativity become dominant and must be taken into account in interpreting the experimental results.

The Bevalac was further upgraded in 1982 to accelerate *all* the natural elements of the periodic table to relativistic energies, culminating with uranium at 1 GeV per nucleon (see Figure 4.1). Thus, a vast new domain of nuclear physics has been opened up, in which nuclear temperatures and densities can be achieved—for brief instants—that far exceed those existing even in most stars.

High Nuclear Temperatures

Implicit in the concept of temperature is the assumption of a system of particles in a state of equilibrium—even if only for a very short time, such as 10^{-22} second (the typical duration of a nuclear collision). In a central (head-on) collision of two heavy nuclei at relativistic energy, a nuclear *fireball* is created in which hundreds of individual nucleon-nucleon collisions occur very rapidly before the produced particles are blasted outward in all directions. (This fireball is so infinitesimal that, if it exploded in one's eye, it would only appear as a pinpoint flash of light.) The statistical nature of the overall event suggests analysis by means of *nuclear thermodynamics*.

A consequence of thermodynamic equilibrium in such a system would be a uniform distribution (the same in all directions) of the momenta of the emitted particles. To test for this pattern, one needs a detector capable of capturing and identifying hundreds of particles—charged hadrons and light nuclear fragments—simultaneously, at all possible angles of emission of the particles. Such a detector, the Plastic Ball/Plastic Wall, has been built by a team from the GSI laboratory (Darmstadt, West Germany) and the Lawrence Berkeley Laboratory (see Figure 4.2).

Investigations have been carried out with this detector on collisions of calcium beams with calcium targets and niobium beams with niobium targets, both at 0.4 GeV per nucleon. The measured momenta of all the observed particles were transformed mathematically from the laboratory frame of reference (in which the experiments were done) to the center-of-mass frame (in which the data analysis is easier), and the momentum distribution of particles was calculated and plotted. The markedly nonuniform angular distribution for the relatively light calcium system showed clearly that thermodynamic equilibrium had not

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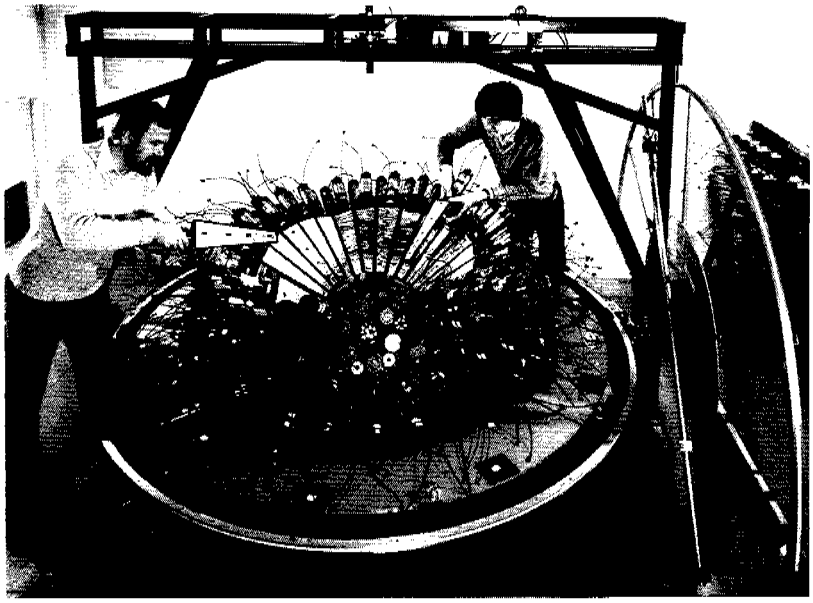


FIGURE 4.2 One hemisphere of the Plastic Ball detector during its assembly. Consisting of 815 pyramidal scintillator detector modules, each with its own electronics package, the complete detector covers 96 percent of the total solid angle into which nuclear-reaction products can be emitted. (Courtesy of the GSI/LBL Collaboration, Lawrence Berkeley Laboratory.)

been fully achieved—not even in central collisions, where the highest multiplicity of emitted particles occurs. By contrast, the more nearly uniform angular distribution for the heavier niobium system indicated a much closer approach to equilibrium. This demonstrates the need for using the heaviest possible projectiles and targets in relativistic nuclear collisions. To make valid thermodynamic analyses—and hence meaningful estimates of nuclear temperature—one needs as many nucleon-nucleon collisions as possible within the fireball.

Experimental and theoretical results indicate that central nuclear collisions at energies of 1 to 2 GeV per nucleon do indeed produce a fireball at extremely high temperatures: about 100 MeV, or 10^{12} K, which is about 60,000 times hotter than the core of the Sun! Much of the kinetic energy of the collision is converted directly to mass in the form of created particles, such as kaons and pions, whose kinetic energies reflect the temperature of the fireball. It has been observed that the kaons emitted by the fireball are appreciably hotter than the

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protons, which, in turn, are hotter than the pions. This surprising result is thought to mean that the kaons reflect the fireball temperature at an early, hot stage of its evolution, whereas the pions reflect the temperature at the final, "freeze-out" stage. Thus, it could be that different kinds of particles produced in the collision serve as nuclear "clocks" in their record of the event.

High Nuclear Densities

Measuring the nuclear density in fireballs that last about 10^{-23} second is very difficult. First, the average mass of the fireballs is not known accurately (although it can be estimated), because none of the collisions that produce them are perfectly central. Most are sufficiently off center that some of the nucleons in the projectile and target nuclei do not participate in the fireball formation; they are merely spectators (see Figure 4.3). Furthermore, the volume into which the participating nuclei are compressed by the energy of the collision is not known either. Surprisingly, however, an indirect way of measuring this

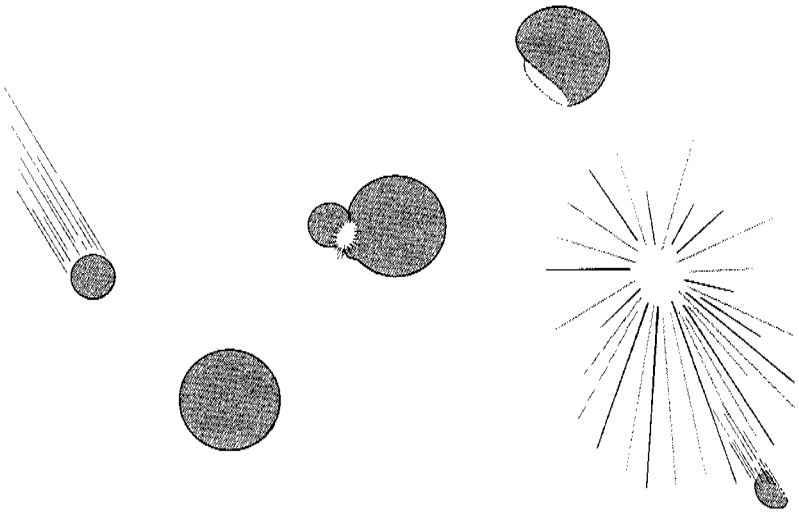


FIGURE 4.3 The participant-spectator model of relativistic nuclear collisions. The participant (overlapping) regions of the two nuclei coalesce to form an intensely hot, dense nuclear fireball, which explodes in a shower of high-energy particles. The spectator fragments, meanwhile, remain relatively cold, at normal nuclear density.

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infinitesimal volume has been found in a technique borrowed from the science that deals with the largest sizes imaginable: astronomy.

The technique, *intensity interferometry*, was developed in 1956 for measuring the sizes of galaxies, but it can be applied in nuclear physics as a means for measuring the sizes of the fireballs formed in relativistic nuclear collisions. These events produce many pairs of identical particles, such as protons or positive or negative pions. From measurements of such particle pairs, correlations are determined that depend on the spatial and temporal properties of the source. The results of these correlations indicate source sizes 2 to 4 fermis in radius, which are typical of most atomic nuclei and hence plausible.

Theoretical calculations using an *intranuclear cascade* model—in which the nuclei are treated as collections of independently interacting particles—for central argon-on-argon collisions at energies of 1 to 2 GeV per nucleon yield mean nuclear densities of about 4 times normal, or about 10^{15} grams per cubic centimeter. This value is within the range of densities believed to exist in the cores of neutron stars. Similar results are obtained from hydrodynamic models, in which the nuclear medium is treated as a fluid. Extrapolations of the cascade calculations to heavier nuclear systems predict mean densities of about 5 to 6 times normal.

With some knowledge of high nuclear temperatures and densities finally in hand, the stage is set for seeking the solution to a very important problem: the determination of the *equation of state* of nuclear matter.

Nuclear-Matter Equation of State

Equations of state are among the most valuable tools in science, because they describe the behavior of a physical system over a wide range of conditions, on the basis of a few measurable quantities, called *state variables* (for ordinary gases, these variables include the pressure, volume per molecule, and temperature). If all but one of their values are known for a given state, then the unknown one can be calculated. To determine an equation of state, the appropriate state variables must be identified and their values measured over wide ranges.

Until the advent of relativistic nuclear collisions, there was almost no direct experimental evidence on which to base a nuclear-matter equation of state for conditions of high temperature and density,

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although a great deal of theoretical work had already been done. However, recent experiments on the interaction of argon with argon at bombarding energies of 0.36 to 1.8 GeV per nucleon may be a major new step toward understanding hot, dense nuclear matter. One interpretation of the surprisingly low pion yields in these experiments is that much of the kinetic energy that was expected to be transformed into pions was used for nuclear compression instead. When the results were combined with those from an intranuclear cascade calculation, a tentative equation of state was extracted for nuclear matter at about 2 to 4 times normal density.

If confirmed, this development would be a major advance for at least three reasons:

- It would buttress the bridge between the hydrodynamic models that are used to explain many experimental observations and the more detailed (but difficult) many-body calculations that seek to relate observed nuclear properties to various aspects of the underlying nucleon-nucleon force.
- It could provide a testing ground for the growing list of theoretical ideas—such as the existence of extraordinary forms of nuclear matter called density isomers and pion condensates—that have been among the foremost stimuli for experimental work in relativistic nuclear collisions in the past decade.
- It would be progress toward the determination of such global nuclear properties as viscosity and thermal conductivity, which are important indicators of otherwise hidden aspects of the internucleon force. The behavior of these quantities as functions of the temperature and density is expected to reveal aspects of many-body behavior that are not accessible in simple scattering experiments.

With the relatively light argon-on-argon system described above, the compressional energy produced in the collisions increases smoothly with bombarding energy, showing no sign of a discontinuity that could be associated with a new state of matter or a phase transition. With a very heavy nuclear system at very high relativistic energies, on the other hand, it is very likely that there will be a transition from hot hadronic matter to the *quark-gluon plasma*, the state of matter believed to have existed briefly at the moment of creation of the universe—the big bang. This prospect, surely one of the most exciting that nuclear physics has ever contemplated, is discussed in Chapter 7.

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THE HEAVIEST ELEMENTS

New Transfermium Elements

Ever since the infancy of nuclear science, chemists and physicists have tried to discover new elements beyond uranium (atomic number $Z = 92$). With the advent of particle accelerators and nuclear reactors, rapid progress was made, culminating with the synthesis of lawrencium ($Z = 103$) in 1961. For the next 13 years, the only proven method of synthesizing transfermium elements (Z greater than 100) was the bombardment of radioactive targets heavier than uranium with nuclear projectiles as heavy as neon, to produce compound nuclei. Since heavy-ion accelerators are required for this research, the efforts have been concentrated at the Lawrence Berkeley Laboratory, the Joint Institute for Nuclear Research (JINR) at Dubna, USSR, and, most recently, the GSI laboratory at Darmstadt, West Germany. Although these searches have succeeded in producing transfermium elements through atomic number 105, their already very low yields have been steadily decreasing with increasing atomic number.

In 1974, element 106 was produced and unambiguously identified at Berkeley by this method. The bombardment of californium-249 ($Z = 98$) with oxygen-18 ($Z = 8$) yielded the unnamed nuclide $^{263}106$, which decayed by emitting alpha particles, with a half-life of 0.9 second, to known daughter-granddaughter nuclei that decayed in turn by alpha emission with distinctive energies and half-lives. The reaction yield was only about one atom produced per 10^{10} nuclear collisions.

At about the same time, however, another isotope of element 106 may have been observed at JINR in the bombardment of a somewhat lighter target, lead-208 ($Z = 82$), with a much heavier projectile, chromium-54 ($Z = 24$). These experiments were of great interest because the excitation energy of the compound nucleus with 106 protons was much lower (one can say that the fused system was colder) when produced with the chromium-54 projectile, so that fewer low-energy neutrons had to be emitted in order to stabilize the system; this resulted in a greater yield of the specific isotope of interest.

More recently, the Darmstadt group has brought an exquisitely sensitive new technique to the search for elements 107 and higher, adding new dimensions to these *cold-fusion* reactions. They coupled their 12-m-long recoil velocity selector to an elegant solid-state detector system installed at its focus. This carefully tuned filter is able to reject essentially all of the bombarding beam while transmitting a high

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percentage of the final reaction products to the detector system, in times of the order of a microsecond. An array of seven detectors made of single-crystal silicon is used to record the time of flight of a reaction product, its energy, and where it stopped in the detector array. Subsequent alpha-decay or spontaneous fission events can then be correlated by their positions. For an alpha-decay daughter-granddaughter chain stemming from the implantation of a single heavy nuclide, such correlation evidence can be extremely powerful.

With this impressive system, the bombardment of bismuth-209 (Z = 83) with titanium-50 (Z = 22) was found to produce a new alpha-emitting nuclide, $^{257}105$, which in turn decayed to new alpha-emitting nuclides of elements 103 and 101. Similarly, the nuclide $^{258}105$ was identified, along with new or known descendants, by alpha emission or electron-capture decay.

With their basic work on element 105 completed, the Darmstadt group then bombarded bismuth-209 with chromium-54 to look for element 107. In 1981 they found $^{262}107$, with a half-life of 4.7 milliseconds (msec); the assignment was proved by the nuclide's decay to its by-then-known descendant $^{258}105$.

The most elegant experiment of all in this extensive series was that which appears to have produced element 109, *one single atom* of which was observed in August 1982. In a 12-day experiment, bismuth-209 was bombarded with iron-58 (Z = 26) to produce a single chain of events in one of the detector crystals. The only observed candidate for complete fusion of the projectile and target nuclei had a calculated mass of 264 $\pm$ 13, from its time of flight and energy. Five milliseconds after its implantation, it decayed by emitting an 11.1-MeV alpha particle. A second alpha particle emitted from the same spot 22.3 msec later escaped from the detector after depositing only 1.14 MeV. Finally, 12.9 seconds after that, a spontaneous fission event was observed, releasing an energy of 188 MeV. This sequence of events is compatible only with a decay series starting with the nuclide $^{266}109$ and proceeding—via two successive alpha emissions and one beta capture—to the nuclide $^{258}104$, which then undergoes spontaneous fission. If corroborated, this event will represent the first identification of a new element through the characteristics of a single atom.

In March 1984, the gap between elements 107 and 109 was closed: the Darmstadt group presented convincing evidence for the discovery of element 108, based on the observation of three distinctive events.

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The Search for Superheavy Elements

In the mid-1960s, the interest of many nuclear scientists was aroused by theoretical calculations that showed the strong possibility of a *magic island* of superheavy elements in the region around proton number $Z = 114$ and neutron number $N = 184$. This island would be characterized by a relatively high stability associated with the closed nucleon shells predicted by the shell model of the nucleus. The calculations, which were based on logical extrapolations of properties of ordinary nuclei, indicated that some half-lives might even be long enough for superheavy elements to be found in nature.

Since that time, many unsuccessful attempts to find such elements have been made throughout the world, using a great variety of techniques and covering many possibilities—including primordial ores, meteorites, and lunar rocks. The effort has recently become focused on the use of heavy-ion accelerators to make nuclear species as close as possible to $N = 184$ in the general vicinity of $Z = 114$.

The most direct way to make superheavy elements in accelerators is by the complete fusion of a projectile nucleus and a target nucleus. Even under optimal conditions, however, the resulting compound nucleus contains substantial internal excitation (tens of MeV) and angular momentum, which must be quickly dissipated by the emission of light particles (mostly neutrons), followed by the emission of gamma rays, before the ground state of the final reaction product is reached. At each step in the de-excitation process, there is a much better chance for fission to occur instead, so the final probability of producing a superheavy element may become minuscule.

At Berkeley, Darmstadt, and Dubna, complete fusion has been pursued vigorously, using reactions such as the bombardment of curium-248 ($Z = 96$) with calcium-48 ($Z = 20$) and detection methods sensitive to lifetimes as short as 1 second. However, nothing has been seen that can be attributed to superheavy elements. The most promising ideas at present seem to be those involving the bombardment of heavier and very exotic short-lived radioactive targets, such as 276-day einsteinium-254 ($Z = 99$) or even 40-day einsteinium-255, in that bombarding these targets with a calcium-48 beam brings one closer to the goal of 184 neutrons. (Perhaps, as another tool, accelerated beams of radioactive nuclei such as calcium-50 will become available in the future.) The available amounts of these materials are very small, however, and the experiments are extraordinarily difficult to perform. Also, it may simply be that even the best projectile-target combination does not produce a nucleus close enough to the center of

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the magic island to take advantage of the expected higher stability there.

The focus of research in this area now is on trying to understand why these elements have not yet been identified. Is it because such nuclei cannot be made with the tools we have available, or because they cannot exist at all?

HIGHLY UNSTABLE NUCLEI

Theoretical models of nuclear structure suggest that some 8000 different nuclides of the chemical elements should exist and be observable in the laboratory, but only about 2700 have been discovered so far. Of these, about 300 are the well-known stable nuclides. The other 2400 are radioactive ones that, for the most part, have been artificially produced in particle accelerators or nuclear reactors; about 30 to 40 new ones are discovered each year. Studies of these unstable nuclides provide a wealth of valuable information about exotic nuclear decay modes, about the behavior of the nuclear ground state (mass, shape, and angular momentum) as the neutron-to-proton ratio shifts into highly abnormal regimes, and about the spectroscopic properties of nuclei so strangely composed.

When a nucleus is formed, a small amount of the mass of its constituent nucleons is converted to energy. This becomes the *binding energy* of the nucleus, which overcomes the electrostatic (Coulomb) repulsion between the protons. The more nucleon mass is converted to binding energy, the more stable—and less massive, for a given number of nucleons—is the resulting nucleus. Thus *less* stable nuclei have proportionally *more* mass than more stable ones, and the difference is called the *mass excess*.

Figure 4.4 maps the mass excess for the ground states of the lighter nuclides; the most stable ones, with minimal mass, occupy the *valley of stability*. Nuclides some distance from the bottom of the valley are radioactive, typically decaying by beta decay but also by alpha decay or spontaneous fission. Farther up the slopes, near the edges of stability, it becomes energetically possible for exotic new radioactivities to appear, and several new decay modes have been discovered in recent years.

Exotic Radioactivities

Beta-delayed particle emission—in which a nucleus beta-decays to an excited state of its daughter, which then emits a neutron, proton, or

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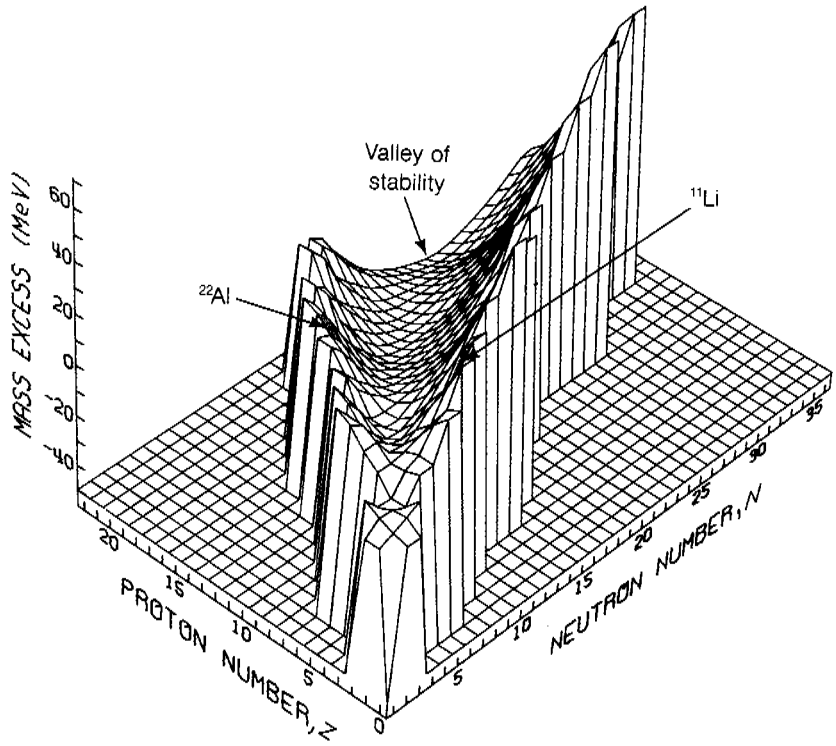


FIGURE 4.4 A computer-graphic plot of the mass excess for nuclides of the elements up to titanium. The greater the mass excess, the less stable the nuclide, so the nuclides on the upper slopes of the valley in this diagram are extremely unstable. Conversely, the nuclides along the bottom of the valley are the most stable of all. The nuclides ^{11}Li and ^{22}Al are discussed in the text. (After J. Cerny and A. M. Poskanzer, *Scientific American*, June 1978, p. 60.)

alpha particle—has been known for several decades. Within the past decade, however, as developing techniques have permitted the observation of predicted nuclides at or near the edge of stability, decay modes have been observed that involve the emission of more than one particle after the beta decay—namely, beta-delayed two-neutron, three-neutron, and two-proton emission.

Consider two representatives of these exotic nuclei, each of which lies at a limit of stability for the element in question. First, on the neutron-*rich* side of the valley, is lithium-11 (3 protons, 8 neutrons, and a half-life of 8.7 msec). This nuclide's decay energy is so high (greater than 20 MeV) that a great variety of decay modes are open, and decays

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by both beta-delayed two-neutron and three-neutron emission have been observed. Since these studies require the detection of neutrons, which is difficult because they are neutral, the parent lithium nuclide is first separated and identified by an ingenious technique developed at the Laboratory for Nuclear and Mass Spectroscopy at Orsay, France. In this technique, the target for the accelerator beam also acts as a preferential collector of product alkali metal nuclei, which in turn—owing to their particular surface-ionization properties—act as the ion source for an attached mass spectrometer.

Second, on the neutron-*deficient* side of the valley, is aluminum-22 (13 protons, 9 neutrons, and a half-life of 70 msec). Here the decay energy is again extremely high (greater than 18 MeV), and a number of decay modes are open, including beta-delayed two-proton emission. A particular beta-decay channel produces the daughter nucleus magnesium-22, which emits two protons that are detected simultaneously. The mechanism for this decay is of considerable interest: is it actually an extremely fast two-step sequential emission of the protons, or does the decay occur by the predicted mode of diproton (helium-2) emission? (The diproton is considered a transient nuclear species.) The angular correlation of the two protons in the aluminum-22 decay has been measured. The mechanism is complex and appears to be largely sequential; however, some component of helium-2 emission cannot be ruled out.

Beta-delayed fission, which is analogous to beta-delayed particle emission, is another exotic form of radioactivity. It allows "ordinary" spontaneous fission studies to be extended to regions far from beta stability, because the beta-delay effect makes these nuclides sufficiently long-lived for experimental measurements. A knowledge of the energy barriers to fission in nuclei far from stability is useful in understanding the production of heavy elements in the astrophysical r-process, one of the principal mechanisms of stellar nucleosynthesis.

In neutron-deficient nuclei at the limits of particle stability, decay by the direct emission of a proton (similar to alpha decay) is possible. This decay mode, direct proton radioactivity, was originally observed in an unusual, long-lived excited state of cobalt-53, a nuclide close to the valley of stability. Ground-state proton radioactivity has recently been observed in two rare-earth nuclides, thulium-147 and lutetium-151. The proton-decay results can provide valuable empirical tests of nuclear models that predict both the masses and the half-lives of the parent nuclei.

A surprising exotic radioactivity was just discovered in 1984. Using a relatively simple laboratory setup, a team of physicists at Oxford

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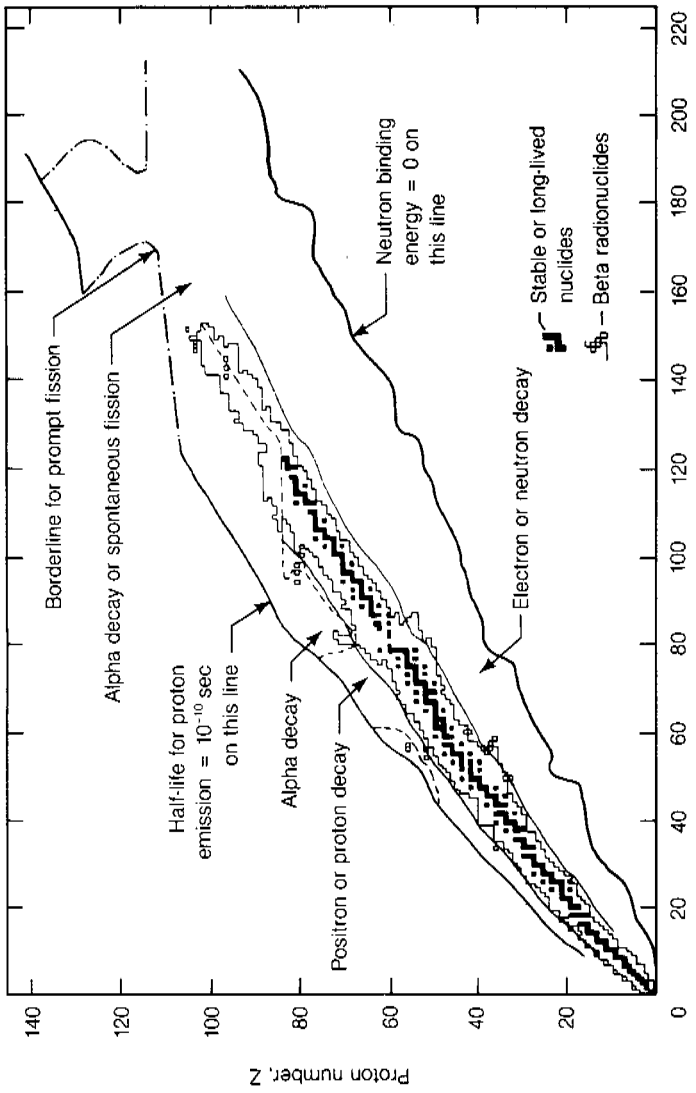


FIGURE 4.5 Chart of the nuclides, showing various kinds of nuclear decay in regions far from the valley of stability. Among the many challenges in current nuclear-physics research is the extension of the boundaries of the region of known nuclides outward in all directions. (After G. N. Flerov, Joint Institute for Nuclear Research, Dubna, USSR.)

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University found that radium-223, which ordinarily decays by alpha emission with a half-life of 11.4 days, occasionally emits a carbon-14 nucleus instead; this occurs about 2 times in every 10^9 decays. That such a novel decay mode should be observed in a naturally occurring nuclide (radium-223 is a member of the radioactive decay series that begins with uranium-235) is particularly significant because it suggests that many other decays by the emission of relatively large nuclei might also be found in nature. Searches for such massive, highly charged decay products (neon-24, for example) are now under way at many laboratories around the world.

Long Isotopic Sequences

One of the best ways to learn about a physical system that can be characterized by two quantities is to change the value of one of them while holding the other one constant. If we vary the proton number Z or the neutron number N while holding the other one constant, we can examine a long series of nuclides whose properties change more or less smoothly from one extreme to another (any of the columns or rows in the map shown in Figure 4.5). This allows models of nuclear structure to be tested critically by their predictions of changes in behavior as Z or N is varied.

Certain values of Z or N are called *magic numbers* because they correspond to the completion of nucleon shells in the shell model of the nucleus. Any nucleus that has a magic (or near-magic) number of protons or neutrons will be slightly more stable than one would otherwise expect, and if it is near stability, it will be spherical. In regions of the chart of nuclides away from the magic numbers, on the other hand, the nuclei will be deformed by varying amounts into a variety of shapes.

It is most interesting and fruitful to follow a long isotopic sequence through the spherical and deformed regions and across the magic numbers; every such sequence crosses the valley of stability in one direction or the other. Generally, deformations in the ground states of nuclei agree rather well with theoretical calculations; the few observations of discrepancies have led to refinements in the theory.

Among the most significant developments in the study of nuclei far from stability has been the increasing use of atomic-beam and laser techniques, which provide extremely accurate determinations of such quantities as the nuclear spin and the magnetic moment. The sensitivity of these methods permits measurements to be made on very small quantities of relatively short-lived isotopes, and long sequences of

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isotopes can thus be studied. Here, on-line mass separators, as employed by the ISOLDE collaboration at the European Center for Nuclear Research (CERN) in Geneva, have made great progress possible.

Nuclei with Extremely High Spin

Nuclear reactions between heavy nuclear projectiles and heavy-element targets often produce compound nuclei that are spinning extremely fast, i.e., they have high angular momentum. Studying these compound nuclei as they de-excite, or relax, to the ground state helps us to understand the interplay among the various forces that control nuclear behavior under such extreme conditions. Among these forces are the centrifugal and Coriolis forces, which are familiar from classical physics. As they increase in magnitude, they affect the nuclear structure in major ways.

The *centrifugal force* tends to stretch the nucleus out into nonspherical shapes involving collective rotations of the nucleons. These deformations, which can be oblate (doorknob-shaped) or prolate (football-shaped), eventually result in nuclear fission. It is the onset of fission, in fact, that generally limits the amount of angular momentum that a nucleus can support. On the Earth, the *Coriolis force*, arising from the Earth's rotation, causes east-west shifts in north-south winds. In a rotating nucleus, the Coriolis force tries to align the spin of an individual nucleon with the axis about which the collective rotations occur, much as a gyrocompass tries to align itself with the Earth's rotation axis. These alignments of the single particles tend to weaken the collective rotations, while the centrifugal stretching tends to stabilize them. It is the interplay between these two opposing effects that makes high-spin phenomena so richly varied.

One such phenomenon, discovered in 1971, came as a complete surprise. In measuring the rate of decrease of the nuclear rotation rate as certain rare-earth nuclides were relaxing from high-spin states, physicists found that the otherwise smooth curves had occasional sharp kinks, or *backbends*. Every such backbend signifies an abrupt *increase* in the rotation rate, followed by a resumption of its steady decrease. This is caused by a sudden internal rearrangement of the nuclear structure that decreases its moment of inertia (the ratio of angular momentum to angular velocity) and hence increases its rotation rate. (A spinning skater, pulling the arms in close to the body, spins faster for exactly the same reason—the law of the conservation of angular momentum.)

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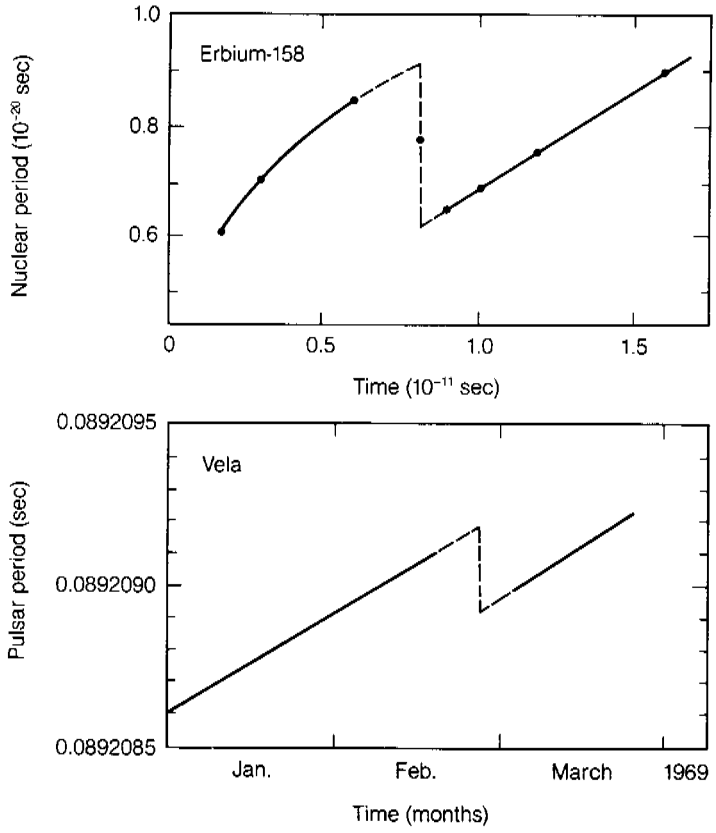


FIGURE 4.6 Plots of the rotation period (the time required for one complete rotation) versus time, for the nucleus of erbium-158 and for the Vela pulsar. (The nucleus is initially in a high-spin state.) In each case, the rotation period increases with time, i.e., the rotation slows down—except when a backbend occurs, as described in the text. (Courtesy of R. M. Diamond and F.S. Stephens, Lawrence Berkeley Laboratory.)

The sudden internal rearrangement of the nucleus could be called a *nucleusquake*. As tiny as it is, it mimics a similar (though unrelated) phenomenon on a colossal scale—the starquakes that were first detected in the Vela and Crab pulsars in 1969. A pulsar is a rapidly spinning neutron star that, like a high-spin nucleus, is slowing down as it loses energy and angular momentum; it is, in fact, very much like a giant nucleus in many ways. Backbends ("glitches" in the jargon of astrophysics) that resemble those of nuclei appear in its rotational decay curve when sudden internal rearrangements in its structure cause the starquakes (see Figure 4.6).

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Although the effects of nucleusquakes and starquakes are the same, the causes are not. Nucleusquakes are related to the pairing correlations of nucleons in nuclei (i.e., the tendency of like nucleons to form pairs with oppositely directed spins) and are proportionally much larger than starquakes. The latter are poorly understood but are now thought to be caused by vortexes in the internal flow pattern of the star. Nonetheless, the similarity between these two phenomena from opposite ends of the cosmic scale provides a striking example of the universality of physical laws and of their power to extend our intellectual grasp of events far beyond ordinary experience.

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II

Impacts of Nuclear Physics

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5

Nuclear Astrophysics

When astrophysicists first realized, in the 1920s, that processes producing enormous amounts of heat and outward radiation pressure must be occurring deep inside the Sun to prevent it from collapsing under its own gravitational field, the study of nuclear physics had only barely begun. The neutron itself was not discovered until 1932, and it was another 6 years before a plausible explanation for the Sun's energy was advanced by nuclear physicists: in a type of reaction called *nuclear fusion*, four hydrogen nuclei combine to form one helium nucleus, with the release (on a stellar scale) of vast amounts of energy. Since that time, a fruitful symbiosis has arisen between nuclear physics and astrophysics, with progress in each field spurring progress in the other. Studies of nuclear reactions in laboratories on Earth tell us a great deal about the birth, evolution, and death of stars, while astrophysical measurements tell us much about nuclear processes that are difficult or impossible to produce on Earth.

Nuclear astrophysics is concerned with the mechanisms of stellar nuclear reactions that generate energy and that lead to the formation of the chemical elements in the process of *nucleosynthesis*. Some of the most active areas of nuclear astrophysics today are concerned with the mechanisms of supernova explosions, where nucleosynthesis of the heavy elements occurs, and the formation of neutron stars. The latter represent nuclear matter under conditions of high temperature and density, from which a unique insight can be gained on the fundamen-

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tally important nuclear-matter equation of state. Perhaps most interesting of all, however, is the neutron stars' status as a kind of ultimate nuclear laboratory: they are the only known "nuclei" in which the effects of all three of the fundamental forces—the strong force, the electroweak force, and gravitation—are intimately interwoven.

In this chapter we look at a few of the most active current topics in nuclear astrophysics research, which epitomize the ways in which progress in basic nuclear physics benefits the development of other sciences and, ultimately, of our technological society as a whole.

NUCLEI UNDER EXTREME ASTROPHYSICAL CONDITIONS

The most extreme condition of matter imaginable existed for only an instant at the beginning of our universe, but a plausible account of this awesome event and its aftermath has been reconstructed from data available today. Among the most important of these data are the known abundances of the chemical elements in the stars and nebulas—and in the Earth itself—because these values impose certain constraints on the theoretical mechanisms by which nucleosynthesis could have occurred. These constraints are based not only on the nature of nuclear reactions as we know them from terrestrial studies but also on the conceivable dynamical processes by which stars can undergo a spectacular death by supernova explosion.

Nucleosynthesis of Light Elements

In the first seconds after the big bang, there were no nuclei—just elementary particles and hadrons. The latter were primarily nucleons, and it was only after about 3 minutes—when the temperature of the nascent universe had cooled to about 10^9 K—that these particles could begin to coalesce to form deuterons (^{2}H) and nuclei of helium-3 and helium-4 (^{3}He and ^{4}He); it now seems possible that nuclei of the isotope lithium-7 may also have formed at that time. These four nuclides are thus the *big bang nuclides*. It took at least half a million years more for the universe to cool sufficiently for these nuclei to capture electrons and become atoms, and a few billion years for stars to form. Only when the stars' nuclear fires began to burn did nuclei of the remaining elements begin to form. In the universe today, hydrogen and helium constitute roughly 93 and 7 percent, respectively, of the nuclei, while all the heavier elements make up only about 0.1 percent.

Although most of the lighter elements are believed to be produced in

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the stellar interiors, a few are too fragile to survive the intense heat and must be formed at cooler sites. These elements are the ones that lie between helium and carbon in the periodic table: lithium, beryllium, and boron. The nuclides in question are ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B, and their observed abundances in the universe can now be accounted for fairly well in terms of a model based on the bombardment of heavier nuclei in the interstellar medium by cosmic rays. In these *spallation reactions*, a very energetic projectile breaks the target nucleus up into several fragments. Measurements of nuclear spallation reactions at cosmic-ray energies have recently become sufficiently extensive to allow a meaningful test of the astrophysical model, and it has been found that these *cosmic-ray nuclides* are produced in roughly their observed relative cosmological abundances.

The four big bang nuclides mentioned above are the only four that can be attributed to that stage of the evolution of the universe. Remarkably, the modern theory of nucleosynthesis can account for the observed abundances of these four nuclides in terms of a single assumed value of the baryon density of the early universe. In terms of the expanding universe, this primordial density would give rise to a present density between 0.6×10^{-31} and 11×10^{-31} gram per cubic centimeter (g/cm^3), a range that neatly brackets the observed density of visible matter, 3×10^{-31} g/cm^3 (see Figure 5.1). For the universe to be *closed*—i.e., for its own gravitational self-attraction to be sufficient to stop the expansion eventually—this density would have to be about 10 times greater. Whether the universe *is* closed is not known, nor is it known where the missing mass, if any, is to be found.

A possible source of the missing mass may be neutrinos—*if* they turn out to have some mass after all. Neutrinos exist in enormous numbers throughout the universe, but a limit can be set on the number of *kinds* of neutrinos (the three now known correspond to electrons, muons, and tauons) from the observed abundance of ^{4}He produced in the early universe. If there were still another (as yet undetected) kind of neutrino—and if it were present in great numbers—it would have added substantially to the overall energy density of the universe during the first 3 minutes, and the universe would therefore have expanded more rapidly. Among other things, this more rapid expansion would have increased the neutron-to-proton ratio, and because most of the neutrons were eventually incorporated into helium nuclei, the result would have been a greater abundance of ^{4}He than is actually observed.

It could be, therefore, that we have already discovered all the kinds of neutrinos that exist in the universe, although a fourth kind cannot be

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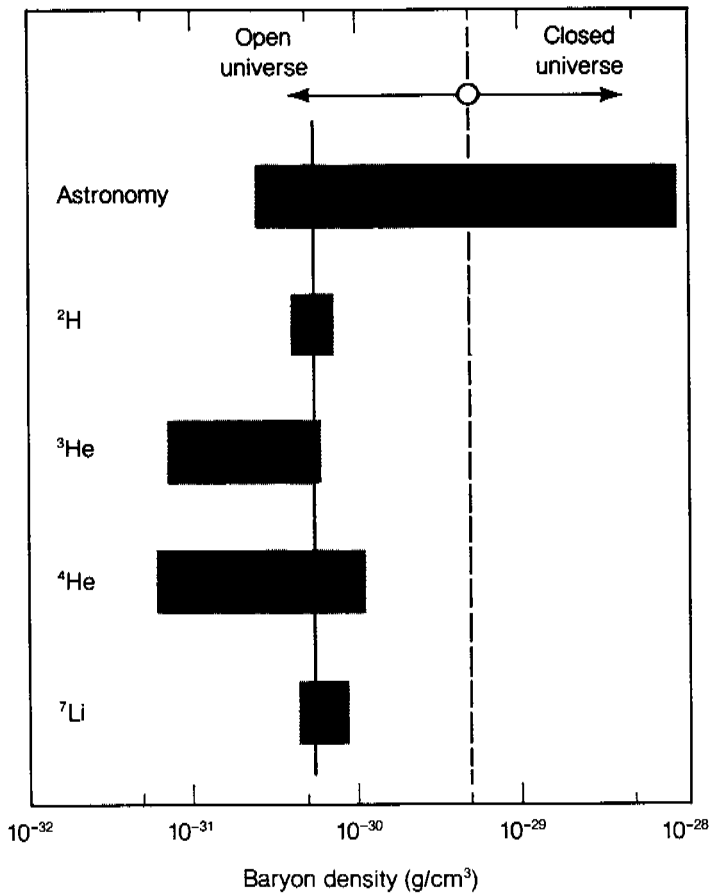


FIGURE 5.1 From the observed abundances of the four big bang nuclides, it is possible to infer the present baryon density of the universe. The shaded bar for each nuclide represents the range of values calculated from its abundance, and the solid vertical line represents the best fit to these data. The inferred baryon density of about 5×10^{-31} g/cm^3 is about 10 times less than that which would be required for the universe to be gravitationally closed (dashed vertical line). Thus, this evidence is consistent with an open universe. (After S. M. Austin, in *Progress in Particle and Nuclear Physics*, Vol. 7, D. Wilkinson, ed., Pergamon Press, Oxford, 1981.)

entirely ruled out. Uncertainties in the observed abundances of the nuclides, as well as certain assumptions in the big bang model that have not yet been validated, make various details of the picture unclear. What *is* clear is that the nucleosynthesis of the light elements is closely connected to fundamental questions of particle physics and cosmology.

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Supernova Explosions and Neutron-Star Formation

The study of supernovas and neutron stars has opened up a new area of nuclear astrophysics and has motivated theoretical and experimental research leading to a deeper understanding of the rich properties of nuclei and nuclear matter, especially at high densities. In ordinary stars, such as our Sun, the inward force of gravity is balanced by the outward hydrodynamic pressure of the hot gases and, to a lesser extent, by the radiation pressure of photons. When their nuclear fuel is exhausted, however, some stars undergo gravitational collapse and then explode as a supernova (see Figure 5.2); a small, extremely dense neutron star may be left as a remnant of this stupendous event. The physics of neutron-star formation and the establishment of a new equilibrium against gravity are intimately tied to the behavior of nuclear matter under extreme conditions. In particular, it now appears that neutrinos play an important role in the mechanism of supernova collapse.

The hydrogen fusion reaction in stars produces two positrons and two neutrinos. Most nuclear matter is almost perfectly transparent to neutrinos, so most of them depart the star, headed for deep space. (Experiments to detect solar neutrinos passing through the Earth are described later in this chapter.) The escaping neutrinos cool the star by carrying away some of its fusion energy, but this energy loss is slight during the middle period of a star's life.

As the star reaches old age and the hydrogen in its interior is consumed, its central temperature will rise, causing the outer layers to expand to form a *red giant*—as our Sun is most likely to do. In later stages of its evolution, the star's interior may collapse, with the release of huge amounts of gravitational energy. As the collapse progresses, the heated nuclei are reformed into much heavier, more neutron-rich species than are normally found in stars. Changing a proton into a neutron, however, requires the capture of an electron, a process that releases a neutrino. (The competing reverse reaction of neutrino capture raises new problems in the study of weak-interaction processes.) The increased neutrino flux produced by the collapsing star increases the rate of energy loss by the star; this, in turn, decreases its internal pressure and hastens the collapse. At a later stage of the collapse, however, neutrinos will become trapped inside the star because of the greatly increased mass density of the star, which decreases its transparency to neutrinos; this trapping inhibits further electron capture and halts the synthesis of heavy elements.

As the nuclei become crushed together by the colossal gravitational

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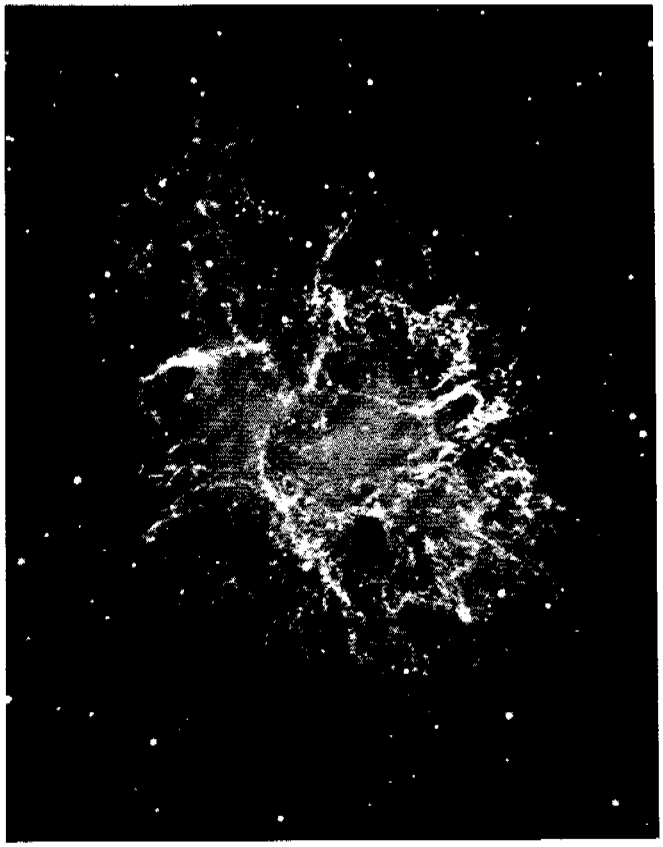


FIGURE 5.2 The Crab nebula, about 5 light-years in diameter with a neutron star at its center, is believed to be the remnant of a supernova explosion that was observed and recorded by Chinese and Japanese astronomers—and also, perhaps, by North American Indians—on July 4, 1054. It remained visible to the naked eye, in the constellation Taurus, for almost two years. Why there is little evidence of its having been chronicled by European or Arabic astronomers is a matter of conjecture. (Courtesy of the Lick Observatory, University of California.)

field, the supernova collapse is eventually halted by the repulsive part of the strong force at very short internucleon distances. One effect of this compression to about twice normal nuclear density is an intense, rebounding pressure wave that forms a gigantic, outward-moving shock wave. The shock wave is believed to be principally responsible for the supernova explosion that blasts the outer mantle and envelope of the star into space. Understanding the propagation of the shock

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wave is complicated, however, by the dissociation of nuclei as the shock passes through them—a process that dissipates some of its energy.

Many other aspects of this model are not yet clear. The ability of the shock wave to blast away the outer layers, for example, depends critically on the temperature, density, and composition of the original star; these factors are, in turn, highly sensitive to the rates of electron capture by the various nuclei present and to the rate of cooling by the accompanying neutrino emission. Refining the model is hampered by inadequate knowledge of the properties of nuclei and of the equation of state of hot, dense nuclear matter. Predicting the amount of energy transmitted to the outer layers, for instance, requires an accurate equation of state. A key parameter, the compressibility of nuclear matter, is known for ordinary nuclear density (2.5×10^{14} g/cm^3) from observations of the giant monopole resonance, as discussed in Chapter 2. Relativistic heavy-ion collisions can reach the regime of densities (up to 10^{15} g/cm^3) existing in supernova collapse, but such experiments have only recently begun (see Chapter 4).

The supernova shock wave forms outside a central core of about one solar mass, so the explosion of a very massive star leaves behind only a small fraction of its mass as a remnant. If the mass of the remnant is less than about 2.5 solar masses, the remnant becomes a small, dense, rapidly rotating neutron star, of the order of 10 km in diameter; more massive remnants become black holes and disappear from direct view.

A neutron star can make its presence known to us by electromagnetic radiation as a *pulsar* or *compact x-ray source*. Neutron stars can also be detected indirectly, if they perturb the motions of a visible star with which they are associated in a *binary system*. To date, well over 300 neutron stars have been identified in our neighborhood of the galaxy, and some black holes may also have been detected indirectly.

Weak-Interaction Processes in Supernovas

As far as we know, the conditions required for the nucleosynthesis of heavy elements occur only in supernovas. All the gold and uranium found on the Earth today, for example, may have come from a single supernova whose cast-off outer layers were swept up into the interstellar gas cloud that eventually evolved into our solar system. Although the nuclear reactions in supernovas are dominated, as in all other forms of nuclear matter, by the strong force, it is also crucial to a description of supernova dynamics to understand the key weak-interaction pro-

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cesses that occur there. One such process is *electron capture*, or inverse beta decay.

Electron-capture rates by nuclei under conditions of high temperature and density appear to be dominated by excitation of the Gamow-Teller giant resonance (see Chapter 2) in the product nucleus; here the values of both the spin and the isospin of the nucleus are simultaneously flipped as a proton is transformed to a neutron upon capturing the electron. Calculated rates based on this picture provide not only information necessary for constructing supernova models, but also a self-consistent analysis of the electron-capture process through the region of moderate atomic mass numbers from 21 to 60. To supplement this work experimentally will require high-energy neutron beams having a narrow spread in energy. The purpose of such beams would be to excite and study the Gamow-Teller resonance in those nuclei that result from electron capture in the corresponding stellar reactions.

The extremely neutron-rich nuclei produced in supernovas can be far from the relatively narrow valley of nuclear stability described in Chapter 4; indeed, the last neutron may be bound so weakly that it is almost ready to "drip" from the nucleus. Recent theoretical work on beta decay of nuclei far from stability has emphasized the role of the spacing of highly excited energy levels in the product nucleus. The half-life for beta decay is quite sensitive to this quantity, and the half-lives are a crucial ingredient for calculating the production of heavy elements in supernovas.

Recently refined beta-decay calculations lead to relative nuclear mass abundances that match measured values extremely well. The abundances of these heavy elements and their decay products can also be used to estimate the age of the universe (actually, the age at which heavy-element production began), using the calculated beta-decay half-lives and updated beta-delayed fission rates. The result obtained is about 20 billion years, which is not inconsistent with the value of 15 billion to 18 billion years, derived for the age of the oldest globular clusters (using the theory of stellar evolution), or with the value of 13 billion to 18 billion years, derived from the rate of expansion of the universe.

NUCLEAR REACTIONS IN STARS

Modern experimental and theoretical techniques have provided a great deal of information on many of the nuclear reactions that generate energy and synthesize elements in the stars. In our own Sun, for example, the main path to hydrogen fusion starts with the p-p reaction,

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in which two protons react to form a deuteron by emitting a positron and a neutrino. Our Sun, being the nearest star, is naturally the most thoroughly studied. An indirect way of checking the validity of models of solar structure and dynamics is to compare calculated results with measured physical properties of the Sun or with measured abundances of the elements.

The Solar-Neutrino Problem

About 25 years ago, an improved understanding of neutrino interactions led to the suggestion of a relatively direct way of observing nuclear reactions taking place in the Sun's core: use an earthbound detector to measure the flux of neutrinos released by these reactions. Because neutrinos interact only via the weak force, they stream relatively unimpeded from the Sun's center and offer us a glimpse of the processes occurring there. Photons, by contrast, undergo the much stronger electromagnetic interaction with the solar material, and it takes them about 10^7 years to wend their way from the Sun's center to its surface.

In 1970 a solar-neutrino detector built by Brookhaven National Laboratory began operating in a South Dakota gold mine, a mile underground to help shield against cosmic-ray background counts. In experiments carried out during the past 14 years, the average counting rate has been about three neutrino captures per week, roughly one fourth the rate predicted by solar models. The discrepancy, which is still unresolved, is called the *solar-neutrino problem*.

Solar-neutrino detectors are based on a nuclear process, related to beta decay, in which a nucleus absorbs a neutrino and transforms to a daughter nucleus by emitting an electron. In the Brookhaven radiochemical detector (see Figure 5.3), the target nucleus is chlorine-37 (^{37}Cl), in the form of 100,000 gallons of perchloroethylene cleaning fluid. The daughter nucleus, argon-37 (^{37}Ar), is a gas, which is relatively easy to sweep out of the liquid and measure. The reaction in question, however, requires a minimum neutrino energy of 0.81 MeV. Unfortunately, this restriction makes the detector insensitive to the p-p reaction, which provides 90 percent of the total solar-neutrino flux but whose neutrinos have a maximum energy of only 0.42 MeV.

An analysis of relevant nuclear reactions shows that 80 percent of all the neutrinos that *should* be detected by the ^{37}Cl come from a minor solar reaction (about 0.01 percent of the total) in which a proton reacts with beryllium-7 to produce boron-8, which then decays to beryllium-8 by emitting a positron and a neutrino with a maximum energy of 14

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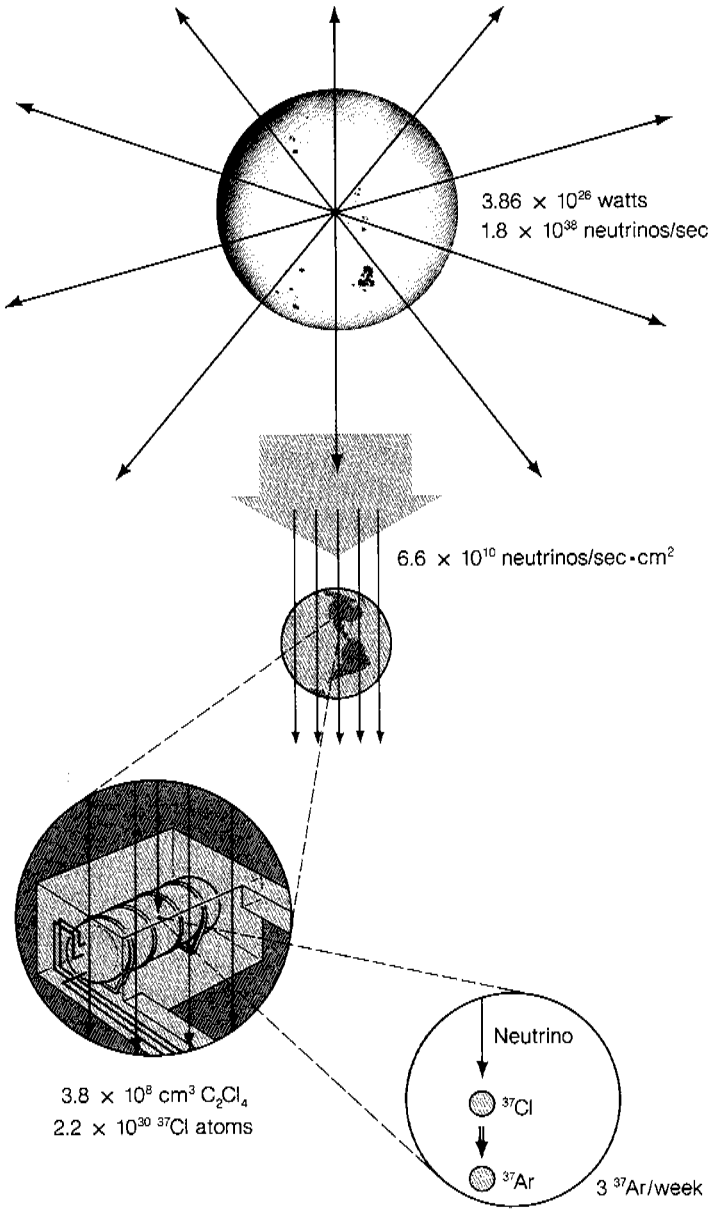


FIGURE 5.3 The solar-neutrino experiment being conducted in a South Dakota gold mine (see the text for details). Of every 10^{22} neutrinos that pass through the 100,000-gallon tank of perchloroethylene, fewer than one interacts with a ^{37}Cl nucleus. Each such interaction produces a ^{37}Ar atom, which can be extracted and counted. The counting rate of about three neutrino-produced events per week is about one fourth the expected rate.

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MeV. The selectivity of the ^{37}Cl detector for this minor reaction is actually an advantage for solar diagnostics, however, because the reaction (unlike the p-p reaction) sensitively reflects conditions at the core of the Sun.

The solar-neutrino problem represents the only major failure of the otherwise extremely successful standard solar model, and this discrepancy between the predicted and measured neutrino counting rates has prompted critical re-examinations of various aspects of solar physics and nuclear physics. The nuclear-reaction rates in question have been substantiated by new results in many laboratories. It has also been suggested that the electron neutrinos, on their way to the Earth from the Sun, may undergo neutrino oscillations to their muon or tauon counterparts, as discussed in Chapter 3. There is no real evidence for this, however, and the problem remains under investigation.

The next logical step would seem to be the construction of detectors having target nuclei that could respond to other parts of the predicted solar-neutrino spectrum. The proposed detector currently receiving the most attention is based on gallium-71 (^{71}Ga), which produces germanium-71 (^{71}Ge) upon reacting with a neutrino. The ^{71}Ga detector has the advantage that most of its counts (63 percent of the total) would be due to neutrinos from the p-p reaction, which is the basic reaction responsible for the Sun's luminosity.

The neutrino flux from the p-p reaction is relatively insensitive to detailed conditions inside the Sun. Therefore, if the measured counting rate in the ^{71}Ga detector were still less than the predicted rate, we would be left with only two possible explanations: either (1) some form of neutrino oscillation or decay occurs between the center of the Sun and the Earth, or (2) the Sun is producing energy through some nonequilibrium process (so that it is currently producing less energy than it is radiating). Conversely, if the measured and predicted counting rates *were* in agreement, we could infer a limit on the neutrino mass differences of approximately 10^{-6} eV or less, and we could verify that the Sun is currently producing energy at a rate consistent with its observed luminosity, although this fact alone could not rule out the possibility of nonequilibrium processes.

Tests on a pilot detector made with 1.8 tons of gallium have shown an efficiency of 95 percent or better for collecting the ^{71}Ge reaction product; at present, it is estimated that a full-scale detector would require between 15 and 30 tons of gallium. Meanwhile, various other possible detectors are under consideration, including two that would be able to measure the solar neutrinos directly. One of these would be able to measure both the energy and time of interaction of a given neutrino,

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and the other would be able to measure these quantities as well as the direction of arrival of the neutrino.

Stellar Evolution

As a star evolves from youth to old age, its primary energy-generating reactions shift from hydrogen fusion to other processes involving progressively heavier elements. An understanding of stellar evolution therefore requires a thorough study of the corresponding nuclear reactions. Recent interest in stellar energy generation and nucleosynthesis has been focused on these later stages of stellar evolution. In a red giant star, for example, a primary process is the fusion of three ^{4}He nuclei (alpha particles) to form carbon-12 (^{12}C), a process called *helium burning*. Some of the ^{12}C nuclei can react further with ^{4}He to form oxygen-16 (^{16}O), so that the ratio of ^{16}O to ^{12}C from nucleosynthesis depends on the reaction rate of ^{12}C with ^{4}He relative to its rate of formation through helium burning. There is currently a discrepancy by a factor of 2 between different laboratory measurements of the ^{4}He plus ^{12}C reaction, which needs to be resolved by further experiments.

Considerable work has been done recently on stellar nuclear reactions involving aluminum and magnesium, triggered by the discovery in 1976 that aluminum mineral inclusions in the Allende meteorite contain an excessive proportion of ^{26}Mg relative to the other magnesium isotopes. The excess ^{26}Mg is directly proportional to the amount of aluminum present; this leaves little doubt that the excess ^{26}Mg is the decay product of radioactive ^{26}Al, which has a half-life of only 7.2×10^5 years. Recently, gamma rays from the decay of ^{26}Al in the interstellar medium have been identified with high-resolution detectors in orbiting satellites. These observations point to the presence of a substantial amount of ^{26}Al distributed in the plane of our galaxy and suggest that the most likely source of this material is from nova explosions. This is consistent with recent nuclear-physics measurements that suggest that red giant stars and novas are more likely sources of ^{26}Al than are supernovas.

Another example of the value of nuclear physics in furthering our understanding of stellar evolution is that of very hot stars, such as *white dwarfs*. Here certain radioactive nuclear species—both ground states and long-lived excited states—are important in nucleosynthetic reaction cycles even though their half-lives are relatively short. For example, the reaction of a proton with nitrogen-13 (half-life 9.97 minutes) to give oxygen-14 (half-life 70.6 seconds) forms part of the

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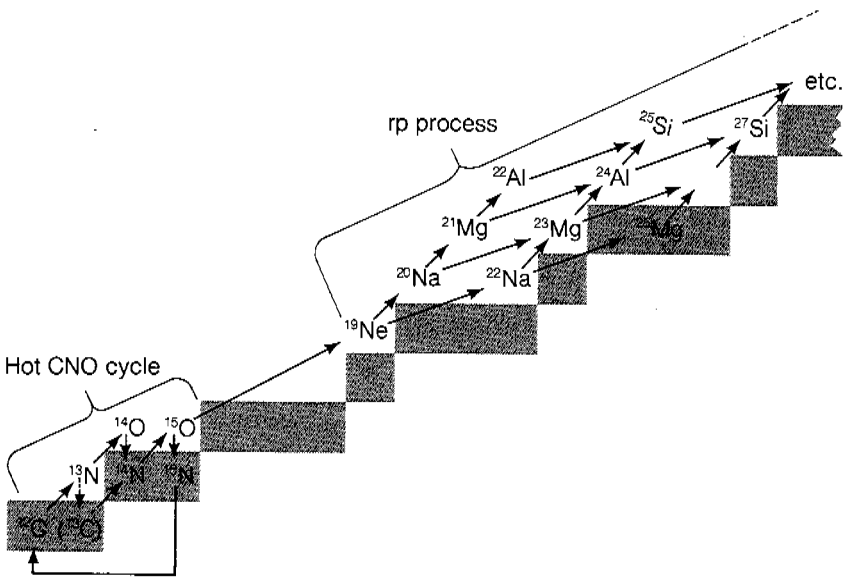


FIGURE 5.4 Series of nuclear reactions such as the hot CNO cycle and the rp (rapid proton capture) process occur on time scales that are short compared with the half-lives of nuclides such as ^{13}N (10 minutes) and ^{19}Ne (17 seconds). These explosive phases of nucleosynthesis are thought to occur on the surfaces of white dwarfs and neutron stars that are accreting fresh hydrogen on their surfaces. They may be responsible for novas, which occur at a rate of about 25 per year in our galaxy.

so-called *hot CNO cycle* (carbon, nitrogen, oxygen; see Figure 5.4). Studying such reactions experimentally is technically very challenging, requiring the production of intense secondary beams of radioactive nuclides. At least four different methods have been proposed for producing the required beams. This technical capability would provide important information for astrophysical processes, and it would also open up the possibility of investigating otherwise inaccessible nuclear reactions.

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6

Scientific and Societal Benefits

Nuclear physics presents a remarkable paradox: its awesome technological progeny, nuclear power and nuclear weapons, are among the most well-known and hotly debated topics of our age, yet the physics of the nucleus itself is possibly the least understood of the basic sciences. This is all the more puzzling in light of the profound impact that nuclear physics has had on the development of the other sciences as well as on countless areas of modern technology. From solid-state physics to molecular genetics, from food technology to forensic medicine, from mineral prospecting to cancer therapy, the principles and techniques of nuclear physics are applied in ways far too numerous to survey comprehensively in a book of this size.

In this chapter we touch on a few applications of nuclear physics that reflect its broad impact on science and technology. Although these applications cannot evoke the cosmic themes of nuclear astrophysics, discussed in the preceding chapter, the benefits they confer on a technological society are both more immediate and more tangible—even if we tend to take many of them for granted. It is noteworthy that most of these applications are derived from research carried out at low-energy facilities, which have provided much of the basis for our present understanding of nuclear physics.

Implicit in our discussion of the impact of nuclear physics, of course, is the realization that it is a two-way street. Many advances in nuclear physics, for example, depend critically on state-of-the-art accelerator

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technology, which hinges, in turn, on new developments in solid-state electronics, physical chemistry, materials science, cryogenic engineering, and computer-aided design, to name a few. Theoretical nuclear physics, which contributes much to our understanding of the basic forces that govern all natural phenomena, likewise benefits greatly from the development of physical concepts and mathematical methods in other disciplines as well as of faster, more powerful computers.

CONDENSED-MATTER PHYSICS

The condensed phases of ordinary matter—solids and liquids—exhibit an enormous diversity of form and function, owing in part to the great variety of the chemical elements and the types of chemical bonding that they undergo. Atomic and molecular interactions are purely electromagnetic, which simplifies the description of solids and liquids compared with that of nuclear matter. In analogy with nuclear matter, however, there can be a variety of cooperative motions of large numbers (here, essentially infinity) of interacting particles, whose net effect—superconductivity, for example—transcends the underlying properties of the particles. Much of the richness of solid-state phenomena, in particular, is due to such cooperative effects.

In probing the structure and behavior of ordinary solid matter (typically, crystals), physicists have found that accelerated nuclear beams are extremely useful, since nuclei (ions) of almost every element can be implanted into a chosen crystal lattice to any desired depth. The value of this *ion implantation* technique for solid-state physics research lies in studies of the ensuing *hyperfine interactions*: subtle interplays between the electromagnetic properties of the implanted ions and the electron configuration of the crystal. Such studies can reveal details of the crystal's vibrational modes and of its microscopic magnetic and electrostatic properties. One can also study aspects of the crystal structure, such as the locations and mobilities of impurities, as well as the radiation damage caused by the implanted ions, the healing of this damage through heat treatment, and the effect of the ions on the crystal's electrical conductivity.

Information obtained by the ion-implantation technique and by other techniques derived from nuclear-physics research, such as *perturbed angular correlations*, is of great value in developing new materials—magnetic compounds and alloys, for example—with properties that are tailor-made for specific purposes.

Another phenomenon of solid-state physics that makes use of nuclear physics techniques is the *channeling* of charged particles in

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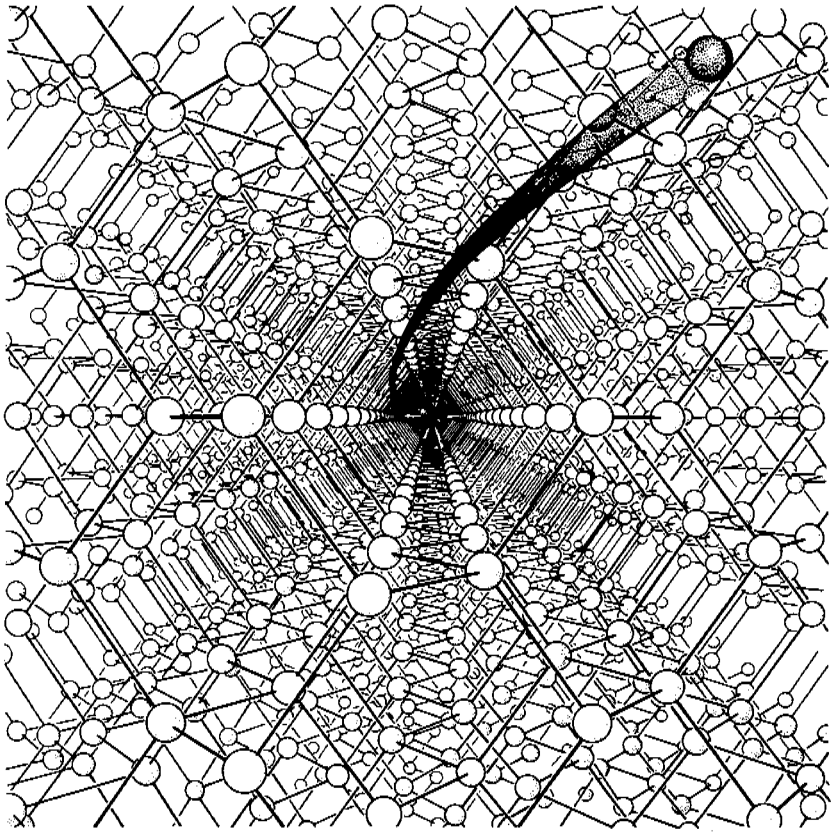


FIGURE 6.1 Artist's conception of the channeling of a positively charged particle in a diamondlike crystal lattice. The particle typically follows a spiral path that actually consists of a series of oblique ricochets from lattice nuclei along the channel, caused by the repulsive Coulomb force between the particle and the nuclei. The distance traveled by the particle in one turn of the spiral is of the order of 100 interatomic distances. (From W. Brandt, *Scientific American*, March 1968, p. 91; © 1968 by Scientific American, Inc.)

crystals. Here the energetic projectiles bombarding the surface of the crystal are found to be channeled through the tunnels formed by adjacent rows of atoms in the lattice structure (see Figure 6.1). Studies of the behavior of charged particles as they are channeled—or sometimes blocked—inside crystals have yielded much information on surface conditions and the locations of impurities, for example. These studies can reveal a much deeper level of detail than that provided by

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even the best electron microscopes. They are particularly useful in evaluating the effects of radiation damage in solids.

Research on channeling is now being conducted at many accelerators around the world, including the highest-energy ones. There is apparently no practical upper limit to the kinetic energy of charged particles that can be made to channel in crystals. Relativistic effects associated with extremely high velocities are being exploited in order to measure ultrashort time intervals, in an effort to determine the lifetimes—down to perhaps 10^{-20} second or even less—of some elementary particles. An intriguing offshoot of these experiments was the discovery that by bending the crystal, even the most highly relativistic particles—at energies of hundreds of GeV—can be made to follow curved paths; to bend such particle beams through equivalent deflection angles in an accelerator would require immensely powerful superconducting magnets.

The *positrons* emitted by some radioactive elements have been used for many years as a sensitive probe with which to map the charge and energy distributions of electrons in solids. In recent years, however, the intense, high-quality beams of *muons*, both positive and negative, developed at nuclear-physics laboratories have proved to be even more versatile than positrons in the study of solids. Muons are heavy leptons—much heavier than electrons or positrons, but much lighter than nucleons. This intermediate mass alone makes them a valuable probe with which to study solid-state phenomena such as particle diffusion. Their characteristic decay properties are also valuable.

In addition, muon beams have the useful property of being almost 100 percent spin-polarized, i.e., their spins are all oriented in the same direction. This property provides the basis for the technique of *muon spin rotation*, in which the changing direction and gradual degradation of the spin polarization are monitored after the beam is injected into a crystal. The rate and degree of these changes provide information about the muons' local magnetic environment, at any of several kinds of sites within the crystal lattice.

As a local probe of solid-state structure and dynamics, muon spin rotation nicely complements several other techniques derived from nuclear physics, such as *nuclear-magnetic-resonance spectroscopy*, *Mössbauer spectroscopy*, and *neutron scattering*. These last three are also used, to varying degrees, by chemists, biologists, geologists, and others in countless analytical applications. The influence that nuclear physics exerts in these sciences is far-reaching and beneficial.

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ATOMIC PHYSICS

Although every atom contains a nucleus, many of the physical properties of the atom are determined by its cloud of orbital electrons. The electrons interact not only with each other (through the repulsive Coulomb force) but also with the electric and magnetic fields of the nucleus. As the properties of nuclei vary throughout the periodic table or through an isotopic sequence of a given element, so, to different degrees, do the characteristic features of the associated optical spectra of the atoms, which are determined by the electron energy levels and the transitions between them. For many years, much information about nuclear properties has been deduced from analyses of atomic spectra.

Now, however, with nuclear accelerators that can produce ion beams of precisely controllable energy and ionization state, it is possible to create exotic atomic species unlike any that exist under ordinary conditions, and thus to use nuclear beams to study novel aspects of atomic physics. Such experiments and the corresponding atomic-structure calculations are interesting in their own right. They also have a direct bearing on our understanding of the nature of thermonuclear fusion plasmas—both in stellar interiors and in terrestrial machines such as tokamak fusion reactors.

In collisions between very heavy ions (uranium and curium, for example, for which the combined Z value is 188), a massive nuclear system can be created that exists long enough for the electrons of the two ions to rearrange themselves in a configuration corresponding to the combined Z value. In the formation of this extremely high-Z pseudo-atom, however, a vacancy is sometimes created in the lowest electron shell. This shell becomes tightly bound while the nuclei are close together, and if the vacancy is filled during this period, the effect is formally equivalent to the creation of a positron. Recently positrons have, in fact, been detected in heavy-ion collisions at the GSI accelerator in Darmstadt, West Germany. Surprisingly, one observes a discrete structure superimposed on a continuum spectrum. The origin of the sharp features in this structure is a mystery. Speculations have arisen as to whether it is due to the formation of relatively long-lived giant nuclear complexes or to some hitherto unknown physical phenomenon.

In a different kind of atomic-physics experiment, accelerated heavy ions are stripped of most of their electrons by passing the beam through thin films or low-pressure gases. Careful stripping can yield heavy nuclei with only one orbital electron (a hydrogenlike ion) or two electrons (a heliumlike ion). These species thus exhibit a huge imbal-

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ance between the positive nuclear charge and the surrounding negative electron charge. Studying their atomic spectra affords a unique opportunity for making stringent tests of some of the predictions of quantum electrodynamics (QED), the quantum field theory of the electromagnetic interaction. One of these predictions concerns a fundamental but subtle spectroscopic effect called the *Lamb shift*, which can be measured with great accuracy. To date, all measurements of the Lamb shift in hydrogenlike ions (e.g., one-electron chlorine) and heliumlike ions (e.g., two-electron neon) have confirmed the correctness of QED.

It is also possible to strip all the electrons from an accelerated ion, leaving a bare nucleus as the projectile. In 1982 the production of relativistic beams of fully stripped uranium (U^{92+}) was demonstrated at the Bevalac accelerator at the Lawrence Berkeley Laboratory. Also recently, very-low-energy, fully stripped heavy ions have been produced at the Double Tandem facility at Brookhaven National Laboratory. Collisions between these slow nuclei and target atoms produce relatively long-lived, very heavy pseudo-atoms. The study of x rays resulting from such collisions is expected to provide a better understanding of the processes that are critical for the production of superheavy atoms and to enable further tests to be made of the attendant QED phenomena in very heavy atomic species.

The experiments described above illustrate only a few of the ways in which the techniques of nuclear physics have expanded the boundaries of atomic physics, thereby both broadening and deepening our understanding of this vital subject.

GEOLOGY AND COSMOLOGY

Ancient objects—whether man-made or natural, whether of geological or cosmological origin—are fascinating to scientists in many fields because of the invaluable clues they provide about the nature of the environment in which they were formed. Along with the chemical and, sometimes, microbiological analyses of such objects, their accurate dating is clearly of great importance. The familiar technique of radiocarbon dating (using carbon-14, which has a half-life of 5730 years) was one of the earliest practical applications of nuclear physics. It has proved to be of inestimable value in archeology and paleontology, enabling scientists to date events that occurred as far back as 50,000 years ago. Similar measurements of the decay products of other long-lived radionuclides have extended the applicability of the technique.

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Another dramatic advance in dating technology has taken place in the last few years, again as a spinoff of basic nuclear-physics research. Various heavy-ion accelerators around the world have been modified for use as ultrasensitive mass spectrometers, in which the atoms of long-lived radionuclides in the sample of interest are counted directly, rather than indirectly (and slowly) by detecting the radiations associated with their decay. The immediate result of this ability to circumvent the tedious process of radiation monitoring of specimens has been a spectacular increase in the sensitivity of dating measurements—by a factor of as much as 10^{12}! This sensitivity, in turn, allows the use of much smaller samples (in the range of micrograms to milligrams) than before.

Thus the technique of *accelerator mass spectrometry*, still in its infancy but developing rapidly, has vastly enlarged our scientific window on the past. Among the growing list of subjects being investigated with this powerful new tool are atmospheric methane, polar ice, lake and ocean sediments, manganese nodules, tektites, meteorites, and long-lived radionuclides produced by cosmic rays.

Geophysicists, paleoclimatologists, cosmologists, and others have much to gain from such studies, which reveal new information on changes that have occurred both on the Earth and outside the Earth over periods ranging from thousands to tens of millions of years. Already it has been learned, for example, that some manganese nodules on the ocean floor have grown at a uniform rate (of the order of a few millimeters per million years) for as long as 10 million years, whereas others have grown at sharply different rates during different periods of geologic time. The latter phenomenon suggests that significant changes in the manganese and iron content of local undersea growth environments have occurred at certain times in the past.

Another interesting discovery from the deep is that ocean sediments at plate-tectonic boundaries are not scraped off during the subduction process, in which the edge of one crustal plate is bent downward and very slowly slides beneath the edge of the other. Instead, the sediments are carried down with the subducting plate, eventually to reappear in volcanic eruptions in these geologically volatile areas. The radionuclide whose atoms were counted in these studies, as in those of the manganese nodules, was beryllium-10, which has a half-life of 1.6×10^6 years; it thus allows the dating of events that occurred over the last 10 million to 20 million years. Similarly useful in geochronological studies over an even greater time scale are the radionuclides manganese-53 and iodine-129 (half-lives of 3.7×10^6 years and 1.6×10^7 years, respec-

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tively), whereas aluminum-26 (half-life of 7.2×10^5 years) is useful over a time scale of a few million years.

Of obvious scientific interest are any objects, such as meteorites and cosmic rays, that reach the Earth from outer space. Until recently, it was thought that most tektites—strange, glassy objects that have been found widely distributed on land and under the seas—were of extraterrestrial origin. However, a careful comparison of their nuclidic compositions with those of terrestrial and extraterrestrial rocks, using accelerator mass spectrometry, has now made it certain that tektites are terrestrial objects after all. Whatever the ultimate significance of this fact may prove to be, its discovery exemplifies part of the excitement of scientific research—knowing that progress will be made, but never knowing exactly from which quarter the breakthrough will come.

NUCLEAR AND RADIATION MEDICINE

For many years, nuclear physicists have been collaborating with physicians, chemists, pharmacologists, and computer scientists in a highly successful effort to solve some of society's most pernicious health problems. Their efforts have firmly established nuclear medicine as a standard part of modern medical practice. While the most widely applied techniques of nuclear medicine entail the use of radioactive tracers to diagnose diseases and monitor their treatment, radionuclides and accelerated particle beams also play important therapeutic roles. In addition, nuclear physics serves medical science through the development of exotic materials for use in prosthetic implants.

In a typical nuclear-medicine examination, of which many millions are performed annually, a radiopharmaceutical agent is administered intravenously, and gamma rays emitted by the tracer nuclide are recorded with an array of radiation detectors positioned about the patient; this technique is called *emission tomography*. The tracer compounds are usually chosen for their selective uptake by a particular organ or type of tissue so that the detected gamma rays provide a detailed image of the region of interest. Advances in detector design and in data acquisition and analysis have led to markedly improved instruments for emission tomography of both the photon and positron types (see Figure 6.2). To the trained eye, the images produced can reveal structural or metabolic abnormalities whose recognition can lead to a diagnosis that might otherwise be more difficult or even impossible.

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FIGURE 6.2 A computerized tomographic (cross-sectional) image of the human brain, showing regional metabolic demand for oxygen. A few seconds after the subject inhaled oxygen labeled with the positron-emitting radionuclide ^{15}O (half-life of 122 seconds), the distribution of oxygen in the brain was revealed (bright areas) by gamma rays resulting from annihilation of the positrons with electrons in the surrounding tissue. The technique of positron-emission tomography has become a powerful tool of nuclear medicine. (Courtesy of R. J. Nickles, University of Wisconsin.)

The recent development of the radionuclide thallium-201 from the research stage to commercial production for worldwide clinical use provides an illustration of how progress results from multidisciplinary investigations. One out of every six Americans is afflicted with cardiovascular disease, often undiagnosed, and over 70,000 deaths from heart attacks occur in the United States each year. Until about 10 years ago, the available tracer nuclides for early diagnosis of cardiovascular disease were generally unsatisfactory. Following the demonstration that after thallium is administered it is rapidly and selectively

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localized in the heart muscle, however, nuclear scientists devised techniques for producing pure thallium-201 (half-life of 73 hours) in commercial quantities at affordable cost. As a result, nuclear cardiology tests using this nuclide were administered to some 250,000 patients in 1981.

An even more impressive example of progress in nuclear medicine is the development of the radionuclide technetium-99m (a metastable excited state of technetium-99, with a half-life of 6 hours) over the last two decades. Radiopharmaceuticals incorporating this nuclide have proved to be invaluable for studying the brain, liver, thyroid, lungs, skeletal system, kidneys, heart, and hepatobiliary system. About 5 million patient studies using technetium-99m were performed in the United States in 1981.

Roughly half of the 850,000 new cases of cancer that occur in the United States each year receive radiation therapy, either alone or in conjunction with surgery or chemotherapy. The effectiveness of radiation therapy can be increased by improving both the dose localization and the biological effect of the delivered dose. Either of these will result in proportionally more damage to the tumor and less damage to normal tissue. Improved dose localization can be achieved by using accelerated beams of charged particles such as electrons, protons, heavy ions, and negative pions. Biological effectiveness depends in part on the stopping power of the tissue for the particle in question and can be increased by using the particle in its characteristic stopping region.

Nuclear physics contributes in a number of ways to this research. A thorough understanding of nuclear as well as atomic phenomena is required not only for determining the optimal type and energy of the primary beam, the production target material, and the shielding requirements but also for calculating dose distributions. Because of the slim margin between the responses of tumors and normal tissues, differences as small as about 5 percent in dose must be carefully monitored and controlled for proper treatment. In therapeutic radiology, as in nuclear medicine, progress depends on close collaboration among physicists, chemists, and physicians, with the additional requirement of coordinated advances in accelerator physics and instrumentation. For example, the improved design of compact, relatively inexpensive linear accelerators has led to their widespread use in clinical x-ray and electron-beam radiotherapy.

A final example in this abbreviated survey of ways in which nuclear physics is contributing to medicine concerns some new work on surgical alloys used for articulating orthopedic implant devices, such as

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artificial hip joints. Over 75,000 hip-joint replacement operations are performed in the United States each year. Unfortunately, with prolonged use, these joints are subject to gradual deterioration caused by the corrosive effects of normal body fluids; the resulting metallic debris can then poison and inflame the surrounding tissues. This can necessitate a second replacement of the joint—an obviously undesirable prospect.

Recently, however, materials scientists have taken a major step toward solving this problem. Using ion-source and accelerator technology originally developed by nuclear physicists for basic research, they have found that the implantation of nitrogen ions to a concentration of 20 atom percent to a depth of about 100 nanometers (100×10^{-9} meter) into the surface of a typical surgical alloy reduces the wear corrosion by a factor of at least 400. The successful clinical application of these new results could be of great benefit to patients requiring artificial articulating joints.

MATERIALS MODIFICATION AND ANALYSIS

Armed with ion sources, accelerators, and instruments developed in low-energy nuclear-physics research, investigators in numerous disciplines are using energetic ion beams to modify and study the near-surface properties of materials in highly selective and often unique ways. When these beams stop in 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.

Perhaps the most impressive application of ion implantation arises in solid-state electronics. Most semiconducting devices require the selective doping of silicon or germanium crystals with impurity atoms, and ion implantation has rapidly become the dominant doping technique in the semiconductor industry. Among its many advantages is that it permits extreme miniaturization; consequently, most semiconductor devices and integrated circuits for watches, calculators, computer chips, and other electronic porducts requiring small components are fabricated by this method.

Ion implantation has also been exploited in a myriad of other applications. Controlled ion damage to insulators and semiconductors is used to alter the index of refraction of such materials for the fabrication of optical waveguides and mixers and to modify magnetic-bubble memory devices selectively. Ion implantation holds promise as

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a fabrication method for high-temperature superconducting materials, since these require the formation or stabilization of a metastable phase that need exist only within a few tens of nanometers of the surface. Ion bombardment has also recently been discovered to be effective in bonding thin films to substrates.

Studies of the dynamic behavior of light impurities such as hydrogen and helium embedded in materials—and of the changes in the properties of materials induced by the presence of these impurities—have been carried out in recent years with new accelerator-based techniques. The depth distribution of the impurity can be precisely mapped by making use of the sharp resonance behavior of nuclear reactions as a function of the incident beam energy. These reactions, using ion beams such as lithium-7, boron-11, nitrogen-15, fluorine-19, and chlorine-35, have very fine depth resolution (about 5 nanometers) and high sensitivity (better than 1 part per million). Problems for which this technique is used include the erosion of thermonuclear fusion reactor walls, the characterization of amorphous silicon solar cells, the embrittlement of steels and niobium by hydrogen contamination, and the effects of the solar wind (high-energy hydrogen and helium nuclei ejected by the solar corona) on moon rocks.

ENERGY TECHNOLOGY

Basic research in nuclear physics has created—and continues to create—a fund of advanced technology that pervades energy-related research and development. The most familiar examples, of course, are those of nuclear fission and fusion. Nuclear fission reactors currently satisfy about 13 percent of the electric power demand in the United States, and nuclear fusion holds the promise of satisfying the bulk of this demand in the twenty-first century and beyond.

The impact of nuclear physics on energy technology is also felt, however, in other, less-well-known areas. Nuclear techniques are used by the drilling industry to help probe geologic formations and locate hydrocarbons and other valuable resources that are deep underground. Passive forms of nuclear well-logging employ gamma-ray detectors to distinguish regions containing clean sands and carbonates (low natural radioactivity) from the less productive but more radioactive regions containing clays or shale rock. More sophisticated well-logging techniques generate neutrons with the aid of miniaturized nuclear accelerators that can be lowered into the test bores, which are typically about 10 cm in diameter. The apparatus produces fast neutrons by bombarding a tritium target with an accelerated, pulsed deuteron beam, and the

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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 well log is inspected for the characteristic yield that indicates the presence of carbon, the main 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 saltwater. 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.

Whenever research and development efforts lead to increased efficiencies in existing energy technologies, the result is energy conservation. Here too, the impact of nuclear physics is felt in various ways. For example, tracer techniques have been used to study friction and wear in gasoline engines by incorporating radioactive carbon in steel piston rings. Inhibiting friction and wear—and hence improving efficiency—can often be accomplished by using the ion-implantation method to modify the surface properties of materials. Wire-drawing dies that have been ion implanted with nitrogen, at a cost of only a few dollars per die, can be kept in service about five times longer than ordinary dies, with consequent savings in tooling costs, plant downtime, and other tool-replacement costs.

Ion implantation also shows promise for the fabrication of corrosion-resistant surface alloys, the use of which would conserve rare or strategic alloying metals such as chromium, platinum, cobalt, and tungsten. The conservation occurs not only through corrosion reduction but also because nuclear accelerators permit the implantation of these scarce elements selectively into the surface of the material—precisely where they are needed for corrosion resistance.

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 reactors. Examples of the problems that must be investigated are the stability of waste-containment materials and the embrittlement and damage of reactor materials due to irradiation by neutrons, protons, and alpha particles. Such studies have already helped to identify metallurgical

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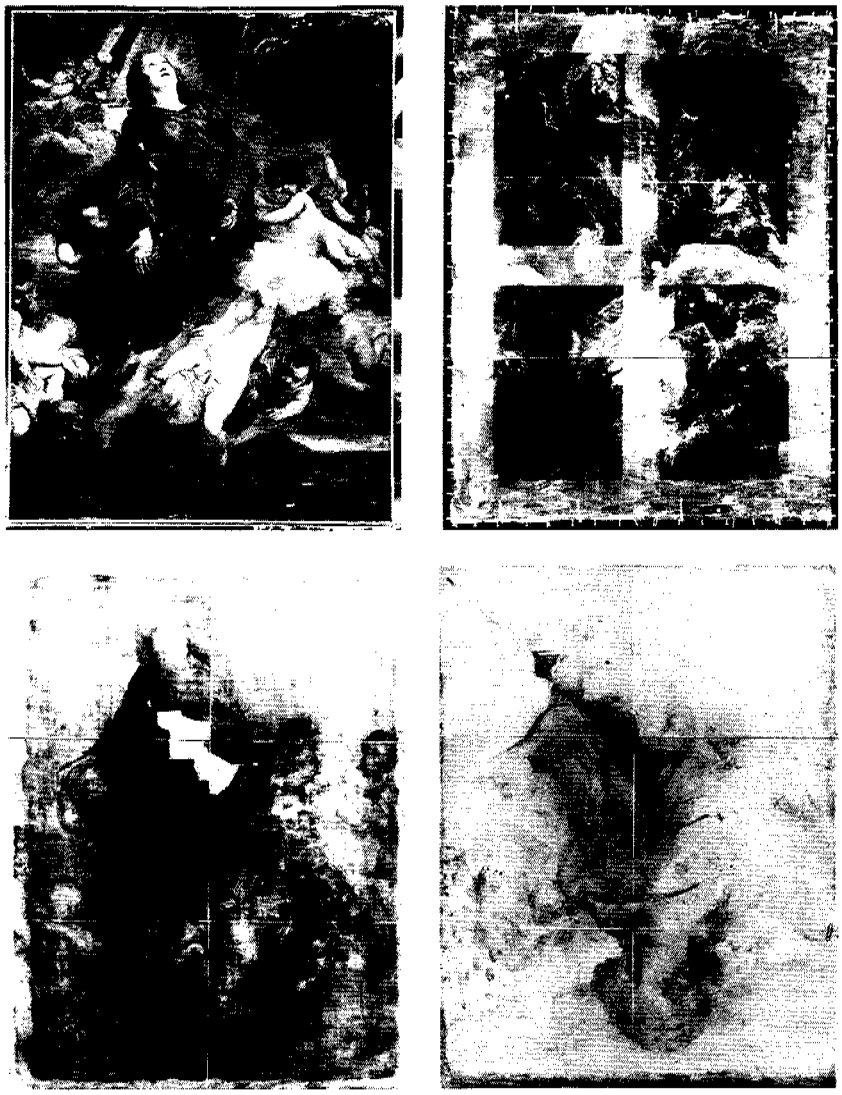


FIGURE 6.3 *Saint Rosalie Interceding for the Plague-Stricken of Palermo*, by Anthony Van Dyck. A conventional photograph of this oil painting is shown at the top left. At the top right is an x-ray radiograph, which reveals traces of a hidden painting underneath. This underlying painting is revealed more clearly in the two neutron autoradiographs shown at the bottom. The hidden painting turned out to be a self-portrait. (Courtesy of the Metropolitan Museum of Art, New York, and the Brookhaven National Laboratory.)

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techniques for minimizing high-temperature swelling and grain-boundary embrittlement. They are also being used to look for possible ways of minimizing radiation damage by annealing the materials, using either controlled preirradiation or the ambient radiation of the reactor itself.

THE FINE ARTS

Nuclear techniques based on the use of neutron-induced radioactivity in art objects have been used for many years as tools for determining the elemental composition and thus, often, the origin of these objects. Recently, however, the complete neutron irradiation of paintings, followed by autoradiography, has proved to be a valuable technique for studying the underlying paint layers, which record the evolution of paintings by the great (and lesser) masters. The technique involves making a series of radiographic exposures over periods of many days following the neutron irradiation. Because of the difference in half-lives of radioactive nuclides of elements such as manganese, sodium, copper, arsenic, mercury, and antimony, it is possible to view selectively the images contained in the many layers of paint present in a typical oil painting.

In a program conducted by the Metropolitan Museum of Art in New York, many oil paintings by masters such as Rembrandt, Hals, Van Dyck, and Vermeer have been examined. Many reveal not just one but several previously unknown underlying images (see Figure 6.3), which reveal the compositional evolution of the painting and the thoughts and moods of the artist.

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III

Current Frontiers of Nuclear Physics

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7

Approaching the Quark-Gluon Plasma

About 20 billion years ago, the universe began in a stupendous explosion called the big bang. At that instant, all matter is believed to have had a temperature corresponding to about 10^{19} GeV, or 10^{32} K. During the earliest moments (much less than 1 second) after the big bang, the fundamental forces that we know today—strong, electroweak, and gravitation—were all comparable in strength, according to present theories. None of the many composite particles—the mesons and baryons—existed, since they could not have survived such unimaginable heat. Only the elementary leptons, quarks, gluons, photons, and intermediate vector bosons could have existed.

As time progressed during the first second, the nascent universe expanded and therefore started to cool. About 10^{-10} second after the big bang, with the universe at a temperature corresponding to about 10^3 GeV (10^{16} K), the unity between the weak force and the electromagnetic force began to disappear. The quarks (and their antiquarks) were still free, however, not yet bound up in hadrons. Later, at about 6×10^{-6} to 7×10^{-6} second, when the universe had cooled down to a temperature corresponding to 100 to 200 MeV (1×10^{12} to 2×10^{12} K), the quarks and antiquarks started to coalesce into the strongly interacting particles (mesons and baryons). As the universe continued to cool, the nucleons themselves coalesced to form light nuclei. This nucleosynthesis started about 3 minutes after the big bang; the process leading to the formation of stars and galaxies had begun.

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Today we find ourselves in a relatively cold universe at an overall temperature of 3 K. To investigate the universe during its first few microseconds, therefore, we need, in a sense, to go back in time and try to recreate the conditions that existed then. The tools at our disposal are the descendants of the big bang itself: the abundant heavy nuclei all around us, which were formed long ago in stars. Our goal is to accelerate such nuclei to extreme relativistic energies and then smash them together. At a high enough collision energy, the temperature and pressure will become so great that the nucleons will disintegrate into a dense, blazing fireball of quarks and gluons.

This process, called *quark deconfinement*, has never been seen on Earth but may occur in the cores of neutron stars. The study of quark deconfinement will thus provide insight into questions of great cosmological interest and at the same time give us a stringent testing ground for some of the fundamental ideas of quantum chromodynamics (QCD). During quark deconfinement, a new state of matter, the *quark-gluon plasma*, will be created. In this state, quarks and gluons are no longer bound inside individual hadrons but are contained inside a much larger volume; this will allow the *long*-range behavior of QCD, which is at present very poorly understood, to be examined.

This chapter deals with the various states of nuclear matter, the values of temperatures or densities that are required for achieving quark deconfinement (based on present theoretical models), and the detectable signatures expected to be left behind by the quark-gluon plasma. It concludes with a brief discussion of other frontiers in relativistic heavy-ion physics.

STATES OF NUCLEAR MATTER

Let us first consider an everyday form of matter and see what happens as we heat it up by providing energy to its internal constituents. If an ice cube is placed on a hot plate, it first melts to water, which represents a higher energy state than ice. After further heating, the water evaporates to a still higher energy state—water vapor. These changes are called *phase transitions*. In each change of phase, the internal energy of the matter (per molecule) is increased, and a different aspect of its structure is revealed to us. In an analogous fashion, we expect to heat ordinary nuclear matter to temperatures sufficiently high that an extreme energy state, the quark-gluon plasma, will be created.

What are the possible phases of nuclear matter? Previous research using nuclear collisions below 100 MeV per nucleon has dealt primarily with the ground-state properties of cold nuclear matter. Even the

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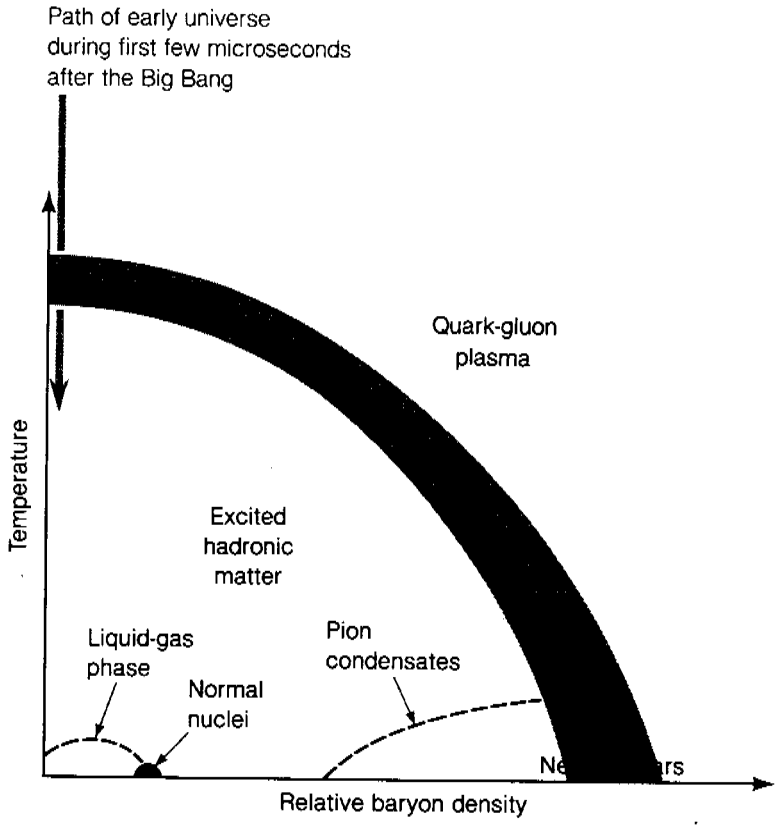


FIGURE 7.1 Some of the phases of nuclear matter that are expected to exist at high temperatures and low-to-high relative baryon densities are shown in this phase diagram, which is described in detail in the text. The shaded band schematically represents the transition region for quark deconfinement, beyond which lies the quark-gluon plasma. The scope of known nuclear physics is confined almost entirely to nuclei under normal conditions.

highest-energy heavy nuclear beams currently available are not thought to be sufficiently energetic to produce a fully developed quark-gluon plasma.

Now let us see what happens as we heat ordinary nuclei. Figure 7.1 illustrates some of the possible phases of nuclear matter in terms of two variables: temperature and relative baryon density (the number of baryons—mainly protons and neutrons—per unit volume, compared with this number for ordinary nuclei). Normal nuclei, of which

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everything on Earth is made, are found only in one small region of this phase diagram. There are much larger regions of the diagram, each corresponding to a different phase in which nuclear matter can exist. We will refer to these phases as *hadronic matter* (which encompasses normal nuclei) and the quark-gluon plasma, or simply *quark matter* (on the far side of the diffuse boundary region in which quark deconfinement occurs).

At normal nuclear density and low temperature (close to 0 MeV—cold nuclear matter), we find the nuclei that make up the everyday world. As we start to heat the nuclei through collisions at ever higher energies, the individual nucleons gain more energy and try to move apart. The nuclear system becomes larger, and its density necessarily decreases. Thus, at slightly elevated temperatures, but at subnormal densities, a *liquid-gas* phase transition from nuclei to nucleons may occur. Heavy-ion collisions below 100 MeV per nucleon and high-energy proton-nucleus collisions, in which the incident proton deposits a local *hot spot* in the nucleus (which then propagates through the nucleus, heating it up), are currently being used for probing this phase transition.

At high baryon densities, on the other hand, but still at relatively low temperatures, new and unusual phases of nuclear matter are postulated to exist. One of these, called a *pion condensate*, would be a highly ordered form of nuclear matter, analogous to the atoms in a crystal lattice. No positive evidence for its existence has yet been found, but it might exist deep in the interiors of neutron stars. At the highest densities, we enter a region that is characteristic of neutron stars. It seems ironic that in order to gain information on some of the most massive objects that we know about—stars—we must study some of the tiniest objects known—nuclei.

At high temperatures (20 to 100 MeV) in the nuclear medium, we produce many new excited levels of the individual nucleons themselves. Nuclear matter at such temperatures is referred to as *excited hadronic matter*. If there were no internal structure to the individual nucleons, this state of matter would continue indefinitely, since in principle there can be an infinite number of excited states.

But there *is* an internal structure. The nucleons are composed of confined quarks and gluons, and as the temperature or density is raised sufficiently, we expect to experience a transition in which hadronic matter becomes deconfined: the nucleons decompose into a quark-gluon plasma similar to the one from which mesons and baryons condensed a few microseconds after the big bang.

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ACHIEVING QUARK DECONFINEMENT

Relativistic nuclear beams will be used for the production and study of the quark-gluon plasma. What are the appropriate physical parameters and critical values needed to achieve and describe this state? The only currently conceivable method is to accelerate heavy nuclei to enormous energies and cause them to collide head-on. In this catastrophic impact, we expect high temperatures and densities to be created throughout a volume of space comparable with the size of the nuclei themselves. The larger the nuclei that are used, the more individual nucleon-nucleon collisions will occur, each helping to heat and, to some extent, compress the system. Ideally, therefore, the facility for such experiments should be able to accelerate heavy nuclei such as the uranium nucleus.

Estimates of the critical values of the temperature and baryon density needed for quark deconfinement have been made. Simple calculations based on compressing nuclei until the space between individual nucleons disappears predict that deconfinement could occur when a critical *baryon density* only a few times that of normal nuclear matter is exceeded at sufficiently high temperatures. (Normal nuclear density is 0.16 nucleon per cubic fermi.) Other calculations, reflecting a different view of the effective size of the nucleons, yield substantially higher values for the critical baryon density. One still expects, however, that a fundamentally important change in the nature of nuclear matter will occur at a relatively low baryon density, as the nucleons are squeezed together.

An alternate approach is based on filling the space between the nucleons by creating mesons (for example, pions and kaons) and other particles, such as proton-antiproton pairs, in the collision process. Such an argument leads to the prediction that a critical *energy density* (the amount of energy per unit volume residing in the system), again as low as a few times that of normal nuclear matter, would be sufficient to initiate the deconfinement of quarks from hadrons. [The energy density of normal nuclear matter is 0.15 GeV per cubic fermi (GeV/fm^3).]

Sophisticated theoretical calculations support these simple estimates and predict the following critical values for the transition to a quark-gluon plasma: a temperature between 140 and 200 MeV and an energy density in excess of 0.5 GeV/fm^3. The requirement for much higher bombarding energies than are available with today's heavy-ion accelerators lies in the fact that only with such higher energies will we be able to achieve the extreme temperatures and energy densities needed to deconfine hadronic matter and produce the plasma.

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The basis for the calculations mentioned above is a mathematical technique called *lattice gauge theory*, which has provided new insights into many areas of theoretical physics. It is based on the hypothetical concept of a regular lattice of points in a four-dimensional space-time. On each point, and along each link between points, some physical property of the system (in this case, a system of strongly interacting particles) is defined. Using the concepts of group theory (the mathematics of symmetry operations) and sophisticated numerical methods of computation, the values of these properties can be calculated for a given spacing of the lattice. As this spacing is successively reduced, i.e., as the lattice is "shrunk" indefinitely, the calculated values of the physical properties converge to those that QCD would predict for them in the continuum limit of real space-time. Thus it has been possible for a number of theorists, through the artifact of the lattice, to perform a wide range of calculations that would otherwise be impossible. Such calculations have led to the prediction of quark deconfinement.

At present there are at least two pieces of experimental evidence suggesting that we can indeed achieve quark deconfinement. The first of these is provided by high-energy cosmic-ray events from the Japanese-American Cooperative Emulsion Experiment (JACEE) collaboration. In this experiment, nuclear emulsions (similar to ordinary photographic film) are carried by balloons to the top of the Earth's atmosphere to intercept high-energy, heavy cosmic-ray nuclei before they are destroyed through interactions with the nuclei of air molecules. A few cosmic rays collide with silver or bromine nuclei in the emulsion, and their tracks and those of the interaction products can be seen and measured after the emulsion stack is processed (developed like film from a camera).

In one such event—the most violent one ever seen—an incoming silicon nucleus is estimated to have had an energy of 4000 to 5000 GeV per nucleon. It triggered an explosion for which the number of particles produced (about 1000, mostly pions) indicates that the energy density in the collision was about 3 GeV/fm^3, several times the estimated value required for quark deconfinement. It is impossible from just one event, however, to tell whether deconfinement actually occurred. Detailed investigations of this phenomenon will require accelerator beams, which, unlike cosmic rays, can be controlled. For the results of this kind of accelerator experiment to be interpretable and statistically meaningful, a large number of similar events must be recorded, and an event rate of the order of one head-on collision per second would be required. (By contrast, cosmic-ray events of the kind described above are so rare that they are individually named.)

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The second piece of evidence comes from recent European Muon Collaboration/Stanford Linear Accelerator Center experiments on lepton-nucleus deep-inelastic scattering, which probed the quark structure of nucleons bound in nuclei (this work was discussed in Chapter 3). The results seem to indicate that the quarks are freer to move about in nucleons inside nuclei than in a free nucleon. If this is true, then quark deconfinement might occur at even lower values of temperature and energy density than those currently estimated.

What are the energies of the nuclear beams needed to deconfine quarks from hadronic matter, i.e., what energies will produce sufficient temperatures or densities? The answer depends on whether one tries to maximize the baryon density or to achieve a very-high-energy density in the collision process. To maximize baryon density, the energy should be such that the colliding nuclei stop each other with maximum mutual compression (see Figure 7.2). Present theoretical estimates suggest that this will occur at laboratory bombarding energies near 10 GeV per nucleon.

If very-high-energy density is desired, on the other hand, higher bombarding energies are needed. The most efficient route to this goal is to build a heavy-ion colliding-beam accelerator (as opposed to a fixed-target machine). To achieve the desired energy density will require a *relativistic nuclear collider* with an energy of the order of 30 GeV per nucleon in each beam. Here the impact of a head-on collision is so great that the two nuclei exhibit *nuclear transparency*: they interpenetrate explosively. Three separate regions are created in such an event: the two baryon-rich regions (vestiges of the two projectile nuclei, consisting of recondensed nucleons), which speed away from the collision zone in opposite directions, and the central region, where the high-energy density will occur in the form of created mesons, baryon-antibaryon pairs, quark-antiquark pairs, and gluons.

DETECTING THE QUARK-GLUON PLASMA

The entire process of formation and recombination of the quark-gluon plasma will take about 10^{-22} second, which is comparable with the time it takes light to cross a single nucleus. During this period, the initially hot plasma will expand and cool (by the emission of particles), eventually recondensing to a normal hadronic phase, i.e., the usual mesons and baryons observed in accelerator experiments.

To detect the presence of the plasma, we can look for particles that either originate in the early, hot, dense stage or appear at a later, cooler, more rarefied stage. If we wish to see into the fiery heart of the

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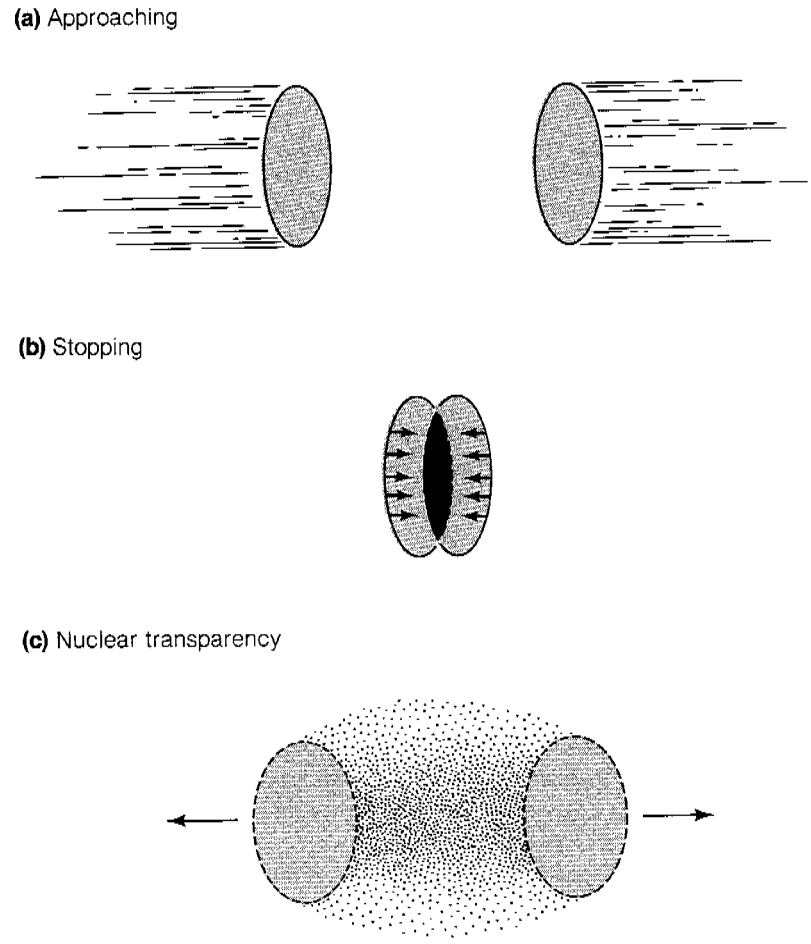


FIGURE 7.2 Quark deconfinement in relativistic nuclear collisions may occur in either of two possible regimes, shown in (b) and (c). (b) In a head-on collision at lower energies (on a relative scale), the two nuclei stop each other, producing a quark-gluon plasma under conditions of maximum nuclear compression and, therefore, of maximum baryon density. (c) At higher energies, the nuclei are transparent as they interpenetrate, producing, in the central region, a quark-gluon plasma under conditions of extremely high energy density and relatively low baryon density.

plasma, we must detect particles that can exit such a hostile environment unscathed. The only viable candidates are charged leptons—which are not subject to the strong force and therefore interact only electroweakly with the hadrons in the plasma—and photons. On the

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other hand, the "frozen" phase of the collision (i.e., when the quarks and antiquarks have recondensed to hadrons) offers a number of possible signatures among the hadrons, including strange particles (hadrons containing the strange quark) and antibaryons, which reflect the quark-antiquark composition of the plasma. Unusual fluctuations in particle numbers could also signal the formation of the quark-gluon plasma. Finally, it should not be overlooked that the observation of free quarks or unusual combinations of quarks would surely indicate the formation of the quark-gluon plasma and would initiate the study of *quark chemistry*.

Some of the interactions occurring in a relativistic nuclear collider will spew forth hundreds—even thousands—of particles in a single event. These particles will materialize out of the energy made available in the violent collisions. (An example of the particle multiplicities observed in current fixed-target experiments at near-relativistic energies is shown in Figure 7.3.) The capabilities of the detectors needed for such experiments will have to be greater than those of the detectors used in even the highest-energy proton-proton or proton-antiproton colliders. Consider, for example, a head-on collision of two uranium nuclei, each having an energy of 30 GeV per nucleon. If *all* the available energy were converted to mass, up to 100,000 pions could be created—an unprecedented number of particles in the final state. More realistically, if we assume that these particles are emitted with a characteristic average energy of 200 MeV, the total number of pions drops to the range of a few thousand—still a huge number for future detectors to cope with.

Because of such high particle multiplicities, many detectors will have to resort to techniques based on *calorimetry*, where the total energy flow rather than the total number of particles is measured. At the same time, some detectors will be constructed that are "blind" to the vast majority of particles but are able to see and record a specific kind (for example, a lepton-only detector) in tractable numbers. Experiments will undoubtedly entail the use of combinations of these two types of detectors.

The path to the quark-gluon plasma will require a state-of-the-art accelerator, and large detector arrays will be needed to unravel its mysteries. These scientific tools will enable us to look across the ages, back to the moment of creation and to a new (to us) state of matter, the quark-gluon plasma. Confirming its existence would have a major impact on fundamental questions common to nuclear physics, particle physics, astrophysics, and cosmology, and this achievement would surely be one of the most exciting in the history of science.

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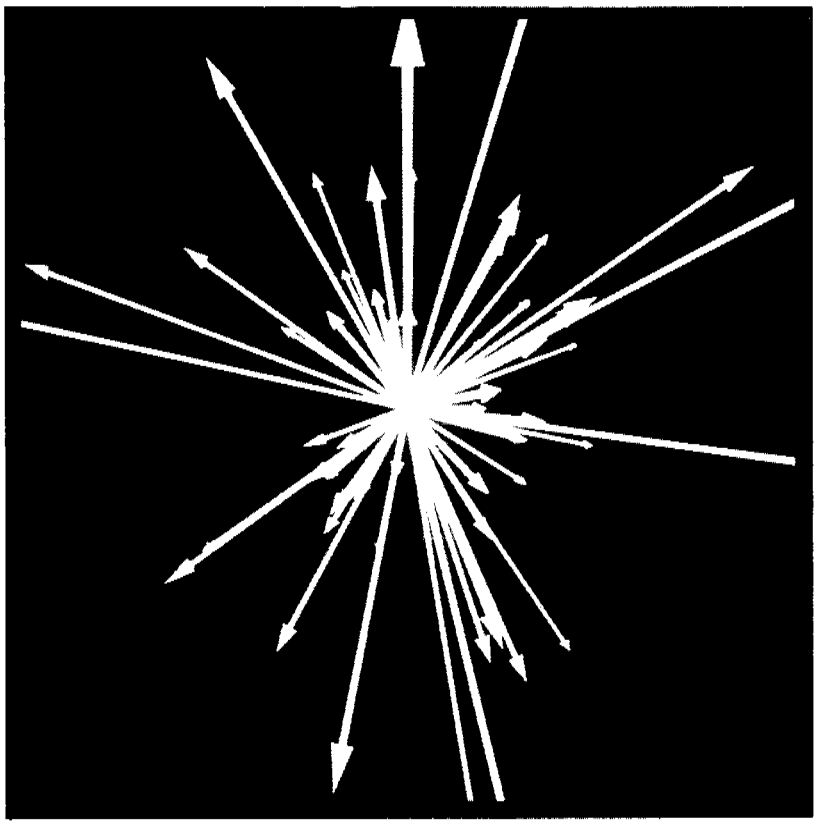


FIGURE 7.3 A computer-graphic reconstruction of an individual event, shown in the colliding-beam frame of reference, from a fixed-target experiment in which a beam of niobium-93 nuclei at 650 MeV per nucleon bombarded a niobium target. The short arrows represent the projectile and target nuclei approaching each other. The length of each arrow emanating from the point of collision is proportional to the momentum per nucleon of the particle it represents. Altogether, 61 charged particles were observed in this event. (Courtesy of the GSI/LBL Collaboration, Lawrence Berkeley Laboratory.)

ADDITIONAL RELATIVISTIC HEAVY-ION PHYSICS

Although a major focus of research with the relativistic nuclear collider will be the quark-gluon plasma, there are many other important physics questions that can be investigated with such an accelerator. Indeed, some of these questions must be addressed in any program whose goal is to establish and classify the properties of the quark-gluon plasma. As such, they will form the basic physics of the program of

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relativistic nucleus-nucleus collisions, spanning a broad range of studies. A few examples will serve to illustrate this point.

From the phase diagram of nuclear matter, we see that there is a large domain of unexplored matter in addition to the quark-gluon plasma. Investigations of excited hadronic matter have just begun, in the last few years, with studies of proton-nucleus and nucleus-nucleus collisions at very high energies. In central relativistic nucleus-nucleus collisions, it should be possible to create nuclear-matter temperatures high enough to produce large numbers of baryon resonances: massive, very-short-lived baryonic states that decay to other baryons and mesons. Chief among these would be *nucleon resonances*, or N* states, which are highly excited states of nucleons, and *delta resonances*, which are also excited baryonic states. Each of the delta resonances exists in four distinct varieties having electric charges of -1, 0, $+1$, and $+2$, owing to their different quark configurations.

Creating and studying such N* or delta matter is important both because it is inherently interesting and because it represents a transitional phase of matter between normal nuclear matter and the quark-gluon plasma. Although single baryon resonances can be made in existing accelerators—either as free species or as bound states in nuclei—it is only by means of central nucleus-nucleus collisions at relativistic energies that one could produce large numbers of them simultaneously and in very close proximity. The consequences of this unique situation are difficult to predict. Conceivably, one could form metastable systems of such exotic nuclear matter that would be analogous to ordinary nuclei: a delta-16 state, for example, in analogy with oxygen-16. It has also been suggested that in the de-excitation of N* or delta matter a sudden burst of pions might be observed, possibly in the form of a *pion laser*. This and many other ideas about excited hadronic matter are admittedly highly speculative, but they do suggest a stimulating and potentially fruitful experimental research program.

In recent heavy-ion experiments at energies of a few hundred MeV per nucleon (in the center of mass), the number of created pions is observed to be significantly lower than expected. One interpretation is that this is evidence of compressional effects, i.e., much of the kinetic energy of the colliding nuclei apparently becomes manifest as a compression of the nuclear matter rather than in the creation of pions. Does this effect persist at higher energies, and if so, is nuclear compression the correct explanation?

To investigate thoroughly this and other questions of the physics of excited hadronic matter will require not only that the accelerator be capable of delivering the full spectrum of nuclear beams but also that

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it be tunable in energy. This is necessary in order to see how a given physical process changes with increasing energy, which provides an experimental basis for extending the theory of nuclear matter. In addition to its colliding-beam mode of operation, the accelerator should be capable of fixed-target operation, because of the advantages this offers for many kinds of experiments. This mode of operation could be accomplished either by extracting one of the two countercirculating beams of the collider or by using a booster synchrotron (albeit at a lower effective energy), which would also act as the *injector* for the collider.

An important feature of fixed-target experiments at relativistic energies is that the particles produced in the collisions become localized within an increasingly narrow forward-projecting cone about the beam axis. This strong collimation of the beam of produced particles can be used to advantage in many nuclear-physics experiments. One example is in the production of nuclei far from stability—exotic forms of conventional nuclear matter. The primary interest here is in peripheral, or grazing, nuclear collisions, in which only a few nucleons in the target and projectile nuclei participate. In such collisions, a few of the projectile nucleons may be chipped off, leaving a high-energy nuclear system moving in the forward direction. In a small proportion of the interactions, the nucleons that are removed can be either mostly protons or mostly neutrons, thus producing very neutron-rich or proton-rich nuclei, respectively.

In the last few years, more than 20 new nuclides have been discovered in such reactions. This technique promises to provide physicists with an expanding array of radioactive nuclides whose properties (for example, masses and lifetimes) are of intrinsic interest. Furthermore, they can be used as projectile beams in their own right for studies of nuclear-reaction mechanisms in processes that are important for cosmic-ray propagation and the observed abundances of the elements in the cosmic radiation. They also have potentially valuable applications in radiobiology and nuclear medicine.

A few final examples—outside the arena of nuclear physics but accessible with a fixed-target relativistic nuclear accelerator—are found in atomic physics. By accelerating partially stripped ions to sufficiently high energies, one can selectively remove most or all of the remaining orbital electrons. For example, by accelerating a uranium-238 beam in the 68+ charge state ($^{238}U^{68+}$) to a few hundred MeV per nucleon and then passing it through a thin foil, one can produce mostly $^{238}U^{91+}$, which has only one electron left, i.e., it is hydrogenlike uranium. Having prepared this beam, one can then study the atomic

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decay schemes of these most unusual heavy ions, providing powerful new tests of the accuracy of quantum electrodynamics. Other possibilities include scattering a beam of laser radiation from an oncoming, very parallel, and very intense beam of partially stripped ions. Theoretical calculations seem to suggest that, under the right conditions, an x-ray laser action might result from such an interaction.

The studies outlined above merely suggest the great potential for scientific gain to be realized from a relativistic nuclear collider beyond its use in producing the quark-gluon plasma. The extent of its capabilities will be defined by the imagination and ingenuity of many physicists from a wide variety of disciplines.

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8

Changing Descriptions of Nuclear Matter

In the preceding chapter, we discussed the exciting opportunity of using relativistic nuclear collisions to produce in the laboratory a previously unobserved form of matter—one whose properties are of fundamental importance in understanding the basic forces of nature and the early moments in the evolution of the universe. While pursuing this goal, it is essential to remember that many properties of nuclear matter under more conventional conditions are not yet well understood. An improved description of nuclear matter would represent a critical advance in addressing one of the most difficult and important questions in physics: how does nature build stable structures from smaller, more elementary building blocks?

We now understand that the most elementary building blocks of nuclei are quarks and gluons. However, the problem of describing nuclear matter completely in terms of quarks and gluons is at present intractable. The fundamental theory of the strong interaction, quantum chromodynamics (QCD), cannot yet be solved for the force between quarks when they are separated by distances comparable with the size of a nucleon. Thus, QCD indicates the existence of—but does not provide a practical treatment for—the crucial transition region between the short-distance regime, where the color force between quarks and gluons is in evidence, and the confinement region, where it is hidden within the exchange of mesons between baryons.

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Is the short-distance quark-gluon regime important in the description of ordinary nuclear matter, or do the neutrons and protons stay far enough apart that they neither significantly affect their internal substructure nor are affected by it? If the latter is true, can we develop a suitable quantum field theory of the baryon-meson, i.e., hadron, interactions—"quantum hadrodynamics" (QHD)—that can accurately describe the substantial influence of meson exchange within the nuclear many-body system? These are central questions to be addressed by the next generation of nuclear-physics experiments and theories.

An important part of the experimental program will be carried out at the 4-GeV Continuous Electron Beam Accelerator Facility (CEBAF) proposed by the Southeastern Universities Research Association. Energetic electrons will interact in well-understood ways with the particles relevant to each possible level of description of nuclei and should thus help to reveal the relative roles of nucleons, mesons, and quarks. Experiments at other accelerators will utilize beams of several-GeV protons to probe the short-distance aspects of nucleon-nucleon interactions inside and outside nuclei. Intense intermediate-energy beams of mesons will be used to implant unusual baryons in nuclei, and low-energy proton-antiproton collisions will study the short-distance phenomenon of particle annihilation under the influence of the strong force. Theoretical progress will hinge on finding a prescription for a smooth transition from a hadronic to a quark-gluon description of nuclear matter.

A successful many-body theory must, of course, improve on existing theoretical accounts of the detailed properties of ordinary nuclear matter that have been inferred from many years of investigation of nuclear structure. In addition, however, we expect it to provide a framework for understanding how the properties of nuclear levels evolve under more and more extreme conditions of excitation, angular momentum, or ratio of proton and neutron numbers. It is thus important to extend current studies of nuclear reactions that produce such unusual conditions even when the experiments are not directly sensitive to the presence of particles other than nucleons in the nucleus.

QUARKS IN NUCLEI

The most fundamental building blocks of atomic nuclei, the quarks, interact with each other via the exchange of gluons, thereby creating mesons, baryons, and, ultimately, nuclei. Very little is known about

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the role of quarks in whole nuclei. Apart from the fact that quarks are *asymptotically free* when very close to each other, and totally *confined* from escaping as individual quarks to large distances, almost nothing is known about their behavior.

Thus far, our best information about quarks in nuclei has come from studies using photons, electrons, and muons. Recently, studies of electron scattering with precise, intense beams of particles at Stanford, MIT, and several European and Japanese laboratories have revealed much about the nature of the quark structure of nuclei, as has the recent work of the European Muon Collaboration, discussed in Chapters 2 and 3. Work done at Stanford over a decade ago showed that the proton is in fact composed of three fractionally charged quarks that, surprisingly, interact weakly when they are close together inside their confining bag. Later work at other laboratories uncovered peculiar structural anomalies in the nucleus of helium-3, which apparently has a dip in the central region of its matter distribution. This finding, as well as similar ones in other light nuclear systems, will likely be explainable only after mesons and quarks are fully incorporated into our descriptions of nuclear matter. These issues will be explored in the future at CEBAF.

If nucleons inside ordinary nuclei spend enough time sufficiently close together that they have an appreciable probability of merging into bags containing six or more quarks, then the description of associated nuclear properties will require explicit treatment of the quarks and gluons. To probe this possibility, it is important to study systematically the correlations in the motions of pairs of nucleons within nuclei. An effective way of carrying out such investigations makes use of electron beams to knock nucleon pairs out of the nucleus. By detecting the scattered electron and the ejected nucleons in time coincidence, one can study short-distance two-body correlations in the nucleus. Experiments of this sort require electron beams of high energy to transfer the requisite momentum to the target nucleus and high duty factor for clean and efficient identification of events in time coincidence; they are thus ideally suited for CEBAF.

Additional quark aspects of the strong interaction can be probed by studying other selected features of it. For example, it is now known that parity is not strictly conserved in proton-proton scattering. The tiny but measurable deviations arise from the very-short-range weak force between nucleons. In order to account quantitatively for the parity violations, one must understand both the strong force and the weak force at very short distances, because the interplay of the two produces the effect. Recent experiments have suggested that the

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observed parity violation is 10 times larger at 5-GeV than at 50-MeV proton energies. Exploration and theoretical treatment of the intermediate-energy region should stringently test models based on QCD, in which the forces between hadrons are built up from the forces among their constituent quarks. The experiments would require high-intensity, high-quality beams of spin-polarized protons throughout the few-GeV energy region.

Another quark-related program of experiments using such proton beams would involve searches for so-called *dibaryon resonances*. The normally occurring hadrons fall into two classes: the baryons and the mesons, consisting, respectively, of three quarks and of a quark-antiquark pair confined inside a bag. Quark models, however, also predict the existence of more exotic combinations, for example, six-quark bags, which do not—for reasons related to the distribution of quark colors inside the bag—readily separate into two normal baryons. Such six-quark objects, or dibaryons, might be manifested as resonances in nucleon-nucleon scattering experiments at energies above 1 GeV, that is, as sharp variations with energy in the probability of scattering or in its dependence on the spin orientations of the two nucleons.

Excellent opportunities for the further study of six-quark physics will be afforded by the new Low-Energy Antiproton Ring (LEAR) recently constructed at CERN. In antiproton-proton collisions, one will have the chance to study the interaction between quarks and antiquarks in a rather uncomplicated way. A collision between matter and antimatter can lead to an intermediate state of pure energy, which can subsequently form many interesting and varied final states, few of which have been extensively investigated.

Of special interest is the proton-antiproton "atom," in which the positively charged proton captures a slowly moving, negatively charged antiproton, pulling it into an atomic orbit. Here one would search for transitions between the atomic bound states (due to the Coulomb force) and the very deeply bound states (due to the strong interaction), which would signify for the first time the existence, however fleeting, of the so-called *baryonium* states. These states are formed very rarely, if ever, because matter-antimatter collisions at close range almost always lead to total annihilation. The confirmation of such events would open an exciting new field of study.

Along similar lines, other atomic systems never before seen could be prepared at the LEAR facility. At the proper energy, the antiproton-proton collision can lead to production of other particle-antiparticle final states. Since these objects are oppositely charged, at the threshold

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for the reaction they will be bound together in an atomic state because of the electrical attraction between them. Some of the completely new systems formed in this way can be used to check the most detailed predictions of quantum electrodynamics. As the system decays, the particles come closer together, until the strong force takes over and the system is annihilated. Here too, the opportunity for studying unknown details of the reaction is presented.

Intense beams of *kaons* can also be very useful in the study of dibaryons, because they permit systems with one or even two strange quarks to be formed. One of the most exciting predictions of the bag models of hadrons is the existence of a stable, doubly strange dibaryon called the *H particle*, with a predicted mass around 2.15 GeV. Even if it is not stable, the relatively low mass of this dibaryon means that it should be fairly easy to separate it from other events that would confuse its identification. The experiments would still be difficult, however, because they typically involve two steps: the production of a very-short-lived hyperon, the *cascade particle*, followed by the interaction of the hyperon with a nucleon in the target. Many other strange dibaryons have been predicted; observation of these objects would be an important confirmation of the dynamics of the quark model.

Finally, based on our experience with other quantum many-body systems, we can expect great opportunities for discovery in physics arising from the underlying quark-gluon nature of nuclear matter. Even when the forces in question are better understood and more tractable (as in quantum electrodynamics) than the strong force, unpredicted phenomena can still appear. Had it not been for the experimental discovery of superconductivity, for example, this phenomenon would not have emerged from our theoretical understanding of the electromagnetic force in the form of QED.

MESONS AND BARYON RESONANCES IN NUCLEI

It has been known for many years that neutrons and protons interact via the exchange of virtual mesons. On even the simplest level, therefore, the nucleus must contain, in addition to nucleons, the force-carrying mesons. Searching for direct evidence of their presence has nevertheless been an elusive chase, because seeing them requires particle beams of very short wavelength.

One of the oldest and least ambiguous ways of examining nuclei is to irradiate them with beams of light of extremely short wavelength (gamma radiation); this interaction can result in the photodisintegration

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of the nucleus, the mechanism of which is then studied. When applied to the deuteron near the threshold for its breakup, such studies gave the first experimental results that required the presence of mesons in nuclei for the data to be understandable.

Within the last decade, much progress along these lines has been made using high-energy electron beams. As mentioned in Chapters 2 and 3, these studies have produced results in light nuclei that can be explained only by introducing the electric currents and distributions of magnetism due to the exchanged mesons themselves. Work at several laboratories is progressing on this subject, and the eagerly anticipated 4-GeV electron accelerator (CEBAF) will greatly extend our knowledge of it.

As might be expected, most of our knowledge of nuclear properties comes from experiments using electrons, protons, and pions to probe the most probable configurations of nucleons in a nucleus; these are the configurations that predominate under ordinary conditions. Recent experimental and theoretical advances have now also made it possible to perform (and understand) experiments designed to examine highly improbable configurations in which, for example, two nucleons are very close together, several nucleons are clustered together as a unit, or one nucleon is moving much faster than the average speed of the others. Most such experiments, which include electron and proton scattering as well as the production of exotic particles from the nucleus, take advantage of processes that could not occur if the nucleus were composed only of relatively isolated nucleons.

These studies are expected to reveal much about the quark structure of the nucleus, the nature of the nucleon-nucleon interaction at short distances, and the ways in which the motions of several nucleons might be correlated in the nuclear environment. Using selective reactions to probe and identify correlations will help us understand the degree to which certain states of nuclear excitation can be characterized as *nuclear molecules* or as relatively unexcited clusters of nucleons, rather than as a *nucleon gas* in which all the particles move rapidly and independently of one another.

To understand better how the nuclear many-body system is constructed, physicists have devised methods for implanting particle impurities inside nuclei and studying the effects of such changes on the nuclear system. The usual way of implanting an impurity in a nucleus is to bombard the latter with a beam of pions or kaons. When these particles interact with neutrons or protons, a *baryon resonance* can be formed inside the nucleus. Examples of such excited baryon species

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are the N* and the delta, which are made in pion-nucleon interactions, and the Y*, which is made in kaon-nucleon interactions. Although the lifetimes of these species inside the nucleus are very short (even by nuclear standards), they are long enough to allow modifications of the nuclear medium and of the baryon resonances themselves to be examined.

Under the right (gentler) conditions, bombardment of nuclei with negative kaons can produce *lambda hypernuclei*, in which a relatively long-lived lambda hyperon is formed within a nucleus rather than within a baryon resonance. Here too, it is not just the nucleus that is modified; the properties of the hyperon itself (such as its lifetime) may change substantially from the free-particle values. Measurement of such modifications will help us understand more about the detailed nature of the interactions taking place. Plans for the future include the study of the properties of exotic nuclei made with other kinds of strange-particle implantations, as well as the creation of such rare objects as *double hypernuclei*, which contain two imbedded hyperon impurities.

NUCLEAR PROPERTIES UNDER EXTREME CONDITIONS

Nuclear spectroscopic measurements—using elastic and inelastic scattering reactions as well as a variety of single-particle and multiparticle transfer reactions to study the properties of nuclear energy levels and their decays—have provided most of our knowledge about the behavior of nuclear systems. While some nuclear physicists are trying to understand the roles of mesons and quarks in nuclei, others are pursuing the study of the properties of nuclear levels (nuclear wave functions) under more and more extreme conditions of such parameters as excitation, angular momentum, and proton/neutron number. The use of more powerful accelerators and more sophisticated detectors will continue to extend our knowledge of the nuclear many-body systems, so that we can refine our nuclear models by testing them under more extreme conditions. While it is clear that we are just now opening up an exciting frontier in the study of the role of subnucleonic constituents in nuclei (as discussed above), a critical test of these new, more microscopic descriptions will have to be their ability to describe accurately the properties of real nuclei and their energy levels.

Some of these conditions can be explored by inducing collisions between nuclei at speeds greater than the speed of sound in nuclear

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matter. As illustrated by the sonic boom of an airplane, dramatic phenomena can occur when the sound barrier is exceeded. In nuclei, however, the speed of sound is 10^5 times greater than it is in air! It is therefore gratifying that nuclear accelerators now allow studies of collisions between heavy nuclei at such speeds, which correspond to energies intermediate between those used to study nuclear spectroscopy and those that will be required to induce the transition to a quark-gluon plasma. Under such conditions, we hope to investigate such phenomena as nuclear shock waves, compression of nuclear material, and the complete disintegration of a nucleus into lighter fragments or even its constituent nucleons. Nuclear properties are expected to change drastically in this region, from the fluidlike cooperative behavior of many nucleons at very low energies to a succession of many individual nucleon-nucleon collisions at high energies.

The experimental problems posed by studies of this transition region are challenging. New accelerators at Michigan State University, the Chalk River Nuclear Laboratories in Canada, and GANIL in Caen, France, will provide the necessary beams. Sophisticated instruments capable of detecting and analyzing the many particles (of the order of 100) in the debris of such collisions must be designed and built, and we must learn how to process and interpret the flood of data from such experiments to reveal the underlying physical phenomena (see Figure 8.1). The theoretical challenges are just as great, since a conceptual and computational framework must be developed for describing a region in which simplifying assumptions present at very low or very high energies are not valid.

Related subjects for future research will include such topics as the properties of nuclear systems with very high angular momentum, up to values beyond which the nuclei are torn apart by centrifugal forces. Another extreme condition is a large excess in the proton number or neutron number of a nucleus, which will cause marked instability. Very proton-rich or neutron-rich nuclei are typically produced in reactions between two heavy elements in which many nucleons are transferred from one nucleus to the other. The study of such nuclei at or near the limits of stability against proton or neutron decay may reveal interesting new radioactive decay modes.

A number of astrophysically important reactions, for example, the rapid capture of neutrons in supernova explosions and the rapid capture of protons on the surfaces of white dwarfs and accreting neutron stars, also depend critically on the properties of nuclei at the

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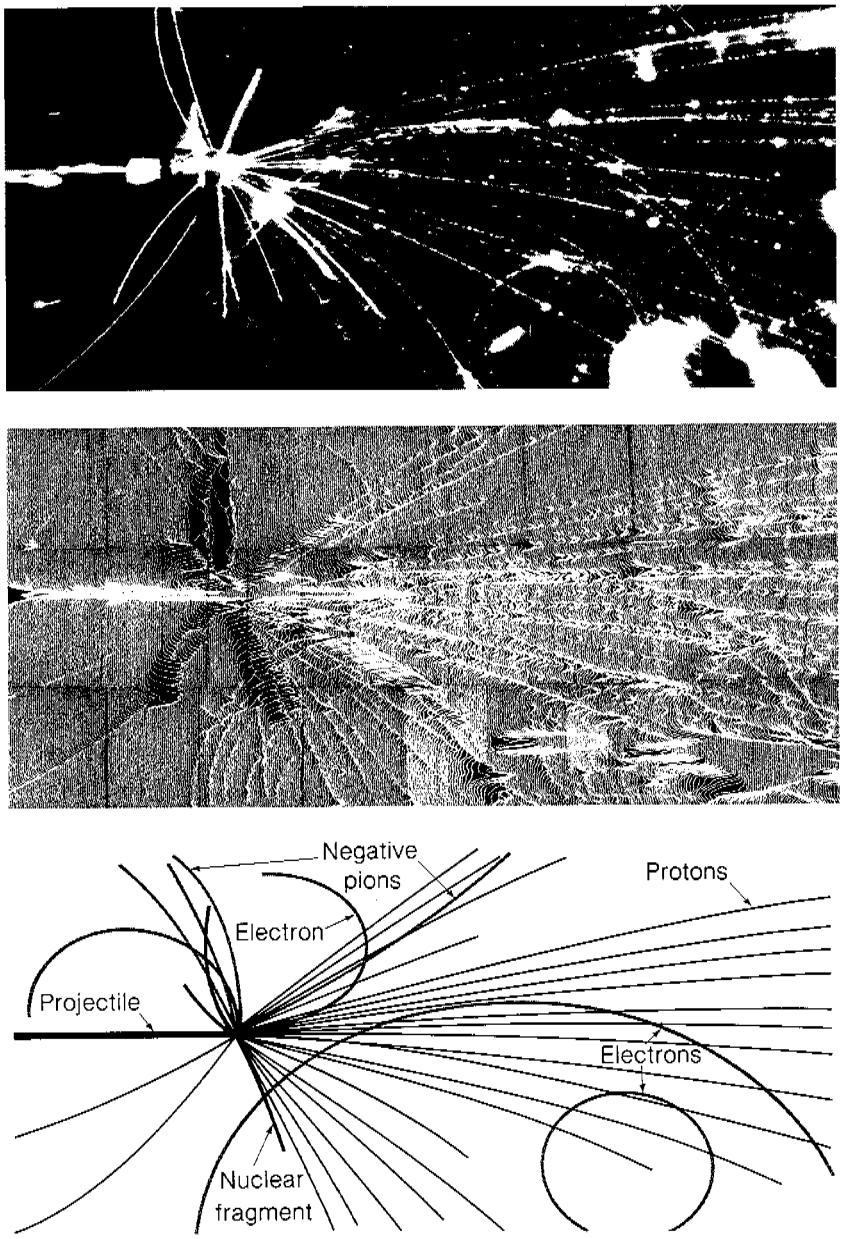


FIGURE 8.1 The tracks left by particles emitted in high-energy nuclear collisions can be recorded photographically in a gas-filled detector called a streamer chamber (top panel; see also the cover of this book). Here an argon-40 projectile with an energy of 1.8 GeV per nucleon collided with a lead target nucleus. A charge-coupled device (in effect, a computer-controlled TV camera) reconstructed the event (middle panel). The diagram at the bottom identifies some of the charged particles produced in the collision. The length shown corresponds to about 1 meter. (After W. C. McHarris and J. O. Rasmussen, *Scientific American*, January 1984, p. 58.)

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limits of stability. Many such nuclei can most readily be created through the use of short-lived radioactive beams as projectiles; these are produced in an initial nuclear reaction and then selected and accelerated to cause a second reaction. Several different approaches are currently being studied for producing such beams, which promise to open up completely new areas of nuclear spectroscopy.

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9

The Electroweak Synthesis and Beyond

Occasionally in the history of science, a new unifying principle has emerged that joins two separate bodies of knowledge whose connection at some deep level had not previously been recognized. The first great unification in physics was probably Newton's demonstration that gravity acts on the heavenly bodies in the same way that it acts on objects in our own world. Later, in the nineteenth century, Maxwell unified electric and magnetic forces by showing that they are just two different manifestations of a single force—electromagnetism. In our own century, Einstein unified the concepts of space and time—surely one of the greatest single intellectual achievements in physics—and of matter and energy, through relativity.

After the mid-1930s, the four fundamental forces of nature were considered to be gravitation, electromagnetism, the strong force, and the weak force. In 1967, however, the work of S. Weinberg, A. Salam, and S. Glashow led to a remarkable synthesis of electromagnetism and the weak nuclear force into a single *electroweak* force. This achievement, one of the triumphs of modern science, has had a profound effect on the development of nuclear physics and particle physics during the last decade. In this chapter we examine a few of the directions in which the electroweak synthesis appears to lead.

THE STANDARD MODEL

The value of great unifying syntheses comes not only from the ways in which they illuminate the underlying simplicity of nature—in a very

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real sense, they change our view of the world—but also from the predictive power of their logical consequences. Maxwell's unification of electricity and magnetism, for example, required the existence of electromagnetic waves moving through a vacuum with the speed of light, and we know that this requirement is fulfilled.

Similarly, the electroweak synthesis already has an impressive list of successful predictions to its credit. One of these is that the weak force should be mediated not only by the exchange of massive charged particles (the W^+ and W^- bosons) but also by the exchange of a massive neutral particle (the Z^0 boson). All three of these particles were discovered at CERN in 1983. Furthermore, the electroweak theory makes detailed predictions about nuclear processes. For example, the weak-interaction decay of a neutral kaon into a positive muon and a negative muon is permitted by the exchange of a neutral particle, such as the Z^0, but this process occurs only very rarely. The electroweak theory explains this result correctly on the basis of subtle effects pertaining to the strange and down quarks. Consideration of this problem led to the postulation of a new type of quark called *charm* (so named because it made the theory "work like a charm"). The charm quark was subsequently shown to exist—another triumph of the theory. It is because the present theories of the electroweak force and the strong force are so successful that together they are called the *Standard Model.*

Every known fact about nuclear and particle physics is consistent with the Standard Model. This does not mean, however, that the Standard Model explains everything that we know—far from it! Despite its spectacular successes, physicists are certain that the Standard Model is incomplete. It does not, for example, include the gravitational force; it does not tell us why there are three lepton families; and it does not explain some important conservation laws or their violations. Parity violation, for example, is a dominant characteristic of the weak force, yet it must be built into the electroweak theory arbitrarily. Similarly, time-reversal-invariance violation is known to occur, but among several possible ways of incorporating it into the theory, it is not clear which way is correct. As for the conservation laws for certain other properties, such as lepton family number, we do not know whether an underlying symmetry principle is at work or whether the law seems to hold only because present experiments are insufficiently sensitive to detect possible violations of it.

The mathematical form of the electroweak theory inspires confidence, however, because it is the only known theory of the weak interaction that is *renormalizable*. In a renormalizable theory, of which

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quantum electrodynamics is the archetype, observable quantities can be calculated to apparently any desired degree of accuracy. Quantum chromodynamics (QCD) is also a renormalizable theory, but its mathematical complexities are so great that reliable QCD calculations are very difficult, except near the limit of asymptotic freedom.

PHYSICS WITH NEUTRINO BEAMS

The advent of very intense beams of protons at meson factories has opened up the possibility of making neutrinos from the nuclear debris created when these beams are brought to rest in matter. Neutrinos interact only through the weak interaction and can penetrate vast amounts of matter without stopping. However, if copious numbers of neutrinos are present and detectors weighing many tons are used, a few neutrino interactions can be observed. Such experiments permit the study of the weak part of the electroweak force and, by comparison with the much more easily studied electromagnetic part, can test the fundamental unity of the electroweak interaction.

An experiment now under way at the Los Alamos National Laboratory is designed to measure the scattering of electron neutrinos from electrons in an advanced detector. According to electroweak theory, this scattering can happen in two ways: the neutrino and the electron can exchange a W^- boson, thereby also exchanging their identities (the neutrino turns into an electron, and vice versa), or they can exchange a Z^0 boson and retain their original identities. There is no way an observer can tell which process actually happened in any given scattering, so quantum mechanics predicts that these processes can interfere with each other: the total probability for the event is *not* just the simple sum of the individual probabilities. Demonstrating this interference and measuring its sign will be a key test of electroweak theory.

With even more-intense and more-energetic neutrino beams, such as might be produced by the next generation of accelerators, one can hope to carry out experiments in which neutrinos scatter from nuclei, sometimes leaving them in excited states. Because the nuclear states have specific quantum numbers, experiments of this sort will be able to dissect electroweak theory into its parts, each corresponding to these different quantum numbers. Such tests have never been performed and would provide a far more searching evaluation of electroweak theory than can be made at present.

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TESTING THE GRAND UNIFIED THEORIES

With two powerful theories of nuclear matter at our disposal—the electroweak theory and QCD—the scientific imperative is obvious: we must try to unify the electroweak and strong forces within a *Grand Unified Theory* that would include them both in one self-consistent mathematical framework. In the previous unifications, the main difficulty was in constructing a viable theory having all the required properties. Now, however, we are faced with an unprecedented and most peculiar problem: there is already a glut of Grand Unified Theories, which turn out to be rather easy to construct. Each reduces correctly to QCD and electroweak theory at low (terrestrial) energies; the catch is that at cosmological energies, such as must have existed briefly after the big bang, they predict a bewildering variety of phenomena that are as bizarre as they are different.

These differences between contending Grand Unified Theories become evident only at particle energies estimated to be about 10^{15} GeV, which is hopelessly beyond the reach of any currently conceivable terrestrial accelerator and far above even the energies of cosmic rays. How, then, can such stupendous energies possibly be achieved so that the correct Grand Unified Theory can be recognized from among the welter of alternatives? The answer may lie in the Heisenberg uncertainty principle, which allows a particle of any arbitrary energy to emerge out of a vacuum as a virtual particle, as long as it disappears back into the vacuum within a certain time, i.e., as long as its lifetime falls within a prescribed limit. The higher the energy, the shorter the allowed lifetime. Thus, ultrahigh-energy virtual particles can enable us—if we are clever enough—to study interactions that would otherwise be inaccessible.

A virtual particle of mass 10^{15} GeV would have some astounding properties, even by the standards of particle physics. In terms of conventional units, its free mass would be about 10^{-9} gram (equivalent to 10^{14} carbon atoms, or about the mass of a typical bacterium!), and it might exist for a fleeting 10^{-39} second, long enough for it to move only 10^{-16} of a nucleon diameter at the speed of light. This incredibly brief virtual existence of such a supermassive *unification particle* means that any effect it may have in a laboratory experiment will be extremely tiny. Experimentalists may have to sift through staggering numbers of nuclear events to find the precious few that reveal the signature of a unification particle. Nevertheless, a number of technically feasible experiments have been designed that bear on the unification of the strong and electroweak forces. A few of these experiments are

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described in the following sections; some of them are already in progress, while others await the construction of specialized new accelerators.

Time-Reversal-Invariance Violation

The origin of time-reversal-invariance violation is unknown. At present, the only known instance of this phenomenon is in the decay of neutral K mesons (kaons). A neutral kaon and its antikaon are exactly alike except for the quantum number called *strangeness*, which is related to the strong interaction. The weak interaction does not respect strangeness and "mixes" the pure kaon and its pure antikaon; the two kaons that are actually observed can be thought of (roughly) as two different hybrids of the pure kaon states.

Now that tentative Grand Unified Theories are available, it appears to be possible to incorporate time-reversal-invariance violation into their framework, based on certain details of the decay properties of these kaons. Experiments to measure the neutral kaon decay precisely and to search for evidence of time-reversal-invariance violation in another possible decay mode may be crucial in finding the correct way to account for the violation in the context of grand unification. However, kaon beams 10 to 100 times more intense than those currently available will be needed for these experiments.

The Electric Dipole Moment of the Neutron

Finding a second example of time-reversal-invariance violation would be a major event in physics. Such an example might conceivably be found in the neutron—if it can be shown to have an electric dipole moment. An electrically neutral particle can possess a measurable electric dipole moment (internal separation of positive and negative charge) only if both parity and time-reversal invariance are violated.

Very sensitive experiments have been carried out over the past three decades to try to measure the electric dipole moment of the neutron. When a neutron is between the poles of a magnet, the interaction with the neutron's intrinsic magnetism produces two possible energy levels, depending on whether the neutron's axis is aligned parallel or antiparallel to the applied magnetic field. An observable change from one level to the other can be induced by bathing the neutrons in an oscillating radio-frequency field having just the right frequency; a representative value is 60 megahertz (60 million cycles per second) in a strong magnet. The principle is just the same as in the nuclear-magnetic-resonance

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equipment routinely used by chemists to detect protons in molecules. However, a beam of free protons is not suitable for the electric dipole moment search, because protons are charged and would be deflected out of the magnetic field. Neutrons, on the other hand, are uncharged and can be obtained as a slow-moving beam; the experimental sensitivity is thus enhanced because of the increased length of time that they remain in the magnetic field.

In the experiment, a strong electric field is applied simultaneously with the magnetic field. If the neutron has an electric dipole moment, the energy added by the electric interaction will slightly shift the difference between the neutron's energy levels in the magnetic field. Current experiments are sensitive to shifts as small as 0.001 hertz.

With the present sensitivities, no electric dipole moment has yet been observed in the neutron. If the neutron does have an electric dipole moment, it must be smaller than that which would be due to a positive electron and a negative electron separated by only 6×10^{-25} cm (roughly 10^{-11} times the radius of the neutron). Thus, if a neutron were expanded to the size of the Earth, the "bulge" of electric charge in one hemisphere represented by this maximum value of the dipole moment would be only about the thickness of a human hair! This infinitesimal limit has ruled out a number of theories that predict an observably large moment, leaving only theories that predict either an extremely small moment or no observable time-reversal-invariance violations outside the kaon system.

To increase further the sensitivity of the experiments, very-slow-moving (cold) neutrons will be needed, because they will remain longer in the magnetic field of the detector, allowing a more sharply defined measurement. Present experiments have reached the limits imposed by the two major reactor facilities (in France and the Soviet Union) that produce cold neutrons. Further progress will require specialized techniques, such as spallation neutron sources and cold moderators at accelerators.

Rare Muon and Kaon Decays

According to the quark model, the six quark flavors fall into three distinct families of two each. It has been known for many years that the weak interaction "mixes" the quark families, so that a quark from one family can change into a quark from another. The lambda hyperon (quark structure *uds*), for example, has a rare decay mode in which it transforms to a proton (*uud*), an electron, and an antineutrino; this

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decay mode evidently requires a strange quark from one family to become an up quark from another.

It is interesting, but not necessarily significant, that leptons also come in three families of two each, and many Grand Unified Theories allow mixing between lepton families, in analogy with the mixing between quark families. Such mixing would, in turn, allow the occurrence of decay modes in which lepton family number was not conserved—for instance, the decay of a muon into an electron and a gamma ray (see Figure 9.1). The observation of this decay would be both an indication of such mixing and a much-needed signpost pointing toward the correct Grand Unified Theory.

Intensive effort at all three of the world's meson factories—the Los Alamos Meson Physics Facility, the Tri-University Meson Facility (Vancouver, British Columbia), and the Swiss Institute of Nuclear Research (Villigen)—has been put into the search for the electron mode of muon decay. The lowest limit to date, established at Los Alamos, shows that this mode occurs no more frequently than once in every 6×10^9 muon decays. This is a very small limit, but a more-intense muon source would allow even lower limits (greater experimental sensitivity) to be achieved. Failure to see one distinctive electron-mode decay in every 10^{15} muon decays might eliminate all but a few of the currently conceived Grand Unified Theories from further consideration.

Rare decays of kaons offer a cornucopia of opportunities for looking at the electroweak synthesis and beyond. Present theory predicts that a positive kaon should decay into a positive pion and a neutrino-antineutrino pair somewhere between 1 and 30 times in every 10^{10} kaon decays. Agreement of experiment with this prediction would confirm the number of quark families, including the existence of the hitherto unobserved top quark, and would even provide a value for the latter's mass. Experiments to search for this decay are planned for existing accelerators and will require large detectors and long measurement times. If the decay probability is significantly less than one event in 10^{10}, then its detection is out of reach at present. Accelerators capable of producing kaon or muon beams of far greater intensity are needed for the study of electroweak interactions through rare decay modes.

Together, the theories of the electroweak and strong interactions explain most of what we know about atomic nuclei. Those things that we know but are unable to explain—as well as many of the innumerable things that we do not yet know at all—may have their origins in levels of understanding that can arise only from a grand unification of these two interactions. Direct tests of grand unification are at present

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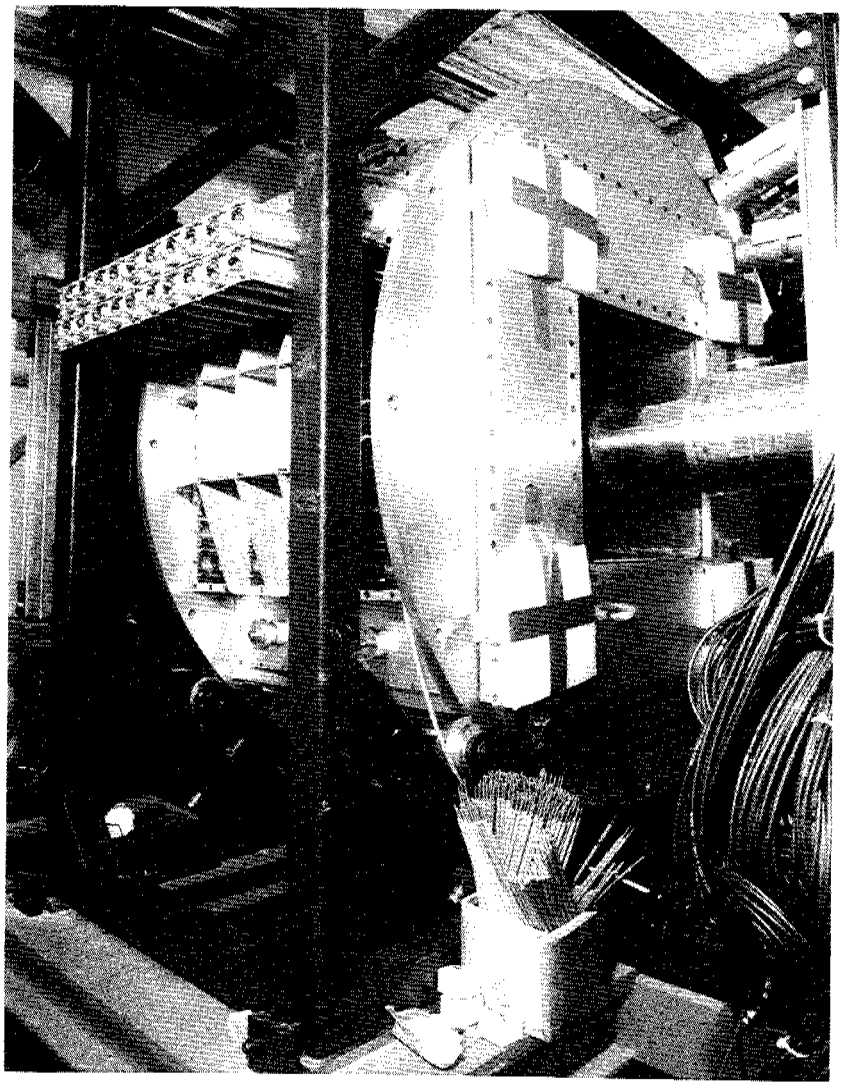


FIGURE 9.1 The Crystal Box spectrometer, an advanced particle and radiation detector currently under construction at the Los Alamos Meson Physics Facility. Consisting of several hundred specially shaped sodium iodide crystals with associated electronics packages, it will be used in searching for the decay of muons to electrons and gamma rays. (Courtesy of the Los Alamos National Laboratory.)

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impossible, of course, because no conceivable accelerator could even approach the necessary 10^{15}-GeV energies.

Instead, the current emphasis is on extremely rare—but profoundly significant—processes that can be observed at accessible energies. In addition to high experimental selectivity and sensitivity, this search requires the maximum possible beam intensities, in order to produce the huge numbers of events among which the occasional rare ones may be found. These invaluable bits of information from nuclear physics may ultimately prove essential for weaving together our fragmentary knowledge into a Grand Unified Theory of the fundamental interactions.

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10

Recommended Priorities for Nuclear Physics

Federal funding for basic nuclear-physics research in the United States began in the late 1940s, first by the Office of Naval Research and then under the auspices of the Atomic Energy Commission. It continues today under joint sponsorship of the Department of Energy (DOE) and the National Science Foundation (NSF). Without the support of these organizations, this vital discipline could not have made the many significant contributions to basic and applied research that have helped to place the United States in a position of world leadership in science and technology. It is the perception of the Panel on Nuclear Physics, however, that American leadership in our discipline is eroding, owing in part to the aggressive pursuit of major research programs in Europe and Japan. Decisive steps must be taken if the United States is to maintain a position in the vanguard of international research in nuclear physics.

In October 1977, the DOE/NSF Nuclear Science Advisory Committee (NSAC) was established in answer to the need for a committee of experts to oversee the general activities and trends in the various subfields of nuclear physics and to make appropriate recommendations to the funding agencies. In 1979 NSAC produced its first Long Range Plan for Nuclear Science; its second Long Range Plan was completed in 1983. The purpose of these studies is to review previous and ongoing programs, evaluate current requirements, and anticipate future needs; they also seek to ensure that existing facilities are maintained and

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upgraded appropriately and that new ones are developed to provide the capabilities required for continuing major scientific advances. The Panel met independently and also joined with NSAC during its week-long Workshop in July 1983, when the major draft of its 1983 Long Range Plan was formulated. The recommendations that follow are a result of these extensive interactions and discussions.

ACCELERATORS IN NUCLEAR PHYSICS

Because accelerators are the basic tools of nuclear physics research, we will briefly review their current status. The probes needed to examine the atomic nucleus are projectile beams of nuclei and subnuclear particles, which must be accelerated to sufficiently high energies to be able to penetrate into or scatter from target nuclei. The projectiles must arrive as a focused beam in the target area, which is often located far from the point at which the beam emerges from the accelerator. One or more detectors are used to record and measure the particles produced by the nuclear interactions. The planning, design, and construction of first-rate accelerators and their associated experimental facilities have become increasingly important to the nuclear physics community at large. Designs must be optimized to support those programs most likely to produce new results in critical research areas and to satisfy the needs of the largest number of users.

An accelerator's capability for providing beams of a given particle with a specific energy can be described by three parameters: the *beam intensity*, or the number of particles striking the target per second, expressed as beam current; the *energy resolution*, or the narrowness of the energy spread of the beam, usually expressed as percent of total energy; and the *duty factor*, or the fraction of time that particles actually strike the target. Some beams, for example, are pulsed: the duty factor is then the ratio of the pulse duration to its repetition time. Optimizing all three parameters is desirable but seldom possible, so designing a particular experiment requires that decisions be made regarding which of them can or must be optimized. A low beam intensity or a low duty factor can greatly increase the time required to accumulate the number of events (nuclear interactions) necessary to make statistically meaningful measurements. Poor energy resolution restricts the accuracy of measurement attainable. Often a trade-off is made; for example, beam intensity might be optimized at the expense of energy resolution, or vice versa.

Accelerators range in size from large, multiuser facilities designed to serve the needs of both resident physicists and users from other

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institutions (both domestic and foreign) to smaller, dedicated university accelerators. Although the latter are generally also available to outside users, they are more closely tailored to the special requirements of their own faculties. All of these facilities make it possible to conduct forefront research in nuclear physics while providing for the education and training of undergraduate and graduate students and postdoctoral fellows.

Existing Facilities

The accelerators in use today provide a wide range of projectiles, energies, and beam intensities for a great variety of research programs. The type of projectile and its energy determine the nature of the information that the experiment will yield. Some experiments require electrons, with their particularly well-understood interactions; others require intense beams of protons or secondarily produced mesons; still others require high-energy heavy ions. The ability to bring such complementary experimental techniques to bear on a variety of research problems in nuclear structure and nuclear reactions has been a crucial element in many of the major advances in nuclear physics during the past decade. There are currently nine large, multiuser, national accelerator facilities spanning this experimental range; the two largest are the Los Alamos Meson Physics Facility (LAMPF), a proton linear accelerator at the Los Alamos National Laboratory, and the Bevalac Complex, a relativistic heavy-ion accelerator at the Lawrence Berkeley Laboratory. In addition, 13 dedicated university accelerators are supported primarily for nuclear-physics research and provide specialized probes for their quite diversified research programs. These 22 accelerators (many of which have been substantially upgraded in recent years), their capabilities, and examples of the kinds of research problems for which they are used are summarized in Appendix A.

With continuing advances in both physics and technology, it is inevitable that accelerators eventually become obsolete as primary research facilities. Since 1976, federal funding by DOE or NSF for basic nuclear-physics research has been withdrawn from 17 accelerators. Although invariably painful and often accompanied by a substantial disruption of graduate-student and postdoctoral training, judicious attrition has been necessary for the evolution of the field, in order that pioneering new machines can be built and operated at maximal efficiency. The 22 accelerators described in Appendix A constitute, for the near future, a vital, highly productive, and balanced force for our development of modern nuclear physics. The imperative to push the

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frontiers ever further also demands, however, that major new initiatives be undertaken. Several of these are described in the following sections.

The Planned Continuous Electron Beam Accelerator Facility

The electron accelerators designed and built in the 1960s for nuclear-physics research contributed much to our understanding of the distribution of electric charge in nuclei, the coherent collective excitations of the nucleus, and the incoherent electrodisintegration of the nucleus. These accelerators, however, had relatively low energy, poor energy resolution, and poor duty factor. In the last decade, a new generation of electron accelerators has produced electrons with energies of up to 750 MeV with excellent energy resolution and with duty factors of 1 to 2 percent—an order-of-magnitude increase over those of the earlier machines. Experiments at these facilities have had an enormous impact on our knowledge and understanding of nuclear spectroscopy, meson production, and meson-exchange currents. Over the same period of time, experiments on the lightest nuclei done at the very-high-energy but low-duty-factor machine at the Stanford Linear Accelerator Center suggested the need for a broader view of nuclei, encompassing the quark structure of the nucleons.

Significant connections between nuclear physics and elementary-particle physics have emerged from these electron experiments, and it appears that a smooth transition in the behavior of the nucleus occurs with increasing energy. This behavior is well described at low energies by independent-particle models of nuclear structure, which take into account only the nucleons as constituents; at higher energies, account must also be taken of the effects of baryons and mesons and, eventually, of quarks and gluons. Coincidence measurements, in which significant results come from only a small fraction of the total number of events, are of extreme importance in these studies and require accelerators with much higher duty factors than now exist. Higher energies and higher beam intensities are needed to extend investigations to the scale of very short distances, where the nucleus can best be described in terms of its fundamental quark and gluon constituents. This research frontier can be reached by an accelerator producing 4-GeV electrons, an energy that is also sufficient for studying the production of baryon resonances (excited states of nucleons), heavy mesons, and "strange" particles in the nuclear medium.

On the basis of both the *DOE/NSF Joint Study of the Role of Electron Accelerators in U.S. Medium Energy Nuclear Science* (the

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Livingston report, 1977) and its own deliberations, NSAC, in its 1979 Long Range Plan, found a critical need for a high-duty-factor electron accelerator with variable beam energies of up to several GeV. Subsequently, in the 1983 report of the NSAC Panel on Electron Accelerator Facilities, a specific recommendation for such a machine, to be operated as a national facility, was made: a 100 percent-duty-factor, 4-GeV linear-accelerator/stretcher-ring complex now called the *Continuous Electron Beam Accelerator Facility* (CEBAF), which was proposed by the Southeastern Universities Research Association. The research and development funding for this machine began in FY 1984, and construction funding is proposed for FY 1987. A total accelerator cost of $225 million (in actual-year dollars) is projected; this includes $40 million for the initial experimental equipment.

We conclude this section by quoting from the NSAC 1983 Long Range Plan (*A Long Range Plan for Nuclear Science: A Report by the DOE/NSF Nuclear Science Advisory Committee*, December 1983, page 75):

> 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* [National Electron Accelerator Laboratory, the original name for CEBAF] *is clearly the major near-term new initiative in nuclear physics.*

The Panel on Nuclear Physics endorses the construction of CEBAF.

THE NEXT MAJOR INITIATIVE: THE RELATIVISTIC NUCLEAR COLLIDER

As discussed in Chapter 7, our increased understanding of the strong interaction between hadrons has led us to believe that, under conditions of greatly increased temperature and density in nuclear matter, there will be a transition from excited hadronic matter to a *quark-gluon plasma*, in which quarks, antiquarks, and gluons will no longer be confined inside individual hadrons but will be free to move about (for about 10^{-22} second) within a much larger volume. This extreme state of matter is believed to have occurred in nature at the very beginning of the universe, in the first few microseconds after the big bang, and it may exist today in the cores of neutron stars, but it has never been observed on Earth. Its production and analysis in controlled laboratory experiments would provide us with scientific information cutting

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across the traditional boundaries of nuclear physics, elementary-particle physics, and astrophysics and would create a common ground on questions relevant to cosmology—the universe and our place in it.

Present theoretical estimates suggest that collisions of heavy nuclear projectiles with energies of the order of 30 GeV per nucleon can generate temperatures and densities high enough to liberate the quark and gluon constituents of the nucleons and—more importantly—to create large numbers of quarks, antiquarks, and gluons from the energy of the collision. At such relativistic energies, the head-on collision of two heavy nuclei will create an extremely hot, dense region of nuclear matter encompassing hundreds of cubic fermis in volume. The enormous energy density achieved throughout this large volume will constitute a unique combination of conditions—not available in the collisions of electrons, protons, or light nuclei—for creating the quark-gluon plasma. The accelerator needed to produce these conditions, a *relativistic nuclear collider* (RNC), would be the world's highest-energy accelerator capable of providing nuclear beams over the full range of the periodic table, from hydrogen to uranium.

Although the production of the quark-gluon plasma—in the regions of both high energy density (the *central* region) and high baryon density (the *fragmentation* regions)—would represent a major focus of research at the RNC, this accelerator would provide many additional new research opportunities in nuclear physics, including the following:

- Extension of the study of quantum chromodynamics (QCD) to large distances (roughly the diameter of a nucleus), complementing its study at very short distances (less than the diameter of a nucleon), in which electrons or hadrons are used as probes.
- The possibility of studying conditions under which the masses of the light quarks go to zero (as predicted by QCD) and the states of the system of quarks obey a right-hand/left-hand symmetry (*chiral symmetry*).
- The first opportunity for investigating the dynamics of extended objects with very-high-energy density—conditions that can be achieved only in relativistic nuclear collisions.
- The possible production of exotic objects, such as free quarks (with fractional electric charge), quark "globs" with unique topological (structural) properties or exceptionally high strangeness, and Centauros—mysterious events, observed in very-high-energy cosmic-ray studies, that produce few or no neutral pions, which suggests a hitherto unknown kind of nuclear interaction.

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In addition to producing colliding nuclear beams for a dedicated program of study of the quark-gluon plasma, the RNC should also have the capability for a variety of fixed-target experiments at energies of the order of 30 GeV per nucleon. Some examples demonstrating the breadth of this fixed-target research program are the following:

- Production and study of radioactive nuclei far from the valley of stability and their use as exotic secondary beams.
- Development of a rich program of nuclear physics with very heavy systems at relativistic energies, using intense beams to investigate rare processes, such as coherent pion production (from a *pion condensate*, for example).
- Investigations of highly excited hadronic matter (in which the quarks and gluons are confined), providing new opportunities for deducing the equation of state of nuclear matter under conditions far from normal.
- Creation of the maximum possible baryon density achievable in a laboratory experiment, thereby opening a new avenue of experimental research in nuclear astrophysics.
- Studies of few-electron, very heavy ions, enabling new domains of quantum electrodynamics to be tested.

Recommendations from the NSAC 1983 Long Range Plan

Because the long-range plans for nuclear physics were reviewed by the Nuclear Science Advisory Committee in 1983, it is important to state the Committee's major recommendation for new facility construction, taken from the summary (page vi) of its 1983 Long Range Plan:

> 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

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with energies of about 30 GeV per nucleon. . . . *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 Panel endorses the NSAC 1983 Long Range Plan in recommending the planning for the construction of an accelerator that can provide colliding beams of very heavy nuclei at energies of the order of 30 GeV per nucleon with which to create the extreme conditions of nuclear matter described above. The cost of this facility, including initial major detectors, is estimated to be $250 million (in FY 1983 dollars), with a construction period of 4 to 5 years. Operating and research costs are estimated at $35 million per year. Research and development will be needed to refine the design of this accelerator and specify its costs. Once designed, construction should begin as soon as possible, consistent with that of the 4-GeV electron accelerator discussed above. Since current funding levels are barely adequate to respond, with the *present* facilities, to the exciting scientific opportunities confronting the field, we recommend an increase in nuclear-physics operating funds sufficient to support the necessary accelerator research and development as well as the operations and research programs at these two new facilities as they come into being.

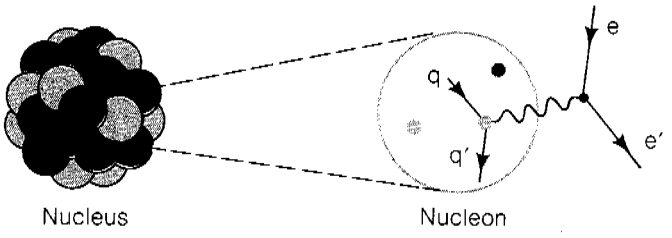
Complementary Aspects of CEBAF and the RNC

Both of the new accelerators being planned by the United States nuclear-physics community—the Continuous Electron Beam Accelerator Facility (CEBAF) and the relativistic nuclear collider (RNC)—will address extremely important questions concerning the quark aspects of nuclear matter. The theoretical and experimental research programs at these two accelerators will be dramatically different, however (see Figure 10.1).

Using intense beams of high-energy electrons, CEBAF will probe the short-range behavior of quarks in nuclei with surgical precision. It will do this by implanting a localized, well-understood electromagnetic disturbance in the nucleus and measuring the response of the nuclear environment to this stimulus. Electrons, being pointlike particles, are well suited to such studies. They will act as a powerful microscope, able to focus on the ways in which the quark substructure affects the properties and interactions of nucleons residing inside the target nucleus.

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(a) Continuous Electron Beam Accelerator Facility (CEBAF)



(b) Relativistic nuclear collider (RNC)

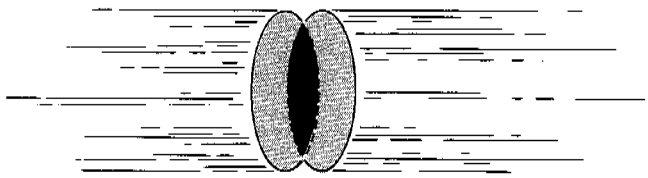


FIGURE 10.1 The complementary aspects of CEBAF and the RNC. (a) CEBAF will test the response of nuclei to high-energy, pointlike disturbances caused by the interaction of electrons with quarks, over distances much less than 1 fermi. (b) The RNC will test the response of heavy nuclei to the high energy densities created throughout large volumes (hundreds of cubic fermis) when they collide head-on at relativistic velocities.

The RNC, on the other hand, will cause beams of heavy nuclei to collide violently with each other. These nuclei are relatively large objects, with volumes of up to several hundred cubic fermis. When they collide head-on, all the nuclear matter can interact and be heated to such enormous temperatures and energy densities that the quarks and gluons become deconfined from the nucleons, and large numbers of quarks, antiquarks, and gluons are created. These particles can then move about inside a relatively large volume—the quark-gluon plasma. It is expected that the macroscopic behavior of quarks will be revealed under these conditions.

Thus, to see how quarks will modify and extend our understanding of nuclear physics, both of the accelerators are needed—to elucidate both the microscopic and the macroscopic aspects of quarks in nuclear matter.

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FURTHER RECOMMENDATIONS

In evaluating the prospects and promise for nuclear-physics research in the next decade, it is also vital to consider facilities and opportunities beyond the construction of the two major new accelerators discussed above. Our analysis of the current state of nuclear physics leads us to make the following recommendations for other important aspects of the field.

Additional Facility Opportunities

A number of additional opportunities are under discussion in the nuclear-physics community. The most important ones are listed in Table 10.1. Here it is again appropriate to quote from the summary (page v) of the NSAC 1983 Long Range Plan:

> 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.

It should be noted that a number of the capabilities listed in Table 10.1 (specifically, the second, fifth, sixth, and eighth items), addressing many of the physics topics mentioned above, could be encompassed by another major new multiuser accelerator. As currently envisioned, such an accelerator might comprise a synchrotron producing very intense proton beams at energies of up to tens of GeV, followed by a stretcher ring to produce a nearly continuous spill of protons that would yield secondary beams of pions, kaons, muons, neutrinos, and antinucleons. The intensities of these beams could be typically 50 to 100 times greater than those available anywhere else, allowing a substantial improvement in the precision and sensitivity of a large class of important experiments at the interface between nuclear physics and

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TABLE 10.1 Additional Facility Opportunities for Nuclear Physics[a]

Research Program (Examples)	Capability Required
Structure of elementary nuclear excitations; form of nuclear momentum distributions; nature of long-range and medium-range nuclear interactions	High-duty-factor electron beams with good energy resolution at energies below 1 GeV
Spin dependence of the nuclear interaction; fundamental symmetry tests; nuclear structure at high-momentum transfer	High-quality, high-intensity polarized proton beams spanning in stages the energy range from 50 MeV to several GeV
Microscopic optical model; nuclear structure and nuclear shape transitions; studies of Gamow-Teller resonances	Secondary neutron beams (polarized and unpolarized) with good intensity and energy resolution at energies of up to several hundred MeV
Nuclear spectroscopy of isotopes far from stability; nuclear astrophysical reaction rates; search for exotic nuclei and superheavy elements	Intense secondary beams of radioactive nuclei
Hypernuclear physics; rare kaon decays and other weak interaction studies; exotic atoms	Intense kaon beams of high purity
Tests of electroweak interactions; weak interactions of leptons with nuclei; muon spin resonance studies of solids	Intense muon and neutrino beams of high quality
Energy dependence of nuclear-reaction mechanisms; multiparticle decay of highly excited compound nuclei; giant resonances	Heavy ions through uranium, at energies between 10 and 100 MeV per nucleon
Nuclear physics with antinucleons; antinucleon-nucleon interactions to study few-quark dynamics; anti-nucleon atomic systems	Low-energy and medium-energy antinucleon beams
Nuclear astrophysics—solar neutrino measurements; neutrino oscillations	Solar neutrino detector sensitive to low-energy (less than 300-keV) neutrinos

[a] The sequence of items is *not* intended to suggest relative priorities.

particle physics. In particular, many experiments that are currently impractical because of low count rates or cosmic-ray backgrounds would become possible. In this context, we quote once more from the NSAC 1983 Long Range Plan (pages 74-75):

A major new "Kaon Factory," a 10-30-GeV proton accelerator with 10^{14}-10^{15} protons per second, would provide substantial opportunities for

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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 [now called the Continuous Electron Beam Accelerator Facility] 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.

Nuclear Instrumentation

A serious national problem exists in the area of appropriate continued support for nuclear-physics instrumentation. The NSAC 1983 Long Range Plan notes that the amount spent by the United States for basic nuclear-physics research relative to its Gross National Product is less than half of that spent in Western Europe or Canada. The effects of this disparity can readily be seen in the quality and sophistication of European instrumentation, which in many instances far surpasses that found in American universities and national laboratories. An increase in dedicated funding for instrumentation at both large and small facilities is therefore deemed essential.

Examples of the need for new equipment abound. Obtaining information about the de-excitation of high spin states formed in heavy-ion-induced reactions requires the use of large, spherical arrays of scintillation detectors called *crystal balls*. The study of relativistic heavy-ion collisions requires large-mass, fine-grained detectors that allow the simultaneous localization, tracking, identification, and energy detection of large numbers of emitted particles. Magnetic spectrometer systems have been steadily improving in performance, and even greater improvements (as well as significant cost reductions) can be made by using superconducting magnets. Studies of effects arising from the aligned spins of particles require both polarized targets and ion sources that will efficiently produce high-intensity polarized beams. Equally pressing is the need for advances in data reduction techniques, as the number of measured parameters grows with the increasingly complex experiments.

Research and development programs are also necessary to determine the most effective solutions for the rapidly increasing requirements for sophisticated instrumentation. Higher-energy beams, for example, will require the development of detector systems whose capabilities far exceed those that have been used in nuclear physics to date. An extensive research and development program for the implementation of detectors at the CEBAF will be needed, as well as a

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program to develop detectors with large solid angle, high segmentation, and good particle identification for the RNC.

Nuclear Theory

In nuclear physics, as in all other branches of physics, theoretical work provides both interpretation and guidance. Although in every field of science there are always some experiments that produce significant and sometimes dramatic progress in and of themselves, steady progress is made for the most part through the informed choice of experiments. Theorists working closely with experimentalists can provide direction in the best choice of experiment by suggesting what the most critical test of a concept would be and the measurements or conditions that would make a complete theoretical analysis feasible. The closer the link between theory and experiment, the more effective they both become in synthesizing a coherent and elegant body of knowledge.

Although the NSAC 1979 Long Range Plan stressed the need for increased support of nuclear theory, a comparison of the current FY 1984 budget for nuclear physics with the FY 1979 budget shows that during the intervening 5 years, funding for nuclear theory has remained essentially constant as a percentage of the whole (5.8 percent in FY 1984 versus 6.0 percent in FY 1979). We believe that there is still a clear need for a substantial relative increase in the support of nuclear theory, especially in light of the new and challenging frontiers that are opening up in nuclear physics. Among these are the study of the behavior of nuclear states ever farther from stability, the study of the nonnucleonic substructure of nuclei, the search for the quark-gluon plasma, and the increasing interaction between nuclear physics and particle physics.

Progress in current theoretical research depends on substantial access to first-class computational facilities. Extensive calculations based on the complex models describing today's experiments require the large memories and rapid processing capabilities of Class VI computers. Access by nuclear theorists to a major fraction of the time available on a central, well-implemented Class VI computer could initially meet this need.

Accelerator Research and Development

Accelerator research and development continues to be vital in meeting the need for new advanced facilities and should be appropri-

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ately supported. One of the most important recent breakthroughs has been the successful use of *superconducting materials* in accelerators. Radio-frequency (rf) superconductivity is now an established technology, with numerous applications to electron acceleration and to heavy-ion beam bunching and acceleration. Other superconducting structures are also currently being investigated. For example, the University of Illinois Nuclear Physics Laboratory is using a superconducting linear accelerator (developed at Stanford) in a microtron, and two superconducting rf linear accelerators are now in operation as postaccelerators at Argonne and at SUNY-Stony Brook. In a related area, the extremely strong magnetic fields obtained from superconducting magnets reduce the size, the power requirement, and hence the cost of cyclotrons that use them for the main field. Two superconducting cyclotrons were begun in the mid-1970s. One is now in operation at Michigan State University; the other, at the Chalk River Nuclear Laboratory in Canada, will be operating in the near future.

A fundamentally new type of accelerator for low-velocity ions, the *radio-frequency quadrupole*, has been pioneered at the Los Alamos National Laboratory. Based on a theory originally developed in the Soviet Union, it makes use of advanced techniques to capture more than 90 percent of the beam from the ion source. It is an extremely efficient preaccelerator for a larger accelerator and is currently being developed at various laboratories in the United States and around the world.

Borrowing a technique developed by elementary-particle physicists, scientists at the Indiana University Cyclotron Facility are adding a *beam cooler*—a storage ring in which the accelerated beam will be circulated and "cooled" via interaction over part of the ring with a collinear electron beam of the same velocity—to reduce greatly its energy spread. This will provide a previously unmatched level of precision for experiments with high-energy protons. The technique represents a cost-effective way to achieve unusual capabilities at other accelerators as well, and it is likely to be extensively developed in the near future.

Studies are in progress to devise effective methods for producing beams of *short-lived radioactive nuclides* with intensities that are adequate for nuclear-physics and astrophysics experiments. For example, radioactive beams can be obtained by methods in which the desired nuclide is produced as a low-energy fragment from the target of a primary beam in a bombardment reaction, captured in an ion source, ionized, and finally accelerated toward a second target. In another, more direct method, the radioactive nuclides emerge at relatively high

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energy from a suitable primary target in the form of a secondary beam that can be used as is or accelerated or decelerated to different energies.

The development of new ion sources has been rapid in the last decade. The *electron-cyclotron-resonance ion source* and the *electron-beam ion source*, both of which underwent their pioneering development in Europe, are currently being put to use in the United States. Along with various schemes for laser-driven ion sources and polarized ion sources, they will be important elements of future nuclear-physics research programs.

Training New Scientists

The Gardner report on excellence in education (*A Nation at Risk: The Imperative for Educational Reform*, The National Commission on Excellence in Education, U.S. Government Printing Office, Washington, D.C., 1983) points out that for the first time in U.S. history, the educational skills of a generation not only do not surpass those of the previous generation, they do not even *approach* them. These educational deficiencies, coming at a time when the demand for high technical skills is accelerating, can result in the loss of America's place of world leadership in intellectual achievement, technical innovation, and material benefits. The report contends, furthermore, that the security of the United States depends on the government's nurturing of its intellectual capital. To maintain the highest level of achievement by their students, colleges and universities must offer the best possible learning tools.

The report states that: "The Federal Government has *the primary responsibility* to identify the national interest in education. It should also help fund and support efforts to protect and promote that interest." It recommends that the government provide student financial assistance and research and graduate training with a minimum of administrative burden and intrusiveness.

In addition to the general decline of trained personnel, a marked decrease in the number of students pursuing graduate courses in physics, and nuclear physics in particular, has become evident since the early 1970s. If this trend continues, it promises to leave the field seriously deficient in skilled scientists. The causes of the decline, although varied, must certainly include as contributing factors the severe financial problems faced by many colleges and universities. This results in diminished financial aid for students, the loss of dedicated, on-site accelerator facilities (indispensable tools for the teaching of

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nuclear physics), and the reduction of new academic positions (which is intensified by the current low retirement rate in university faculties). Futhermore, many who *do* obtain higher degrees in physics are attracted by the much higher salaries in industry and are thus lost to basic research.

Some recommendations to offset these tendencies are the following:

- Attract students to nuclear physics by funding undergraduate nuclear-science research programs and by arranging for the participation of secondary school students in introductory studies.
- Increase National Science Foundation predoctoral fellowships in general, and establish a specific program of Department of Energy fellowships in nuclear physics.
- Increase the emphasis on support of new research initiatives by awarding 3-year funded grants for proposals submitted by young scientists past the postdoctoral stage.
- Increase the funding for university research groups to enable them to hire their own nonacademic staff, such as scientists or engineers specializing in technical problems.
- Instigate a program of temporary support of tenure-track faculty positions to sustain nuclear physicists during the present period of low university retirement rates.
- Consider the educational aspects of new facilities where practicable; they should attract the highest-caliber graduate students and give them the best possible training.

Enriched Stable Isotopes

The Calutron facility at Oak Ridge National Laboratory (ORNL) is the major U.S. source of stable isotopes, which are used both in scientific research and in the production of radioactive isotopes needed for biomedical research and clinical medicine. Several stable isotopes can occur in a chemical element; the isotope of interest, which may constitute only a minute fraction of the total material, must be carefully separated and purified from contamination by other isotopes. The electromagnetic separation method used at ORNL is notable for its ability to respond to changing demands; it represents an invaluable national as well as international resource. The only comparable electromagnetic separation facility is in the Soviet Union.

Acute shortages of stable isotopes now exist (some 50 are currently unavailable from ORNL), and severe funding insufficiencies forecast rapid deterioration in the supply. The worsening shortages could have

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disastrous consequences in many areas of scientific research as well as clinical medicine, where stable isotopes are indispensable tools. The importance of enriched isotopes in nuclear-physics research derives from the specific properties of the isotope in question. Virtually all nuclear studies require separated isotopes, because the properties of a nucleus can change drastically with the addition or removal of a single nucleon. Consequently, an important priority is to replenish the supply of separated isotopes before much nuclear-physics research is crippled. To ensure that the problem is solved, corrective steps must continue to be vigorously pursued, both by the scientific communities affected and by the funding agencies.

Nuclear Data Compilation

For more than 40 years, compilers and evaluators have attempted to keep scientists abreast of detailed nuclear data as they become available. With the rapid experimental advances of the last two decades, however, nuclear data compilations have begun to fall behind. The continuing need for timely, cost-effective, and high-quality evaluations led in 1976 to the formation of an international evaluation network under the auspices of the International Atomic Energy Agency. The network consists of 16 data centers in 11 countries; each center is responsible for the evaluation of specified information in order to avoid costly duplication of effort. All evaluated data are published in *Nuclear Data Sheets* or *Nuclear Physics* and are entered into the computerized Evaluated Nuclear Structure Data File maintained by the National Nuclear Data Center at Brookhaven National Laboratory. These data do not include a comprehensive compilation of charged-particle cross sections, however; the need for such a compilation exists in many areas of research, both basic and applied.

In addition to participating in the international network, the five United States data centers coordinate their activities through the U.S. Nuclear Data Network. These activities are funded primarily by the Department of Energy (DOE) and are reviewed annually by the National Academy of Sciences' Panel on Basic Nuclear Data Compilations, which is advisory to DOE. Because the costs of this program are relatively small, a modest increase in funding would greatly enhance the ability to maintain a thorough compilation/evaluation effort and to ensure the timely publication of these results in the various formats required both by nuclear physicists and by applied users of radioactive isotopes.

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Appendixes

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A

National and Dedicated University Accelerator Facilities

The nine national accelerator facilities devoted to basic nuclear-physics research in the United States are listed in Table A.1. Table A.2 lists 13 dedicated university accelerator facilities. Included in this list are those facilities that are fully supported for basic nuclear-physics research. Not included are additional university and national-laboratory facilities that are only partially supported for basic nuclear-physics research.

The accelerators listed in Tables A.1 and A.2 are of four basic kinds: Van de Graaff electrostatic accelerators, linear accelerators, cyclotrons, and synchrotrons. Because they are all charged-particle accelerators, the charge state of the ion is a determining factor in their energy output. Most commonly, the maximum energy available per nucleon decreases with increasing projectile mass; where a range in energy is given with a corresponding mass range, the high energy corresponds to the low mass, and vice versa. The energy is usually expressed in MeV or GeV per nucleon, where approximately:

- 5 MeV per nucleon is needed to overcome the Coulomb barrier.
- 10 MeV per nucleon will produce moderate excitations of nuclear matter.
- 100 MeV per nucleon will produce high nuclear temperatures and pion creation.
- 1 GeV per nucleon will produce high nuclear energy densities and the formation of exotic states of nuclear matter.

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Somewhat arbitrarily, as described in Chapter 1, these energies can be classified in ranges as follows:

Low energy: less than about 10 MeV per nucleon
Medium energy: 10 to 100 MeV per nucleon
High energy: 100 MeV to 1 GeV per nucleon
Relativistic energy: greater than about 1 GeV per nucleon (electrons become relativistic at about 0.5 MeV)

It is important to note that this classification scheme is not universally accepted; for various reasons, both technical and historical, the interpretations of the first three terms vary considerably among different groups of physicists.

Similarly arbitrary but useful is the following classification of projectile masses. *Light ions* are considered to be the hydrogen ions (protons, deuterons, and tritons) and the helium ions (masses 3 and 4). Lithium ions (masses 6 and 7) begin the *medium-ion* range (although lithium is sometimes included in the light-ion definition), which extends to about mass 40. Above mass 40 the projectiles are classified as *heavy ions*.

TABLE A.1 National Accelerator Facilities

Facility	Accelerator Type	Beams and Energies	Planned Upgrades	Typical Research Problems
VERY LARGE				
Bevalac Complex, Lawrence Berkeley Laboratory	Synchrotron (Bevatron) injected by heavy-ion linear accelerator (SuperHILAC)	Light to heavy ions, to A = 238; at SuperHILAC, 8.5 MeV/N; at Bevatron, A = 4-238, to 2.1-0.96 GeV/N	Radio-frequency quadrupole preaccelerator; full-solid-angle electronic detector	Relativistic heavy-ion reactions; central and peripheral collisions; explosions of compressed nuclei; measurement of size of interacting volume; pion and strange-particle production; exotic forms of nuclear matter
Los Alamos Meson Physics Facility (LAMPF), Los Alamos National Laboratory	Linear accelerator	Protons; pion, muon, and neutrino secondary beams; H^+, 800 MeV; H^-, 212-800 MeV, polarized or unpolarized; muons and pions to 400 MeV	Proton storage ring; time-of-flight spectrometer; low-energy pion spectrometer	Nucleon-nucleon, proton-nucleus, and pion-nucleus interactions; weak interactions; muonic and pionic atoms; selective excitation of proton/neutron states; giant resonances; neutron time of flight
LARGE				
Bates Linear Accelerator Center, Massachusetts Institute of Technology	Electron linear accelerator with recirculator	Electrons, bremsstrahlung photons; 400 MeV at high intensity on first pass; recirculated, 50-725 MeV	Polarized beams; BIGBITE spectrometer; beam sharing	High-resolution nuclear structure studies: electric and magnetic structure of nuclei; motion of pions inside nuclei; role of excited states of nucleons in nuclear structure; deep-inelastic electron scattering; parity violation
Indiana University Cyclotron Facility (IUCF), Indiana University	Isochronous cyclotrons with preinjector	Light ions, to A = 7; protons and deuterons, polarized and unpolarized; p to 214 MeV; d to 45 MeV/N; A = 3-7, to 90-25 MeV/N	Dual-arm spectrometer system; electron-cooling storage ring	Spin- and isospin-dependence of effective N-N interactions; giant Gamow-Teller resonances; nuclear structure at high momentum transfer; pion production; radiative capture; few-nucleon systems; charge symmetry of nuclear forces; fission from high excitation

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TABLE A.1 *Continued*

Facility	Accelerator Type	Beams and Energies	Planned Upgrades	Typical Research Problems
National Superconducting Cyclotron Laboratory (NSCL), Michigan State University	Superconducting cyclotron, Phase I, K = 500	Light to medium ions, to A = 40; light ions, 10-35 MeV/N; A = 14-40, to 40-12 MeV/N	Superconducting cyclotron, Phase II, K = 800	Medium-energy heavy-ion reaction mechanisms; nuclear matter disassembly in heavy-ion reactions; spin-flip rotations; Gamow-Teller strength; deeply bound hole states and giant resonances; exotic nuclei
MEDIUM				
Argonne Tandem Linear Accelerator System (ATLAS), Argonne National Laboratory	9-MV tandem Van de Graaff injecting superconducting linear accelerator	Light to heavy ions, to A = 100; A = 6-20, to 11-10 MeV/N; A = 40-100, to 8.5-5 MeV/N	Additional resonators	Heavy-ion fusion at medium energy; resonance phenomena in dinuclear quasi-molecule formation; nuclear deformation in high-spin states; QED and relativistic effects on energy levels of nuclei
Double MP Tandem Facility, Brookhaven National Laboratory	Two MP tandem Van de Graaffs, 16 MV and 12 MV, coupled to equivalent single 20-MV tandem	Light to heavy ions, to $A \simeq 238$; A = 6-32, 13-10 MeV/N; A = 35-238, to 7.5-3.3 MeV/N	Transfer line to Alternating Gradient Synchrotron (AGS) to provide beams up to A = 32, to 15 GeV/N	Heavy-ion fusion; evaporation studies; new beta activities from exotic nuclei; molecular orbitals in light nuclei; high-spin-state gamma-ray spectroscopy; relativistic heavy-ion rections
88-Inch Cyclotron, Lawrence Berkeley Laboratory	Isochronous cyclotron, K = 160	Light to medium ions, to A = 40; protons and deuterons, polarized, to 55 MeV; A = 2-40, to 32-6 MeV/N	Electron cyclotron resonance ion source	Onset of fragmentation in heavy-ion reactions; exotic nuclei; giant dipole resonance at high spin; moments of inertia near rigid-body value; spin-polarization phenomena
Holifield Heavy Ion Research Facility (HHIRF), Oak Ridge National Laboratory	25-MV tandem pelletron injecting isochronous cyclotron as energy booster	Light to heavy ions, to A = 197; A = 4-40, to 25 MeV/N; A = 56-197, to 18-4 MeV/N	Improved ion source; beam bunching; laser-polarized gas-jet target	Gamma-ray spectroscopy; intermediate- and high-spin states; heavy-ion reactions; on-line studies of short-lived radioactive nuclei produced in heavy-ion reactions

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TABLE A.2 Dedicated University Accelerator Facilities[a]

University	Accelerator Type	Beams and Energies	Planned Upgrades	Typical Research Problems
California Institute of Technology	6.5-MV EN tandem, 1.2-MV JN Van de Graaff, 3.3-MV tandem pelletron	Light to medium ions, $A = 40$		Astrophysical reaction rates; radiative capture; heavy-ion fusion; searches for fractionally charged particles
Florida State University	9-MV super FN tandem Van de Graaff	Light to heavy ions, to $A = 60$; at $A = 40$, to 3 MeV/N	Superconducting linear accelerator; polarized alkali-ion source; upgrade to $A = 40$, to 10 MeV/N	Light-ion transfer reactions; heavy-ion-induced resonances; fusion and total reaction cross-section measurements; gamma-gay spectroscopy with heavy ions
University of Illinois, Urbana	2-MV Van de Graff injecting superconducting linear accelerator with 6-pass racetrack microtron	Electrons to 70 MeV	9-pass microtron, to over 100 MeV; 2-stage cascade microtron, to 280 MeV	Correlated nucleon emission following photon absorption; photon tagging; electron scattering coincidence measurements; resonance fluorescence
University of Notre Dame	9-MV FN tandem Van de Graaff with 3-MV electrostatic injector	Protons and deuterons, polarized and unpolarized, 18 MeV; light to medium ions, to $A = 28$; $A = 6$-28, 20-5 MeV/N		Spin and parity determination; nuclear reaction energies; gamma-ray transitions from high-spin, heavy-ion collective states; heavy-ion total fusion
University of Pennsylvania	FN tandem Van de Graaff	Light to heavy ions, to Cu; protons and deuterons, 18 MeV; medium ions to 6 MeV/N		Light-ion transfer reactions; heavy-ion-induced resonances; angular correlation measurements; condensed matter; heavy-ion elastic and inelastic scattering; accelerator mass spectrometry

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TABLE A.2 *Continued*

University	Accelerator Type	Beams and Energies	Planned Upgrades	Typical Research Problems
Princeton University	AVF cyclotron	Protons to 50 MeV; deuterons to 30 MeV; light ions, 15-20 MeV/N	Improved beam diagnostics and cyclotron tuning	High-resolution charged-particle spectroscopy; radioactive isotope production; parity studies; time-reversal studies; strong and weak interactions
University of Rochester	13-MV MP Van de Graaff	Light to heavy ions, to A = 93; protons and deuterons to 25 MeV; A = 6-93, 9-2.8 MeV/N		Mass spectrometry; search for quarks, solar neutrino; fractional charge; applied programs; heavy-ion reaction mechanisms; gamma-ray spectroscopy; molecular resonances in heavy-ion reactions; high-spin states; deep-inelastic reactions; laser spectroscopy
Rutgers University	8-MV FN tandem Van de Graaff	Light to heavy ions, to Fe; polarized protons and deuterons	SF_6 insulating gas; 90° inflection at source; high-current sputter-ion source	Nuclear spectroscopy; intermediate- and high-spin states; hyperfine spectroscopy; laser-beam interactions; nuclear and atomic polarization; parity nonconservation; high-energy mass spectrometry
State University of New York, Stony Brook	9-MV tandem Van de Graaff injecting superconducting linear accelerator	Medium ions to 7 MeV/N	Beam masses and energies continually increasing to goal of A = 100, 10-5 MeV/N	Medium-energy heavy-ion reaction mechanisms; spectroscopy of high-spin states; nuclear molecular resonances; hyperfine spectroscopy of excited nuclei
Texas A&M University	Isochronous cyclotron, K = 147	Light to medium ions, to A = 40; protons and deuterons, polarized, to 55 MeV; light ions to 32 MeV/N; A = 12-40, 26-8 MeV/N	Superconducting cyclotron, K = 500, as injector for present cyclotron	High-precision measurements of giant resonance states; parity violations in hadronic weak interactions; mass measurement of exotic nuclei; nuclear compressibility; cluster configurations; incomplete fusion

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Triangle Universities Nuclear Laboratory (TUNL), Duke University	Sector-focused cyclotron injecting FN tandem Van de Graaff	Protons, deuterons, and neutrons; p to 31 MeV; d to 24 MeV; polarized p and d to 16 MeV	Cryogenic polarized target; new polarized ion source	Nuclear processes using light-ion and neutron projectiles: charged-particle resonances with very high energy resolution; radiative capture; polarization studies; neutron scattering cross sections
University of Washington	Two FN Van de Graaffs: 7-MV injector, 9-MV tandem	Light to medium ions, to $A = 28$; protons and deuterons, polarized and unpolarized, 24 MeV; light ions, 12-7 MeV/N; $A = 12$-28, 5-3.5 MeV/N	Superconducting linear accelerator booster; new polarized ion source	Weak nucleon-nucleon and electron-nucleon force; nucleon charge conservation; breakdown of isospin symmetry; relativistic wave-equation effects; heavy-ion reaction mechanisms
Yale University	13-MV MP tandem Van de Graaff	Light to heavy ions, to $A = 93$; protons and deuterons, 27 MeV; $A = 6$-93, 9-2.8 MeV/N	22-MV ESTU tandem; large-solid-angle magnetic spectrometer	Nuclear molecular resonance in heavy-ion interactions; new symmetries and simplicities in many-body system within frame-work of interacting boson model; ion-surface interactions; nuclear astrophysics

[a] Included are those facilities that are fully supported for basic nuclear-physics research. Not included are additional university facilities that are only partially supported for basic nuclear-physics research.

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B

Advisors and Reviewers

Participants in the DOE/NSF Nuclear Science Advisory Committee's Long Range Plan Workshop, Wells College, Aurora, New York, July 11-15, 1983

*J. P. SCHIFFER, Argonne National Laboratory, *Chairman*
E. G. ADELBERGER, University of Washington, Seattle
*S. M. AUSTIN, Michigan State University
C. BALTAY, Columbia University
*G. A. BAYM, University of Illinois, Urbana
W. BERTOZZI, Massachusetts Institute of Technology
G. F. BERTSCH, Michigan State University (representing the American Physical Society, Division of Nuclear Physics)
*F. H. BOEHM, California Institute of Technology
*D. A. BROMLEY, Yale University
†J. CERNY, University of California, Berkeley, and Lawrence Berkeley Laboratory
*H. H. CHEN, University of California, Irvine
*D. CLINE, University of Rochester
†P. T. DEBEVEC, University of Illinois, Urbana

* Member of Nuclear Science Advisory Committee.
† Member of Nuclear Physics Panel of the Physics Survey Committee.

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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 William and Mary
*H. A. GRUNDER, Lawrence Berkeley Laboratory
M. GYULASSY, Lawrence Berkeley Laboratory
P. E. HAUSTEIN, Brookhaven National Laboratory (representing the American Chemical Society, Division of Nuclear Chemistry and Technology)
J. H. 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. LUDLAM, 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. J. 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
L. S. SCHROEDER, Lawrence Berkeley Laboratory
*A. Z. SCHWARZSCHILD, Brookhaven National Laboratory
*I. SICK, University of Basel, Switzerland
†S. E. VIGDOR, Indiana University
*E. W. VOGT, University of British Columbia, Canada

---

* Member of Nuclear Science Advisory Committee.
† Member of Nuclear Physics Panel of the Physics Survey Committee.

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Agency Representatives

H. C. BRITT, U.S. Department of Energy
H. L. CRANNELL, National Science Foundation
J. R. ERSKINE, U.S. Department of Energy
J. B. MCGRORY, U.S. Department of Energy
C. R. RICHARDSON, U.S. Department of Energy
E. T. RITTER, U.S. Department of Energy
W. S. RODNEY, National Science Foundation
H. B. WILLARD, National Science Foundation

Chairmen of Working Groups

S. M. AUSTIN, Elementary Excitations
G. A. BAYM, Nuclear Matter and Equation of State
F. H. BOEHM, Fundamental Symmetries
D. A. BROMLEY, Macroscopic Aspects
R. M. DIAMOND, High Angular Momenta
C. B. DOVER, Strange Quarks in Nuclei
K. A. ERB, Societal Applications
G. T. GARVEY, Instrumentation
G. T. GARVEY, Nonnucleonic, Quark Aspects
F. IACHELLO, Nuclear Symmetries
M. J. MARTIN, Accelerator Facilities
E. J. MONIZ, Nonnucleonic, Hadronic Aspects
P. D. PARKER, Nuclear Astrophysics
A. Z. SCHWARZSCHILD, Connections with Other Sciences
S. E. VIGDOR, Nucleons in Nuclei
E. W. VOGT, International Aspects

Participants in Working Groups Who Did Not Attend Workshop

B. R. APPLETON, Oak Ridge National Laboratory
L. M. BOLLINGER, Argonne National Laboratory
J. N. BRADBURY, Los Alamos National Laboratory
G. E. BROWN, State University of New York at Stony Brook
†R. A. EISENSTEIN, Carnegie-Mellon University
J. A. HARVEY, Oak Ridge National Laboratory
R. A. JAMESON, Los Alamos National Laboratory

---

† Member of Nuclear Physics Panel of the Physics Survey Committee.

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F. F. KNAPP, JR., Oak Ridge National Laboratory
F. PLASIL, Oak Ridge National Laboratory
P. THIEBERGER, Brookhaven National Laboratory
†J. D. WALECKA, Stanford University

READERS OF THE NUCLEAR PHYSICS PANEL REPORT (February-March 1984)

J. M. ALEXANDER, State University of New York at Stony Brook
G. F. BERTSCH, Michigan State University (Chairman, Division of Nuclear Physics, American Physical Society)
C. GLASHAUSSER, Rutgers University
C. D. GOODMAN, Indiana University
E. HAYWARD, National Bureau of Standards (Vice-Chairman, Division of Nuclear Physics, American Physical Society)
A. B. MCDONALD, Princeton University
R. A. NAUMANN, Princeton University (Chairman, Division of Nuclear Chemistry and Technology, American Chemical Society)
D. ROBSON, Florida State University
J. P. SCHIFFER, Argonne National Laboratory (Chairman, DOE/NSF Nuclear Science Advisory Committee)
A. Z. SCHWARZSCHILD, Brookhaven National Laboratory
R. E. TRIBBLE, Texas A&M University

† Member of Nuclear Physics Panel of the Physics Survey Committee.

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Bibliography

The articles and books cited below provide more detailed information on some of the topics introduced in this book. They are written at levels ranging from that for the intelligent layman to that for a scientifically knowledgeable person who is *not* a specialist in nuclear physics. Unfortunately, there appear to be no up-to-date books on nuclear physics for the layman. There are, however, many excellent recent books on elementary-particle physics, astronomy, and cosmology, most of which contain interesting material about nuclear physics and its connections to these other sciences.

Articles from Scientific American

G. F. Bertsch, "Vibrations of the Atomic Nucleus," May 1983, p. 62.
D. A. Bromley, "Nuclear Molecules," December 1978, p. 58.
J. Cerny and A. M. Poskanzer, "Exotic Light Nuclei," June 1978, p. 60.
K. A. Johnson, "The Bag Model of Quark Confinement," July 1979, p. 112.
W. C. McHarris and J. O. Rasmussen, "High-Energy Collisions between Atomic Nuclei," January 1984, p. 58.
C. Rebbi, "The Lattice Theory of Quark Confinement," February 1983, p. 54.
D. N. Schramm, "The Age of the Elements," January 1974, p. 69.
R. R. Wilson, "The Next Generation of Particle Accelerators," January 1980, p. 42.
C. D. Zafiratos, "The Texture of the Nuclear Surface," October 1972, p. 100.

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Books

I. Asimov, *The History of Physics*, Walker and Company, New York, 1984.
This lively survey of the entire field of physics, written from a historical perspective, contains six chapters dealing with various aspects of basic nuclear physics. Originally published in 1966 as a three-volume series called *Understanding Physics*, it has now been republished as a single volume with a new title. Regrettably, it has not been brought up to date except for an appendix on the most recent developments in elementary-particle physics, but it remains an excellent introduction to physics for the layman.

P. E. Hodgson, *Growth Points in Nuclear Physics*, Pergamon Press, Oxford. Vol. 1, 1980; Vol. 2, 1980; Vol. 3, 1981.
Each of these small books contains several dozen short articles on subjects of current research interest, written for the nonspecialist and originally published in *Nature*, *New Scientist*, and *Physics Bulletin*. They provide excellent surveys of the field of nuclear physics as of several years ago. Unfortunately, the series has not been continued.

P. F. Schewe, ed., *Physics News in 1983*, American Institute of Physics, New York, 1983.
This is the fifteenth in a series of annual booklets containing dozens of short articles on interesting developments in physics during the past year. Like the Hodgson series cited above, the articles are written for the nonspecialist, but here the subject matter includes all of physics, not just nuclear physics. The volumes are published in November and are available from the American Institute of Physics.

J. S. Trefil, *From Atoms to Quarks*, Charles Scribner's Sons, New York, 1980.
Although the emphasis here is on elementary-particle physics, there are several chapters dealing with nuclear physics and accelerators. This is one of several excellent books on modern physics by the same author, written for the layman.

S. Weinberg, *The First Three Minutes*, Basic Books, New York, 1977.
Written for the layman, this modern classic by one of the creators of the electroweak synthesis describes in detail the evolution of the universe from the moment of the big bang to the beginning of nucleosynthesis about 3 minutes later. There are now a number of excellent, more up-to-date books on this subject, but this one stands as the benchmark.

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Glossary

ACRONYMS AND ABBREVIATIONS

AGS	Alternating Gradient Synchrotron, Brookhaven National Laboratory
ATLAS	Argonne Tandem Linear Accelerator System, Argonne National Laboratory
CEBAF	Continuous Electron Beam Accelerator Facility, proposed for construction at Newport News, Virginia. (Formerly called the National Electron Accelerator Laboratory, NEAL)
CEN Saclay	Centre d'Etudes Nucléaires (Center for Nuclear Studies) de Saclay, Gif-sur-Yvette, France
CERN	Centre Européenne pour la Recherche Nucléaire (European Organization for Nuclear Research; also called the European Laboratory for Particle Physics), Geneva, Switzerland
DDHF	density-dependent Hartree-Fock (method)
DOE	Department of Energy
eV	electron volt
fm	fermi (10^{-15} m)
GANIL	Grand Accelérateur National d'Ions Lourds (National Large Heavy-Ion Accelerator), Caen, France
GeV	giga-electron volt (10^9 eV)

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GSI	Gesellschaft für Schwerionenforschung (Laboratory for Heavy-Ion Research), Darmstadt, West Germany
HHIRF	Holifield Heavy Ion Research Facility, Oak Ridge National Laboratory
IUCF	Indiana University Cyclotron Facility
JACEE	Japanese-American Cooperative Emulsion Experiment
JINR	Joint Institute for Nuclear Research, Dubna, USSR
KEK	Kokuritsu *Ko-E*nerugii Butsurigaku *K*enkyusho (National High-Energy Physics Laboratory), Tsukuba, Japan
keV	kilo-electron volt (10^3 eV)
km	kilometer
LAMPF	Los Alamos Meson Physics Facility, Los Alamos National Laboratory
LEAR	Low-Energy Antiproton Ring at CERN
MeV	mega-electron volt (10^6 eV)
msec	millisecond
NSAC	Nuclear Science Advisory Committee of the Department of Energy and the National Science Foundation
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
NSF	National Science Foundation (United States)
QCD	quantum chromodynamics
QED	quantum electrodynamics
QHD	quantum hadrodynamics
RNC	relativistic nuclear collider
SIN	Swiss Institute of Nuclear Research, Villigen, Switzerland
SLAC	Stanford Linear Accelerator Center
SURA	Southeastern Universities Research Association
TeV	tera-electron volt (10^{12} eV)
TRIUMF	Tri-University Meson Facility, Vancouver, British Columbia, Canada
TUNL	Triangle Universities Nuclear Laboratory, Duke University
V	volt

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TECHNICAL TERMS

Accelerator. A machine designed to accelerate charged particles to some energy suitable for bombarding a target and studying the resulting nuclear reactions. The four major kinds of accelerators are Van de Graaff electrostatic accelerators, linear accelerators, cyclotrons, and synchrotrons.

Allowed process. Any physical process that is allowed by a given theory; it may or may not have been observed to occur. See also *Forbidden process.*

Alpha particle. The nucleus of the helium-4 atom, consisting of two protons and two neutrons. It is also a product of radioactive decay. See also *Beta particle.*

Antimatter. Matter that consists of antiparticles (e.g., positrons and antinucleons) instead of ordinary particles.

Antiparticle. A particle that is identical to an ordinary particle in every respect except for having certain opposite elementary properties, such as electric charge. For every particle, there is an antiparticle; some particles are their own antiparticles.

Asymptotic freedom. A phenomenon in which the strength of the color force between quarks approaches zero when the quarks come very close together and increases when they move apart. See also *Quark confinement.*

Atom. The smallest unit of a chemical element, consisting of a central nucleus surrounded by orbital electrons. It is held together by the electromagnetic force.

Atomic number, Z. The number of protons in an atomic nucleus.

Bag model. The model of hadron structure that views the hadron as an impenetrable bag from which its constituent quarks cannot escape under any ordinary conditions. See also *Quark confinement.*

Baryon. One of the two classes of hadrons, consisting of three quarks or three antiquarks confined in a bag. All baryons are fermions; the three principal kinds are nucleons, hyperons, and baryon resonances. See also *Meson.*

Baryon resonance. An excited state of a baryon, having a greater mass and an extremely short lifetime. The most common baryon resonances are the nucleon resonances and delta resonances.

Beta particle. A synonym for an electron or a positron when it is emitted in the process of beta radioactivity, or beta decay. See also *Alpha particle.*

Binding energy. A measure of the strength with which a given

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physical system is bound; it is the amount of energy needed to break the bond in question and separate the particles.

Boson. Any particle or group of particles (such as a nucleus) having an integral value of spin. Among the bosons, in addition to the elementary vector bosons, are the mesons. The Pauli exclusion principle does not apply to bosons.

Central collision. A head-on collision of two particles, with near-maximum overlap of their cross-sectional areas; the impact parameter is near zero.

Collective model. Any model of nuclear structure in which the nucleons are viewed as moving in concert under the influence of some force. See also *Liquid-drop model.*

Colliding-beam accelerator. An accelerator in which the projectile particles in two counterdirectional beams collide in flight.

Color. The name for a property ascribed to quarks and gluons, somewhat analogous to electric charge. There are three such colors.

Color force. The force through which quarks and gluons interact, by the exchange of gluons. It is the basis for quantum chromodynamics. See also *Strong force.*

Compound nucleus. A heavy nucleus formed by the collision of two lighter nuclei. See also *Fusion.*

Conservation law. A law stating that in every conceivable interaction the total amount of a certain quantity (e.g., electric charge or mass-energy) cannot change, i.e., the quantity is conserved.

Coulomb barrier. The repulsive Coulomb force between a positively charged target nucleus and any positively charged projectile, inhibiting their close contact.

Coulomb force. The force of electrical attraction or repulsion between particles of unlike charge or like charge, respectively.

Cross section. A measure of the probability that an interaction of a given kind will occur; it is expressed in units of area and is one of the most commonly measured quantities in nuclear physics.

Current. See *Exchange current.*

Cyclotron. A circular accelerator in which the charged particles spiral outward from the center of the machine as they are given repeated energy boosts from an alternating electric field in a fixed magnetic field.

Decay. Any process in which a radioactive nuclide or an unstable particle or system changes to another, lower-energy form by emitting one or more particles or gamma rays.

Deep-inelastic scattering. A noncentral collision in which a great deal of the collision energy is converted to internal energy of the nuclei.

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Delta resonance. A baryon resonance; delta resonances differ in isospin from the nucleon resonances.

Detector. Any device that can detect the presence of a particle or nuclear fragment produced in a nuclear reaction and measure one or more of its physical properties.

Deuteron. The nucleus of deuterium (hydrogen-2), consisting of one proton and one neutron.

Electromagnetic force. A component of the unified electroweak force, responsible for holding atoms together and for many other phenomena. It is experienced by all particles with an electric charge or magnetic moment, through the exchange of photons. See also *Weak force.*

Electron. A light, negatively charged lepton with a mass of 0.511 MeV, about 1/1840 that of a nucleon. See also *Beta particle*, *Positron*, *Muon*, and *Tauon.*

Electron volt (eV). The amount of energy acquired by any particle with unit electric charge when it is accelerated through a potential difference of 1 volt. In various multiples, such as keV, MeV, or GeV, it is used as a measure of beam energy, of rest mass, and of temperature.

Electrostatic accelerator. See *Van de Graaff electrostatic accelerator.*

Electrostatic force. See *Coulomb force.*

Electroweak force. One of the three fundamental forces, comprising the actions of both the electromagnetic and weak forces, whose unification revealed them to be two very different aspects of one underlying force. See also *Gravitation* and *Strong force.*

Elementary particle. A particle that, as far as is known, has no internal structure. The elementary particles are the leptons, quarks, and elementary vector bosons. Hadrons are not elementary particles.

Elementary vector boson. One of the three classes of elementary particles, consisting of photons, gluons, and the intermediate vector bosons; these particles are the carriers of the fundamental forces. See also *Lepton* and *Quark.*

Equation of state. A mathematical equation that describes the behavior of a physical system over a wide range of conditions, on the basis of a few measurable quantities called state variables.

Exchange current. The current, either charged or neutral, arising from the exchange of charged or neutral virtual particles as carriers of a force between two particles.

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Exchange particle. Any virtual particle that acts as the carrier of a force between two particles.

Excited state. Any energy level of a bound system of particles, such as a nucleus, above the ground state.

Exclusion principle. See *Pauli exclusion principle.*

Fermi. The common name for the femtometer (10^{-15} meter), the characteristic dimension of nuclear and particle physics. The diameter of a nucleon is about 1 fermi.

Fermion. Any particle or group of particles (such as a nucleus) having a half-integral value of spin. All leptons, quarks, and baryons are fermions. The Pauli exclusion principle applies only to fermions.

Fission. The process—either spontaneous or induced—in which a nucleus of a heavy element, such as uranium, splits into two lighter nuclei, with the release of energy. See also *Fusion.*

Flavor. The name for the property that distinguishes the six basic kinds of quarks: up, down, strange, charm, bottom, and top. Each flavor can have any of the three different quark colors.

Forbidden process. Any physical process that is forbidden by a given theory and that typically has never been observed to occur. If it is observed, the theory is compromised. See also *Allowed process.*

Fusion. The process in which two nuclei of light elements, such as hydrogen or helium, fuse to form one heavier nucleus, with the release of energy. Also, the process in which two heavier nuclei fuse to form a compound nucleus, which may or may not quickly split apart. See also *Fission.*

Gamma ray. An extremely energetic photon, emitted in many nuclear reactions and in the decay of many radioactive nuclides and unstable particles.

Gluon. Any of eight massless, colored particles that are the carriers of the color force. They are elementary vector bosons and are confined within hadron bags.

Grand Unified Theory. A mathematical formalism that seeks to unite the strong and electroweak forces into a single underlying force at a deeper level, in the same way that electromagnetism and the weak force were unified into the electroweak force.

Gravitation. One of the three fundamental forces, responsible for the large-scale structure of the universe. It is experienced by all particles but is so extremely weak that its effect on any but macroscopic objects is negligible. See also *Electroweak force* and *Strong force.*

Ground state. The lowest (normal) energy level of a bound system of particles, such as a nucleus. See also *Excited state.*

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Hadron. Any particle that experiences the strong force. The two classes of hadrons are baryons and mesons.

Hadronic matter. A state of nuclear matter encompassing normal nuclei as well as baryon resonances and other nonnucleonic baryons.

Half-life. The time it takes for half of all the nuclei in a radioactive sample to decay to some other form; each type of radionuclide has a characteristic half-life.

Heavy ion. Any ion with a mass number greater than about 40; this definition is arbitrary but convenient.

Heisenberg uncertainty principle. A fundamental quantum-mechanical law, stating that it is impossible to measure simultaneously both the position and momentum of a particle with arbitrarily great precision; the structure of quantum mechanics leads to an analogous statement for energy and time. It plays an important role in nuclear processes.

High energy. For the purposes of this report, a projectile energy (somewhat arbitrarily) of 100 MeV per nucleon to 1 GeV per nucleon. See also *Relativistic energy.*

Hypernucleus. Any nucleus in which a nucleon has been replaced by a hyperon.

Hyperon. Any baryon containing one or more strange quarks; the most common such baryon is the lambda hyperon.

Impact parameter. A measure of the degree of overlap of the cross-sectional areas of two particles in a collision; it is zero in an idealized, perfectly central collision and significantly greater than zero in peripheral collisions.

Independent-particle model. Any model of nuclear structure in which the motion of a single nucleon is viewed in terms of an average force field produced by all the other nucleons. See also *Shell model.*

Intermediate vector boson. One of three massive, charged or neutral particles that are the carriers of the weak force. Designated as W^+, W^-, and Z^0, they are elementary vector bosons, as are photons and gluons.

Ion. In general, any atom that has lost or gained one or more electrons. In nuclear physics, especially in connection with accelerators, the term is used as a synonym for nucleus, because frequently ions with some electrons still bound are accelerated; bare nuclei, however, are also referred to as ions.

Isospin. A quantum number ascribed to hadrons that permits them to be grouped in simpler ways, such as a generalized nucleon that in different isospin states is either a proton or a neutron.

Isotope. Any specific nucleus of a given chemical element. The

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isotopes of an element (which is defined by its proton number) differ from one another in their neutron number. See also *Nuclide*.

Kaon. A strange meson, i.e., one that contains a strange quark. Like pions, kaons can be positive, negative, or neutral.

Lepton. One of the three classes of elementary particles, consisting of electrons, muons, tauons, their associated neutrinos, and the six corresponding antiparticles. All 12 leptons are fermions; they interact via the weak force but not the strong force. See also *Elementary vector boson* and *Quark*.

Light ion. Any hydrogen ion or helium ion. Lithium ions are sometimes also included in this category.

Linear accelerator. A type of accelerator in which the charged particles follow a straight path as they are given repeated energy boosts from a series of electric fields.

Liquid-drop model. A collective model in which the properties of the nucleus are viewed in terms analogous to those of an ordinary drop of liquid.

Low energy. For the purposes of this report, a projectile energy (somewhat arbitrarily) of less than about 10 MeV per nucleon.

Many-body problem. The mathematical problem of describing the dynamic behavior of any system of three or more mutually interacting particles (such as most nuclei).

Mass-energy equivalence. The principle that mass and energy are equivalent, interconvertible quantities. In nuclear physics, masses are customarily expressed in terms of an equivalent energy, usually in units of MeV.

Mass number, A. The number of protons plus neutrons ($A = Z + N$) in an atomic nucleus. Nuclei of different elements can have the same mass number.

Medium energy. For the purposes of this report, a projectile energy (somewhat arbitrarily) of 10 to 100 MeV per nucleon.

Medium ion. Any ion from lithium up to a mass number of about 40; this definition is arbitrary but convenient.

Meson. One of the two classes of hadrons, consising of a quark-antiquark pair confined in a bag. All mesons are bosons; among the more common ones are pions and kaons. Mesons are the principal carriers of the strong force between hadrons. See also *Baryon*.

Meson-exchange model. A model of nuclear interactions that takes into account the effects of the exchange of virtual mesons between nucleons, rather than considering the nuclei to be composed only of nucleons.

Muon. A moderately massive, negatively charged lepton that appears

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to be identical to the electron in every respect except for its greater mass. See also *Tauon*.

Neutrino. Any of three kinds of neutral, presumably massless leptons that are emitted in weak-interaction processes, such as beta decay.

Neutrino oscillation. The postulated phenomenon whereby neutrinos change periodically from one form (electron neutrino, muon neutrino, or tauon neutrino) to another during their flight through space. Such behavior has not been observed.

Neutron. An uncharged (neutral) baryon with a mass almost identical to that of the proton.

Neutron number, N. The number of neutrons in an atomic nucleus.

Nuclear matter. Matter that consists primarily of nucleons—whether in atomic nuclei or in an extended state, as in neutron stars.

Nuclear reaction. Any change brought about in the states of two nuclei as a result of their collision with each other.

Nuclear spectroscopy. The study of the detailed structure of nuclei—their spectrum of energy levels, associated physical properties, decay modes, and other properties.

Nucleon. A proton or a neutron; nucleons are the least massive, most stable baryons.

Nucleon resonance. A baryon resonance that is an excited state of a nucleon; nucleon resonances differ is isospin from the delta resonances.

Nucleus. The small, dense, positively charged core of the atom, consisting primarily of nucleons (protons and neutrons). It is held together by the strong force, through the exchange of mesons between the nucleons. See also *Ion*.

Nuclide. Any specific nucleus, as defined by a unique combination of proton number and neutron number. See also *Isotope*.

Parity. A fundamental symmetry principle governing the nature of physical laws when the spatial coordinates of the system are totally reflected. The parity principle is obeyed (i.e., nature exhibits no spatial preference) in the strong and electromagnetic interactions, but it appears always to be violated in weak interactions, such as beta decay.

Pauli exclusion principle. A fundamental quantum-mechanical law, obeyed by fermions but not by bosons, stating that in any system of particles, such as a nucleus, no two fermions are allowed to coexist in the identical quantum state. It plays a dominant role in determining nuclear structures.

Phase transition. A change in the physical state of a system from one form to a different form (e.g., ice to water).

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Photon. A massless, neutral particle that is the quantum of electromagnetic radiation and the carrier of the electromagnetic force. It is one of the elementary vector bosons.

Pion. The most commonly observed meson, existing in any of three charge states: positive, negative, and neutral. Virtual pions exist in nuclei and are important for an understanding of nuclear structure.

Positron. The positively charged antiparticle of the electron.

Proton. A positively charged baryon with a mass of 938 MeV, about 1840 times greater than that of the electron.

Proton number, Z. The number of protons in an atomic nucleus.

Quantum. The smallest possible unit of energy associated with any change in a physical system. The best-known example of a quantum of energy is the photon.

Quantum chromodynamics (QCD). The quantum field theory of the color interaction between quarks and gluons. It is also loosely referred to as the quantum field theory of the strong interaction, which derives from the color interaction.

Quantum electrodynamics (QED). The quantum field theory of the electromagnetic interaction between any particles with electric or magnetic properties.

Quantum field theory. A mathematical formalism, based on relativity and quantum mechanics, that describes one of the fundamental interactions. The two most important such theories are quantum electrodynamics and quantum chromodynamics.

Quantum hadrodynamics (QHD). A model quantum field theory that attempts to account for the actions of the strong force in terms of the hadrons themselves rather than of their constituent quarks and gluons.

Quantum mechanics. The physical theory that underlies all phenomena at the level of molecules, atoms, nuclei, and elementary particles.

Quark. One of the three classes of elementary particles. There are six basic kinds of quarks (quark flavors) and six corresponding antiparticles. All 12 quarks are fermions; they interact via the color force as well as the weak force. All have a fractional electric charge and are confined within hadron bags. See also *Elementary vector boson* and *Lepton.*

Quark confinement. The observation that it is apparently impossible, under any ordinary conditions, for quarks to escape from their hadron bags and exist as free particles. See also *Asymptotic freedom.*

Quark-gluon plasma. An extreme state of matter in which quarks and

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gluons are deconfined and are free to move about in a much larger volume than that of a single hadron bag. It has never been observed on earth.

Radioactivity. Any of several kinds of processes in which a nuclide changes to another nuclide by the emission of one or more particles.

Relativistic energy. A projectile energy greater than about 1 GeV per nucleon, i.e., an energy comparable with or greater than the particle's rest mass.

Relativity. The theory of space and time (special relativity) that describes the nature of physical laws in terms of postulates regarding the speed of light and the observation of motion made from moving frames of reference.

Resonance. A large increase in the amplitude of oscillation of a physical system when it is acted on by an external driving force that oscillates at or near a particular frequency, the resonant frequency of the system. Also, an extremely unstable (short-lived) particle state. See also *Baryon resonance.*

Rest mass. The mass of a particle when it is not moving with respect to some frame of reference (such as the laboratory). The mass of a moving particle is greater than its rest mass. See also *Relativistic energy.*

Shell model. An independent-particle model in which the nucleons are viewed as occupying a series of shells analogous to those of the electrons in the theory of atomic structure.

Spin. An intrinsic property of all particles and nuclei, analogous to rotation about an axis. Spin, however, occurs only in multiples of a basic quantum mechanical unit of measure. Particles having an integral value of spin are bosons; particles having a half-integral value are fermions.

Spontaneous fission. See *Fission.*

Standard Model. The combined (but not yet unified) theories of the electroweak interaction and quantum chromodynamics, with which all known facts of nuclear physics and elementary particle physics are consistent.

State variable. One of a minimum set of measurable quantities whose values are sufficient to define the state of a given physical system and predict its behavior over a wide range of conditions. See also *Equation of state.*

Strangeness. The property associated with the strange quark or any particle containing a strange quark.

Strong force. One of the three fundamental forces, responsible for holding nuclei together. It is experienced by all the hadrons through

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the exchange of mesons and is actually a vestige of the much stronger color force between quarks and gluons. See also *Electroweak force* and *Gravitation.*

Sum rule. A rule that sets an upper limit on the magnitude of some quantity within the framework of a given model.

Symmetry principle. A fundamental principle governing the nature of physical laws under the effect of a symmetry transformation of some kind. Two of the most important symmetry principles in nuclear and particle physics are parity and time-reversal invariance.

Synchrotron. A ring-shaped accelerator in which the charged particles follow a fixed circular path as they are given repeated energy boosts from a radio-frequency field in a time-varying magnetic field.

Tauon. A very massive, negatively charged lepton that appears to be identical to the electron in every respect except for its much greater mass. See also *Muon.*

Time-reversal invariance. A fundamental symmetry principle governing the nature of physical laws when the direction of the flow of time is considered to be reversed.

Uncertainty principle. See *Heisenberg uncertainty principle.*

Van de Graaff electrostatic accelerator. A type of accelerator in which the charged particles are given a single energy boost by passing through a very large electrostatic potential drop.

Vector boson. Any spin-1 boson that acts as the carrier of a force between two particles. See also *Virtual particle.*

Virtual particle. A particle, typically a boson, whose ephemeral existence serves to carry a force between two material particles. The virtual particle appears spontaneously near one of the two particles and disappears near the other one. Under certain conditions, a virtual particle can become a material particle.

Weak force. A component of the unified electroweak force, responsible for the decay of many radioactive nuclides and unstable particles and for all neutrino interactions. It is experienced by all leptons, quarks, and hadrons, through the exchange of intermediate vector bosons. See also *Electromagnetic force.*

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