Scientific Opportunities with a RARE-ISOTOPE FACILITY in the United States

Rare-Isotope Science Assessment Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Cover: A chart of the nuclides overlays a view from the cameras of the Hubble Space Telescope. The transparent region of the nuclide chart (which shows isotopes as a function of the number of neutrons and protons in the nucleus) represents the unknown territory of the isotope landscape. Many rare isotopes play an important role in astrophysics, especially stellar nucleosynthesis. Courtesy of K. Rykaczewski and A. Rykaczewski.

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BOARD ON PHYSICS AND ASTRONOMY

Preface

The Rare-Isotope Science Assessment Committee (RISAC) was charged by the National Research Council's Board on Physics and Astronomy (BPA), the Department of Energy (DOE), and the National Science Foundation to define the science agenda for a next-generation U.S. Facility for Rare-Isotope Beams (FRIB); the full charge is presented in Appendix A. By design RISAC consists of scientists who work mostly outside the rare-isotope science community (see Appendix F for biographical sketches of the committee members). After RISAC had begun its meetings, the DOE announced that the budget of what was then understood as the Rare Isotope Accelerator (RIA) should be reduced by half and that there would be no project-engineering definition funding available until 2011.

These developments in facility definition and projected schedule presented the committee with two chief challenges. First, an effort that had started as an analysis of the most compelling intellectual territory addressed by a well-defined facility was transformed into the inverse task. Thus, the committee focused first on the scientific questions of highest importance and then speculated about the technical capabilities that a next-generation facility (FRIB) would need to make progress. Second, with a shift in the anticipated construction start from 2008 to 2011 at the earliest, the committee was forced to guess at not only the scientific developments more than a decade in the future but also the evolving scientific activities of other facilities and nations around the world.

Nevertheless, in response to the DOE announcement and the charge for this study, the committee has focused on articulating the science that could be accomplished at a reduced-scope rare-isotope facility, referred to as a FRIB or a U.S. FRIB in this report. The committee offers conclusions on the potential impact of such a facility in the areas of nuclear structure, nuclear astrophysics, and fundamental interactions, as well as various applications of a FRIB, including national security. The charge called for an evaluation of the impact of a FRIB on the overall context of nuclear physics both nationally and internationally.

Representatives from major regions of the world (Europe/Germany, Japan, and Canada) that have planned and operated existing rare-isotope beam facilities provided the basis for the committee's advice about the international context of a FRIB. To avoid the appearance of bias, the committee membership did not include representatives actively participating in the formulation of proposals to build a U.S. FRIB. However, the committee did hear testimony from members of those groups (in addition to many others; the meeting agendas are presented in Appendix B). The committee heard presentations from appropriate experts about applications of a FRIB to areas of medical research, stockpile stewardship, and national security. RISAC was not asked to recommend a specific facility or to compare a FRIB with other U.S. initiatives in nuclear science. Furthermore, RISAC was not asked to provide overall guidance on how the United States might most effectively leverage its investments in nuclear science as part of a global program.

The committee thanks the speakers who made formal presentations at each of the meetings; their presentations and the ensuing discussions were extremely informative and had a significant impact on the committee's deliberations. And in general, the committee acknowledges the extra work required to prepare remarks addressing the broad spectrum of expertise on the committee. The committee also thanks BPA staff members Donald Shapero, Timothy Meyer, and Phillip Long for their guidance and assistance throughout this process.

On a more personal note, we would also like to extend special thanks and appreciation to RISAC member Gerry Garvey for his help in skillfully weaving together the views of the committee into a consistent whole and in responding to the reviews, which were particularly thoughtful and helpful in refining the report.

John F. Ahearne, *Co-Chair*
Stuart J. Freedman, *Co-Chair*
Rare-Isotope Science Assessment Committee

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Gordon A. Baym, University of Illinois at Urbana-Champaign,
James E. Brau, University of Oregon,
Hans Geissel, Gesellschaft für Schwerionenforschung (GSI),
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Cherry A. Murray, Lawrence Livermore National Laboratory,
Jean-Michel Poutissou, TRIUMF,
R.G. Hamish Robertson, University of Washington, and
Lee Schroeder, Lawrence Berkeley National Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Pierre C. Hohenberg, New York University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

Nuclear structure physics aims to describe nuclei as collections of neutrons and protons. Nuclear structure is the traditional core of nuclear science, and it has been able to describe a broad range of phenomena, from normal nuclei to neutron stars. The understanding of nuclei in this regime provides critical support for important research in nuclear astrophysics and for efforts to exploit nuclei as laboratories for exploring fundamental symmetries.

More than a decade ago, the U.S. nuclear structure and nuclear astrophysics communities proposed that a new rare-isotope accelerator be built in the United States. Such a facility would produce a wide variety of high-quality beams of unstable isotopes at unprecedented intensities. It would enable a new class of experiments to elucidate the structure of exotic, unstable nuclei to complement the studies of stable nuclei that have been the primary focus of nuclear physics in the past century. A facility with this capability could also provide critical information on the very unstable nuclei that must be understood in order to explain nuclear abundances observed in the universe. This facility would also produce large samples of specific isotopes that could enable a new class of experiments for the study of fundamental symmetries. A series of studies by the joint Department of Energy/National Science Foundation (DOE/NSF) Nuclear Science Advisory Committee have supported the need for such a facility, initially termed the Rare Isotope Accelerator (RIA).

To obtain an independent scientific assessment of the scientific agenda for such a facility, the National Research Council convened the Rare-Isotope Science

Assessment Committee (RISAC). The committee was charged by the Department of Energy and the National Science Foundation to define the science agenda for a next-generation U.S. Facility for Rare-Isotope Beams (U.S. FRIB). RISAC members included several experts in rare-isotope science, but the committee consisted largely of scientists from outside the rare-isotope science community; it also included members from Canada, Europe, and Asia. Soon after RISAC was formed, the DOE announced that the budget of what was then understood as RIA would be reduced by about half. In response to this announcement and the charge, the committee focused on articulating the science that could be accomplished at a rare-isotope facility of reduced scope, referred to as a FRIB or a U.S. FRIB in this report. The charge also directed the committee to evaluate the scientific impact of a FRIB in the overall context of the national and international nuclear physics programs.

The committee heard presentations about applications of a FRIB for nuclear physics studies and also about applications in areas of medical research and stockpile stewardship. RISAC was not asked to give advice on whether a facility *should* be constructed or to compare the relative merits of various possibilities. For its analysis, the committee interpreted "U.S. FRIB" as a general-purpose rare-isotope production facility with a cost about half that of the earlier RIA concept. To gain a better understanding of the potential impact on the scientific agenda of such a cost reduction, the committee heard views from some of the proponents of a U.S. FRIB in a public meeting; these individuals gave the committee their views on production techniques and beam intensities that they judged to be technically feasible. As indicated in these presentations, the primary trade-off expected from such a decrease in cost would be a modest reduction in the quantity and diversity of possible isotopes and a significant reduction in the multiuser aspects of the facility.

In developing its conclusions regarding a FRIB, the committee took into account the worldwide portfolio of related experiments and the likely time frame in which the facility might begin operations (2016, according to current DOE plans). Despite the uncertainty inherent in predicting what will be the important scientific questions in the far future, a powerful new rare-isotope facility could resolve scientific issues of clear importance. Arguments from the groups that have conducted the research and development for a FRIB convinced the committee that most of the major technical issues have been addressed. The committee concluded that the case for a next-generation, radioactive-beam facility of the type embodied in the U.S. FRIB concept represents a unique opportunity to explore the nature of nuclei under conditions that only exist otherwise in supernovae and to challenge current understanding of nuclear structure through the exploration of new forms of nuclear matter and the development of a more robust quantitative description.

A rare-isotope facility produces beams of unstable atomic nuclei for direct study or for use in subsequent reactions to produce even more exotic nuclear species. Thus, a FRIB could impact the study of the origin of the elements and the evolution of the cosmos as well as the Standard Model of elementary particle physics with groundbreaking research on nuclei far from stability. The committee identified several key science drivers:

- *Nuclear structure.* A FRIB would offer a laboratory for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a more broadly applicable theory of nuclei will emerge. A FRIB would allow the investigation of new forms of nuclear matter such as the large neutron excesses occurring on the surfaces of nuclei near the neutron drip line, thus offering the only laboratory access to matter made essentially of pure neutrons. A FRIB might lead to breakthroughs in the ability to fabricate the neutron-rich superheavy elements that are expected to exhibit unusual stability in spite of huge electrostatic repulsion.
- *Nuclear astrophysics.* A FRIB would lead to a better understanding of nuclear astrophysics by creating exotic nuclei that, until now, have existed only in nature's most spectacular explosion, the supernova. A FRIB would offer new glimpses into the origin of the elements, which are produced mostly in processes very far from nuclear stability and which are barely within reach of present facilities. A FRIB would also probe properties of nuclear matter at extreme neutron richness similar to that found in neutron star crusts.
- *Fundamental symmetries of nature.* Experiments addressing questions of the fundamental symmetries of nature could likewise be conducted at a FRIB through the creation and study of certain exotic isotopes. These nuclei could be important laboratories for basic interactions because aspects of their structure greatly magnify the size of the symmetry-breaking processes being probed. For example, a possible explanation for the observed dominance of matter over antimatter in the universe could be studied in experiments seeking to detect a permanent electric dipole moment in heavy radioactive nuclei.

The committee concluded that nuclear structure and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Moreover, nuclear-structure-related research provides the scientific basis for important advances in medical research, national security, energy production, and industrial processing. Historically, scientific and technological developments in nuclear science have had extremely broad impact—for example, in the development of nuclear magnetic resonance imaging and the fabrication of more-robust electronics. Failure to pursue a U.S. FRIB would likely lead to a forfeiture of U.S. leadership in nuclear-structure-related physics and would curtail the training of future U.S. nuclear scientists.

The committee concluded that a U.S. facility for rare-isotope beams of the kind described to it would be complementary to existing and planned international efforts, particularly if based on a heavy-ion linear accelerator. With such a facility, the United States would be a partner among equals in the exploration of the world-leading scientific thrusts listed above.

The committee concluded that the science addressed by a rare-isotope facility, most likely based on a heavy-ion driver using a linear accelerator, should be a high priority for the United States. The facility for rare-isotope beams envisaged for the United States would provide capabilities, unmatched elsewhere, that would help to provide answers to the key science topics outlined above.

1

Introduction and Background

Nuclear science is entering a new era of discovery in understanding how nature works at the most basic level and in applying that knowledge in useful ways.[1] This advance is largely the result of technological breakthroughs in the development of equipment for nuclear physics experiments. Until recently, nuclear structure scientists had to be content with conducting experiments using stable nuclei, of which there are only about 300, as beams and targets. In the past decade, however, nuclear structure scientists have learned how to build high-beam-power facilities for producing useful beams of short-lived, radioactive nuclei. With these new beams of unstable nuclei, they can make and study many thousands of exotic nuclear species—most of which have never existed before or are only fleetingly created in the hot interiors of stars. Such experiments will help improve understanding of both the structure of exotic nuclei (see Box 1.1) and the conditions responsible for their synthesis in stars. Rare-isotope beams also offer many opportunities for new medical research and for applications in other areas of research and industry. New, third-generation facilities are now planned or being built in a number of laboratories around the world. They will enable scientists to continue to exploit these new developments in the coming decades.

More than a decade ago, the U.S. nuclear structure and nuclear astrophysics

[1] For additional reading, see DOE/NSF Nuclear Science Advisory Committee, *Overview of Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade*, Washington, D.C., 2002.

BOX 1.1
Exotic Nuclei, Rare Isotopes, and Radioactive Nuclear Beams

The terms exotic nuclei, rare isotopes, and radioactive nuclear beams all refer to essentially the same sector of study, an area to which this report refers as rare-isotope science. The field of rare-isotope science can be characterized in the following way.

Atoms that make up everyday matter on Earth are predominantly stable; that is, they retain their identity in terms of their elemental nature (the numbers of protons and neutrons remain constant over time). The nuclei located at the center of each atom comprise over 99.9 percent of the mass of the visible universe. However, in the broader cosmos, many other nuclei exist and play an important role in the evolution of the universe. These nuclei are exotic (they occur only rarely on Earth) and, in terms of chemistry, are isotopes of the stable atoms on Earth. By vast majority, these rare isotopes are radioactively unstable, meaning that, when left alone on the shelf, they undergo spontaneous decay and transform into different nuclei. Figure 1.1.1 depicts the standard organization of knowledge of rare isotopes.

Nuclear physics is the general study of the principles that govern phenomena of the nucleus, and rare-isotope science is the study of the behavior and interactions of those nuclei that are unstable, exotic, and rare. By studying physical processes that transform nuclei into other nuclei (with the emission of residual particles and energy), scientists learn not only how to control and predict these phenomena, but they also learn about the origins of the chemical elements in the universe.

In particular, the study of rare isotopes allows scientists to expand the basic understanding of nuclear physics in two general ways: (1) rare isotopes present “extremes” to physicists and thereby offer leverage on testing the basic understanding of nuclear physics, and (2) rare isotopes themselves play an important role in physical environments that are hot, dense, or highly interacting, such as those within neutron stars, stellar fusion cycles, nuclear reactions in reactor fuel cycles, and so on.

communities proposed that such a new rare-isotope accelerator be built in the United States. Such a facility would produce a wide variety of high-quality beams of unstable isotopes at unprecedented intensities. Over the years, studies by the joint Department of Energy/National Science Foundation (DOE/NSF) Nuclear Science Advisory Committee supported the need for such a facility. In a landmark report published in 1999,[2] a formal concept was envisioned for achieving these capabilities: it was termed the Rare Isotope Accelerator (RIA). To obtain an inde-

[2]DOE/NSF Nuclear Science Advisory Committee, *ISOL Task Force Report*, Washington, D.C., 1999.

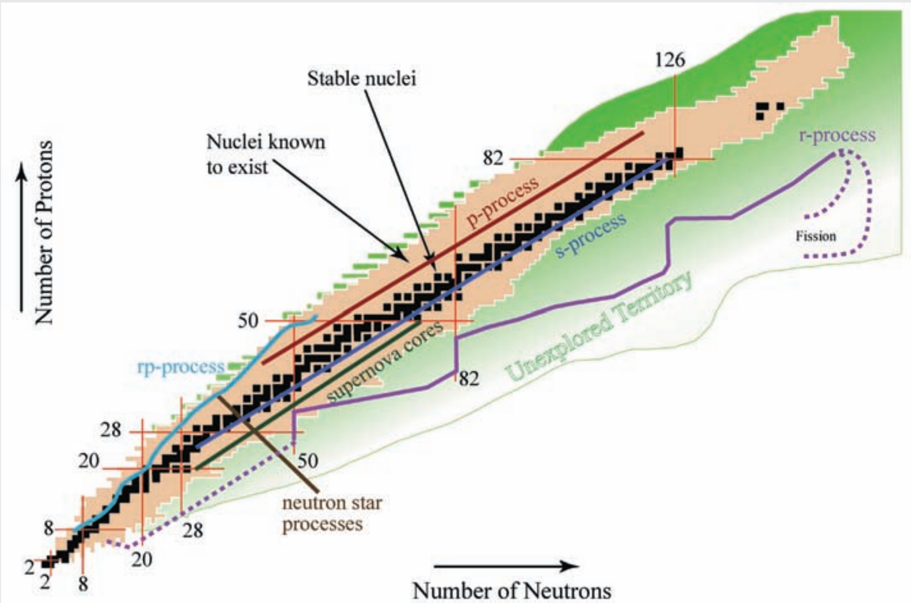

FIGURE 1.1.1 This so-called Chart of the Nuclides depicts the nuclei as a function of the number of neutrons (N) and protons (Z) that they contain. The nuclei that are stable or that have very long lifetimes (more than 10 million years) are shown in black. Unstable nuclei that have been discovered are shown in pink. The areas in green fading to white represent the nuclei that do not immediately fall apart and that play an important role in the evolution of the chemical composition of the universe. Little to nothing is known of the properties of these nuclei. N and Z combinations that lie outside the bounded region (e.g., Z = 20, N = 70) are assumed to fall apart immediately. Nuclei with the same number of protons but differing numbers of neutrons are termed isotopes of the same chemical element.

pendent scientific assessment of the scientific agenda for such a facility, the DOE and the NSF agreed to support a study committee convened by the National Research Council. The Rare-Isotope Science Assessment Committee (RISAC) was charged to define the science agenda for a next-generation rare-isotope beam facility. Soon after RISAC was formed, the DOE announced that the budget of what was then understood as RIA should be reduced by about half and that construction would not start until 2011. This report, therefore, identifies a compelling scientific agenda for a future facility termed the U.S. Facility for Rare-Isotope Beams (U.S. FRIB), the construction-cost envelope for which is roughly half that of RIA and at which the first experiments might not begin until 2016 or so (5 years after the start of construction).

HISTORICAL CONTEXT

Nuclear physics is the study of the tiny, massive cores of atoms. Nearly all the mass in the visible universe is locked away in atomic nuclei, as is nearly all the energy. Nuclear physics has realized the ancient dream of alchemy—transmutation of the elements—and seeks to explain how all the variety of elements on Earth were formed in the alchemical cauldrons of exploding stars. Nuclear reactions power our star, the Sun, producing energy that comes to Earth in the form of sunlight, which in turn generates energy in the form of wind. The Sun is ultimately responsible for the energy that has been locked away for millions of years in coal and oil. The forced disintegrations of a few, very special nuclei, generated by supernovae, generate power in nuclear reactors and are essential for nuclear weapons. It is now known that atomic nuclei are composed of protons and neutrons, and these, in turn, are made of smaller, simpler particles, known as quarks. How do the varied and complex properties of nuclei emerge from the simple laws obeyed by quarks? Or, going the other way, can the study of nuclei lead us to new forces and new symmetries, new insights into the world of quarks? How do nuclear reactions power quiescent stars like the Sun and lead to stellar catastrophes like supernovae? How are complex nuclei made in stars? How can we understand the behavior of nuclei well enough to control nuclear power, limit nuclear proliferation, and manage nuclear waste? These are some of the questions that drive modern nuclear physics.

The history of the 20th century is inextricably intertwined with the emergence of nuclear physics. Certainly a culture that does not understand the major implications of nuclear science will not be prepared to face the challenges of science, energy, and politics in the 21st century.

The first, faint murmur of what was to become nuclear physics came at the end of the 19th century, with Henri Becquerel's discovery that uranium salts emit mysterious forms of radiation. Pierre and Marie Curie isolated other radioactive elements, including radium and polonium, in the first years of the 20th century, and led international efforts to characterize and explain the origins of radioactivity. They sorted radiation into alpha rays—heavy, highly ionizing, and easily stopped; beta rays—light, moderately penetrating, and moderately ionizing; and gamma rays—highly penetrating and very weakly ionizing. In the Curies' day, little was known about the internal structure of atoms. The prevailing model, proposed by J.J. Thomson, held that the atom was a blob of positive electric charge in which electrons, already known as the carriers of electricity, were embedded as "raisins in a plum pudding."

This picture was abruptly shown to be incorrect and modern nuclear physics was born when Ernest Rutherford showed that almost all the mass of the atom is concentrated in a small *nucleus* at its center. The nucleus, it is now known, is a scant 10^{-12} centimeters across. The atom, 10,000 times larger, is mostly empty space, filled with a faint haze of orbiting electrons, each 1/2000th the mass of the lightest nucleus.

These early discoveries in nuclear physics jump-started the development of quantum mechanics. Niels Bohr modeled the atom as a nuclear core surrounded by electrons in quantized orbits. Later, nuclear radioactivity came to be seen as a fundamental example of a nondeterministic quantum process: an unstable nucleus has a calculable average lifetime, but exactly when any particular nucleus will decay is fundamentally unknowable. The new quantum theory took shape in the 1920s, spurred largely by the need to explain the properties of atoms, especially the spectra of light emitted by excited atoms. Nuclear physics progressed rather slowly, awaiting the development of more powerful theoretical tools and some fundamental experimental discoveries. By 1920, Ernest Marsden, working with Rutherford, had shown that the nucleus of the hydrogen atom, the *proton,* was a constituent of heavier nuclei. As beta radiation appeared to be electrons emitted from the core of unstable nuclei, it was natural to suppose that protons and "nuclear electrons" were the constituents of nuclei. This led only to confusion and paradox until James Chadwick, in 1932, discovered the missing building block of nuclei: the *neutron,* nearly identical to the proton in mass but with no electric charge. Once nuclei were recognized as bound systems of protons and neutrons, progress through the application of the new quantum theory and new experimental methods was both swift and inevitable.

In the 1930s, the basic constituents of the nucleus were identified and the basics of certain radioactive decays were first deduced. Isotopes were understood as nuclei with the same number of protons—and therefore the same chemical properties—but different numbers of neutrons. The Chart of the Nuclides, the analog of the Periodic Table of the Elements, began to fill up as nuclear physicists and chemists created, isolated, and identified heretofore unknown and often unstable nuclei by bombarding stable nuclei with protons, neutrons, and alpha particles (now understood to be the nuclei of helium—two protons and two neutrons bound tightly together). Alpha-particle emission from heavy nuclei such as radium provided dramatic confirmation of the bizarre phenomenon of tunneling predicted by quantum mechanics. The first models of the nucleus, Niels Bohr and John Wheeler's "liquid-drop" or "compound nucleus" model and Eugene Wigner's "supermultiplet" model of light nuclei, began to apply new quantum ideas to nuclear structure. Enrico Fermi wrote his famous paper proposing a theory to explain beta decay, an early step on the path to the discovery of the Standard Model of fundamental physics.

Two early discoveries by nuclear physicists in the 1930s had profound impact, one on society and the other on appreciation for the role of nuclear physics in shaping the universe. The first was the 1938 discovery by Otto Hahn and Fritz Strassmann of nuclear fission and its theoretical interpretation by Lise Meitner and Otto Frisch. Nuclear fission and the subsequent construction of the first nuclear weapons brought nuclear physics out of the esoteric world of universities and research laboratories and forced politicians and citizens to confront moral questions at the boundary where great science and the potential for great destruction meet.

The second was Hans Bethe's discovery in 1939 that nuclear fusion powers stars. Recently, nuclear physicists have directly confirmed his theory of the Sun's energy source by a quantitative measurement of the flux of neutrinos from the Sun. Bethe's work not only led to an understanding of the energy sources that power the universe but also initiated the field of nuclear astrophysics, which now includes the study of supernovae where heavy nuclei are created and of degenerate collapsed stars such as neutron stars, which are, in essence, gigantic nuclei of stellar proportions.

After World War II, scientists started to consider peaceful uses of nuclear energy. The first nuclear power plant produced electricity in 1951. Despite its checkered history—great initial promise and rapid growth followed by misgivings over safety, waste management, and weapons proliferation—energy from nuclear fission will play an important part worldwide in any smooth transition away from a carbon-based energy economy to a more sustainable energy future.

The world of fundamental particles has never again seemed as simple as it did in 1945: the "elementary particles" required to describe nature were very few—the proton, neutron, and electron (the neutrino and muon—unnecessary for ordinary matter—lurked in the shadows, with the neutrino somehow needed in radioactive decay). The rules were relatively simple and the possibilities immense. If the forces among protons and neutrons could be understood, then all of nuclear and atomic physics might be understood, and with it all of everyday phenomena and much of astrophysics.

However, already during the golden era of the 1930s, Hideki Yukawa, working in Japan, had made a proposal that led eventually in a different direction. Yukawa proposed that an as-yet-undiscovered particle, the "mesotron," now the pi meson, was the carrier of the nuclear force. After a false start, which turned out to be the muon, and after the war had intervened, the pi meson was discovered in 1947. On the one hand, it awakened the hope that nuclear forces and interactions could be described by some simple underlying dynamics. On the other hand, it marked the beginning of elementary particle physics.

In the 1950s the discovery of "elementary particles," on the same footing as the proton, neutron, and pi meson, proliferated. In the same decade, Robert Hofstadter and coworkers discovered that the proton is not a point particle. Instead, it has extended structure typical of a composite particle. The effort to explain the forces that bind protons and neutrons into nuclei in terms of these newly discovered particles did not succeed. By the end of the 1950s the stage was set for nuclear and elementary particle physics to part ways: particle physicists set off to figure out the next level of structure beneath protons, neutrons, pi mesons, and their brethren; nuclear physicists meanwhile continued to explore the wealth of quantum phenomena that are displayed in nuclei, to use nuclei as laboratories to test new concepts and look for new regularities and symmetries in nature, and to seek understanding of the nuclear astrophysical processes that make the stuff of the universe.

A large and vibrant community continued the study of nuclear physics after the birth of elementary particle physics. There was much to understand about nuclear structure, nuclear reactions, and other nuclear phenomena. By 1950 it was known that the forces between nucleons (protons and neutrons) are very short range (about 10^{-13} cm) and complex. They are moderately attractive at 10^{-13} cm and beyond, but strongly repulsive at separations less than 0.5×10^{-13} cm. Because of this, the nuclear force "saturates." A nucleon in a nucleus experiences a net attraction to nearby nucleons, but because of the short-range repulsion, the system does not collapse. The nuclear force was found to be roughly the same for neutrons and protons. However, the fact that a proton and neutron bind to form the smallest nucleus, the deuteron, while two neutrons do not bind, showed that the nuclear force between a neutron and proton can be slightly stronger than that between two neutrons or, indeed, two protons.

The nucleus is a system with two different species of strongly interacting particles, neutrons and protons—quite different from atoms, in which usually only the electrons participate in atomic excitations. Because the nuclear force saturates, so does the binding energy of nuclei containing many neutrons and protons. The nuclear contribution to the binding energy grows approximately linearly with the total number of nucleons (A). If it were not for the electromagnetic repulsion between protons, nuclei with very large (and roughly equal) numbers of neutrons and protons would be stable. Eventually, however, nuclei are destabilized by the electromagnetic (Coulomb) repulsion, which builds up proportional to the number of protons (Z) squared. The binding energy (per nucleon) of nuclei reaches a maximum of about 8 MeV in the vicinity of ^{56}Fe (^{62}Ni actually has the largest).

For nuclei with Z greater than around 56, the effects of Coulomb repulsion reduce nuclear binding. Eventually the attractive nuclear force is overcome, with the result that nuclei with $Z > 92$ are not found in nature. When some heavy nuclei decay (or fission) into two lighter—and more tightly bound—fragments, kinetic energy on the order of 200 MeV is released—more than 20 million times the energy released in a typical chemical reaction. Gravity is an astoundingly weaker force than either the nuclear force or electromagnetism—roughly a factor of 10^{40} weaker than the nuclear force. But as with electromagnetic forces, gravitational forces do not saturate. Instead, the universally attractive force of gravity grows like the total number of nucleons squared and eventually overwhelms all other forces for very large numbers of nucleons. When $A > 10^{57}$, gravitational binding of a giant "nucleus" is responsible for the creation and subsequent evolution of neutron stars, massive objects formed by the collapse of ordinary stars, with interior densities at or above that of normal nuclear matter.

By the early 1950s, two powerful models for describing nuclear spectra and simple reaction rates had emerged and had become the subject of extensive experimental study and further theoretical elaboration. The creators of these models subsequently won a Nobel Prize in physics: J. Hans D. Jensen and Maria Goeppert-Mayer in 1963 for the nuclear shell model; Aage Bohr, Ben Mottelson, and James Rainwater in 1975 for the so-called unified model.

The nuclear shell model pictures the nucleus as a collection of nucleons moving in orbits under the influence of a common spherical potential, which is generated by the average interactions of all the nucleons. As with electrons in the atom, successive nucleons of the same type must be placed in successively higher orbitals because the Pauli exclusion principle forbids identical nucleons from occupying the same state. The participation of two types of nucleons, protons and neutrons, enriches shell phenomena in nuclei compared with atoms. One of the most striking successes of the shell model was the prediction of anomalously stable "closed shell" nuclei, analogous to the noble gases of the Periodic Table of the Elements. The ability to predict the quantum numbers of nuclei with only a few protons or neutrons added to (or subtracted from) a closed shell bolstered belief in the shell model. The shell model in its original formulation, however, had little success describing the spectra of nuclei far from closed shells or in regions of N and Z, where the overall nuclear shape deforms away from spherical symmetry.

The unified model combined the early picture of the nucleus as a deformable, rotating, and vibrating object—a picture that had grown out of Bohr and Wheeler's liquid-drop model—with the shell model. The unified model couples individual particle states to the collective motion of the other nucleons. The most extreme example of collective motion is a nucleus with an equilibrium deformation that rotates as if it were a rigid body. Possible collective nuclear excitations also include vibrations. Clear evidence was found in nuclear spectra for both rotational and vibrational behavior. One of the important successes of the unified model was its ability to account for the much-faster-than-expected electric quadrupole transitions between low-lying nuclear excitations.

During the 1960s, experimental research in nuclear physics was carried out at a large number of research facilities (more than 25) at universities and national laboratories located throughout the United States. In addition, many similar facilities were constructed in Europe and parts of Asia. The research focused almost exclusively on studies of nuclear structure and on those nuclear reactions that could quantitatively illuminate nuclear structure. Since the nuclear shell and unified models could not be expected to describe nuclear spectra perfectly, much of the experimental data collected during the 1960s, while confirming the general concepts of the models, also revealed their limitations. Theorists looked to the fundamental interactions between nucleons both for the origins of both models and for insight on how to improve them. The full complexity of the interaction between nucleons was impossible to handle with the limited computing power available at that time. Simpler effective interactions were employed, and even then the mathematical complexity of finite, many-body systems limited the utility of the nuclear shell model to light nuclei (typically $A < 40$) except for a few nuclei in the near vicinity of closed shells. While clear examples of rotational and vibrational behavior could readily be identified in nuclear spectra, they occurred only in particular regions of the periodic table, and it became clear that such behavior was far from universal. A significant quantitative advance was made when S.G. Nilsson and his collaborators in Copenhagen and in Lund, Sweden, developed a relatively simple and physically intuitive model for characterizing nucleonic orbits in deformed potentials (see Figure 1.1). Much experimental evidence was found to support such a description. This deformed-shell model implemented important principles implicit in the unified model by coupling independent particle models to the collective description.

Significant progress was made during this period in nuclear reaction theory, and the ability to interpret the results of nuclear reactions quantitatively added much to the knowledge of nuclear structure. The so-called direct reaction model was particularly successful in dealing with the reactions involving light projectiles such as protons, neutrons, deuterons, and ^{4}He nuclei. For example, a reaction in which the incoming state consists of a deuteron and the nucleus and the outgoing state consists of a proton and the nucleus can probe the excited states of the nucleus that result when a neutron with a particular value of angular momentum is transferred to the target nucleus. While analysis of these reactions and of electron scattering experiments confirmed much of the underlying physics of the nuclear shell model, they also demonstrated that for a considerable fraction of the time, the nucleons were not in the assumed shell-model orbits but were instead promoted to higher-lying orbits as a result of the very strong, short-range nucleon-nucleon interaction. Refined as a result of intense and thorough studies of nuclear reactions, nuclear models during the 1960s and early 1970s were capable of reproducing most aspects of nuclear structure, although they required a sizable input of

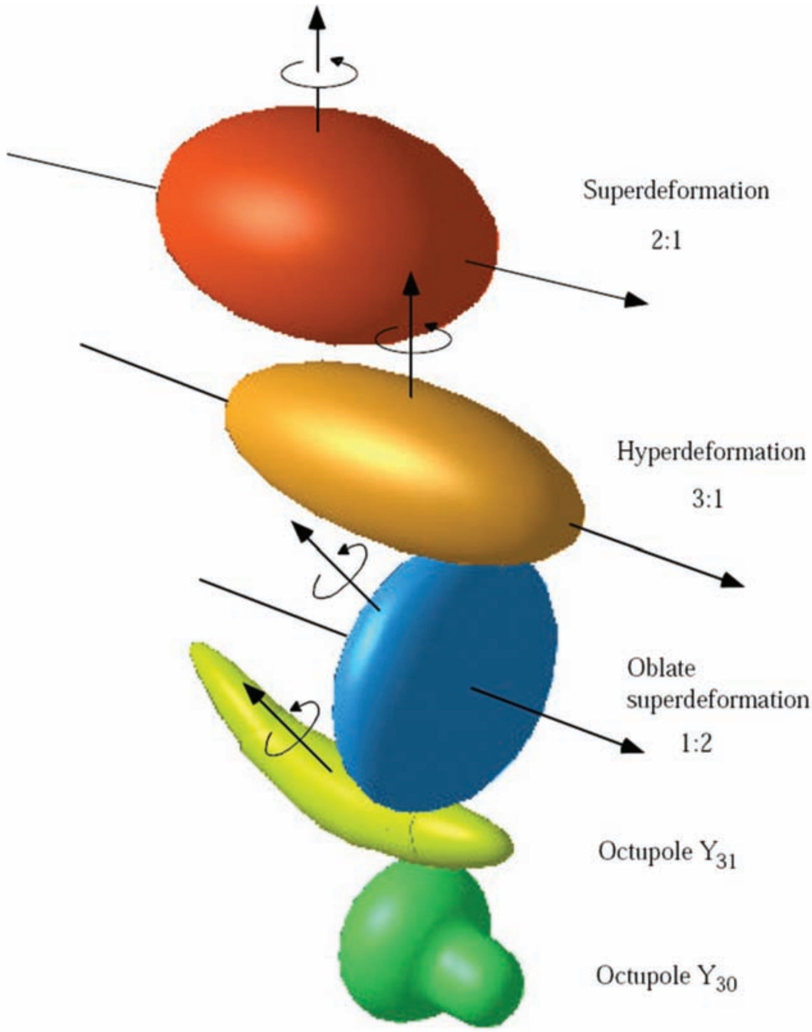

FIGURE 1.1 Various shapes of nuclei either observed or expected. Exotic orbitals that appear in regions far from the stability line may provide some new types of deformation. The superdeformation (top) and octupole pear-shaped deformation (bottom) have been observed experimentally. The oblate superdeformation has been predicted but not observed—less-deformed oblate shapes are, however, quite common. The hyperdeformation (second from the top) has been seen in certain nuclei. The octupole banana-type deformation has not been observed in such extreme form, but vibrations of this kind are well known. Reprinted with permission from *Report of the Study Group on Radioactive Nuclear Beams to the OECD Megascience Forum Working Group on Nuclear Physics*, copyright 1998 OECD.

experimental data to tune their predictions. It was uncertain how well these models could be extrapolated into regions with a very large neutron excess for which little or, more often, no experimental information existed.

In the 1960s, experiments using heavy-ion reactions were beginning to be used to extend the understanding of nuclear spectra and nuclear reactions. The collisions between heavy nuclei—say, ^{12}C on ^{24}Mg [$^{12}C(^{24}Mg, {}^{n}X)^{36-n}Y$]—proved difficult to interpret quantitatively. However, they very effectively brought huge amounts of angular momentum into the nuclei that were created. The use of highly efficient detector arrays with energy resolution on the order of a few keV made possible detailed study of the subsequent multiple gamma radiations, as these high-angular-momentum states radiated away their angular momentum and energy. These decay chains revealed a great deal about the underlying structure in the nuclei in which they were observed. Subsequent research (in the 1980s) of a similar nature revealed that superdeformed nuclear states can carry large amounts of angular momentum with less energy than that of normally deformed nuclei. In superdeformed nuclei, the longer axis may be as much as twice the length of the short axis. The ability of a nucleus to lower its energy sometimes—and therefore gain stability—by assuming a nonspherical shape also accounts for the existence and subsequent discovery of many elements heavier than those found in nature. Currently the observation of nuclei with Z up to 112 has been confirmed, and there is the interesting prospect that it may be possible to make long-lived superheavy nuclei.

By the middle of the 1960s, there was growing awareness that a more robust understanding of the global properties of nuclear matter was needed. Although they would not directly elucidate nuclear spectra, these global properties would describe the features of the nuclear matter common to all nuclei. Most of the spectroscopic properties of nuclei described by the nuclear shell and unified models are determined by the interactions of the least-bound nucleons in the nucleus, the analogue of the valence electrons in an atom or the particles at or near the Fermi surface in a degenerate Fermi liquid. Thus, neighboring nuclei would often exhibit quite different spectra and reveal very different behavior in low-energy nuclear reactions. However, their binding energy per nucleon and their density were virtually identical. How should the bulk properties of nuclear matter be characterized? It was thought that the interaction between nucleons resulted from the exchange of mesons—indeed these virtual mesons also play an important role in the nucleon's response to external fields—and that the detailed differences in short-distance behavior gave rise to the differences in average bulk properties. To investigate nucleon-nucleon dynamics at short distances (<1.5 femtometers), quantum mechanics requires that the probe have momentum of several hundred MeV/c and transfer a sizable fraction of this momentum in the collision. This required building higher-energy accelerators (>400 MeV) than had been employed in nuclear research (the largest up to that time were <50 MeV).

The much greater cost (over $100 million) of these higher-energy facilities dictated that there would be fewer (probably a single facility in the United States) and that they would operate in a user mode.[3] Several smaller accelerator facilities operated in-house at universities were closed, and university researchers initiated new research programs at the new user facilities. There was a resulting decline in emphasis on detailed nuclear spectroscopy, but it still remained an important element in the nuclear physics research program.

Worldwide, three higher-energy user facilities were built: one each in Canada, Switzerland, and the United States. The largest of these was the Los Alamos Meson Physics Facility, with an 800 MeV proton beam and a beam power approaching 1 MW; its user community consisted of nearly a thousand physicists. This facility became operational in 1972, producing intense secondary beams of neutrons, pions, muons, and neutrinos. The worldwide activity in this field produced an extensive body of data on the nucleon-nucleon and pion-nucleon interactions, mounted sensitive tests of the Standard Model, and was essential to the development of a relativistic nucleon-nucleus potential based on a mesonic description of the nucleon-nucleon interaction. This model provided a natural explanation for the strong nuclear spin-orbit force required to account for the observed nuclear shell structure; the origins of the spin-orbit force to that point in time had been obscure.

Even before the heavy-ion and medium-energy research cited above, experiments in the 1950s using beams of electrons at Stanford University, Saclay (France), and the Massachusetts Institute of Technology mapped out the distribution of the charge and magnetization in nuclei and, at Stanford, with the higher energies available, in the nucleon. In the 1960s and 1970s, these facilities and others also provided data on the momentum distribution of the nucleons in nuclei, probed deeply bound shell-model orbits, and investigated charged meson exchange currents in nuclei. Scattering processes involving the relatively weaker electromagnetic force were shown to be easier to treat theoretically. Thus, the desire for a dedicated, world-class electron accelerator emerged in the nuclear community.

At about the same time, a revolution was taking place in the paradigm characterizing strong interactions; it was driven by observations of highly inelastic scat-

[3]The user mode typically refers to the mode of operation whereby a potential user of a facility submits a technical proposal to the facility management explaining the proposed experiment in terms of its scientific interest and the manner of its execution. Upon approval of such a proposal, access to and time at the facility are scheduled for the user. In the case of the DOE and NSF national facilities, the user is not directly charged for the cost of operating the facility during its use.

tering of high-energy electrons from nucleons. In these experiments the electron transfers a large fraction of its energy and momentum to the target nucleon. Surprisingly large cross sections were observed at the largest energy and momentum transfer, requiring that the electrons be scattering from point-like charged particles inside the nucleon. Further observations confirmed that these particles had a spin of 1/2 and electric charges only a fraction of the charge on the electron. These were the properties of the hypothetical *quarks* that had been proposed to explain the spectrum of the strongly interacting particles (hadrons).

The initial observations were made at the Stanford Linear Accelerator Center and then further elaborated at high-energy accelerators around the world. By the early 1970s, a theory of the strong interactions—quantum chromodynamics (QCD)—was rapidly being established as the underlying description of all strongly interacting particles. QCD described the properties and interactions of baryons and mesons in terms of the interactions of colored, fractionally charged, point-like particles called quarks. Quarks interact by the coupling of their color charges to eight massless, colored "gluons," a subtle generalization of the electromagnetic interactions. Baryons are viewed as consisting of three constituent quarks, while mesons are formed from a constituent quark and antiquark.

The development of the quark model and its evolution into the theory of strong interactions, QCD, had a large influence within the nuclear physics community. Even though it was soon recognized that QCD would be extremely difficult to implement on the scale of hadrons and even more so on the scale of nuclei, the emergence of a fundamental underlying theory changed the way that nuclear physicists thought about nuclei and changed the criteria for an "explanation" of nuclear phenomena. Ideally, one would like to be able to trace the properties of nuclei back to the fundamental structure of QCD. The selection of 4 GeV as the initial energy for the Thomas Jefferson National Accelerator Facility was clearly influenced by the desire to connect the hadronic and quark descriptions of hadrons and nuclei. The eventual design for the accelerator at the Jefferson Lab employed superconducting radio-frequency (RF) resonant cavities in a mode that produced polarized and unpolarized electron beams of unprecedented intensity, quality, and duty factor. The facility produced the first beam for research in 1995.

The Jefferson Lab now has some 900 users and has carried out more than 100 experiments. Among the research highlights have been the demonstration of a large difference in the distribution of the proton's charge and magnetization, measurement of the strange-quark contribution to the nucleon's charge and magnetization distribution, and direct evidence that the hadronic description of the nucleon-nucleon interaction works to shorter distances than expected. Figure 1.2 shows the energy and momentum of energetic electrons scattered from a hydrogen target.

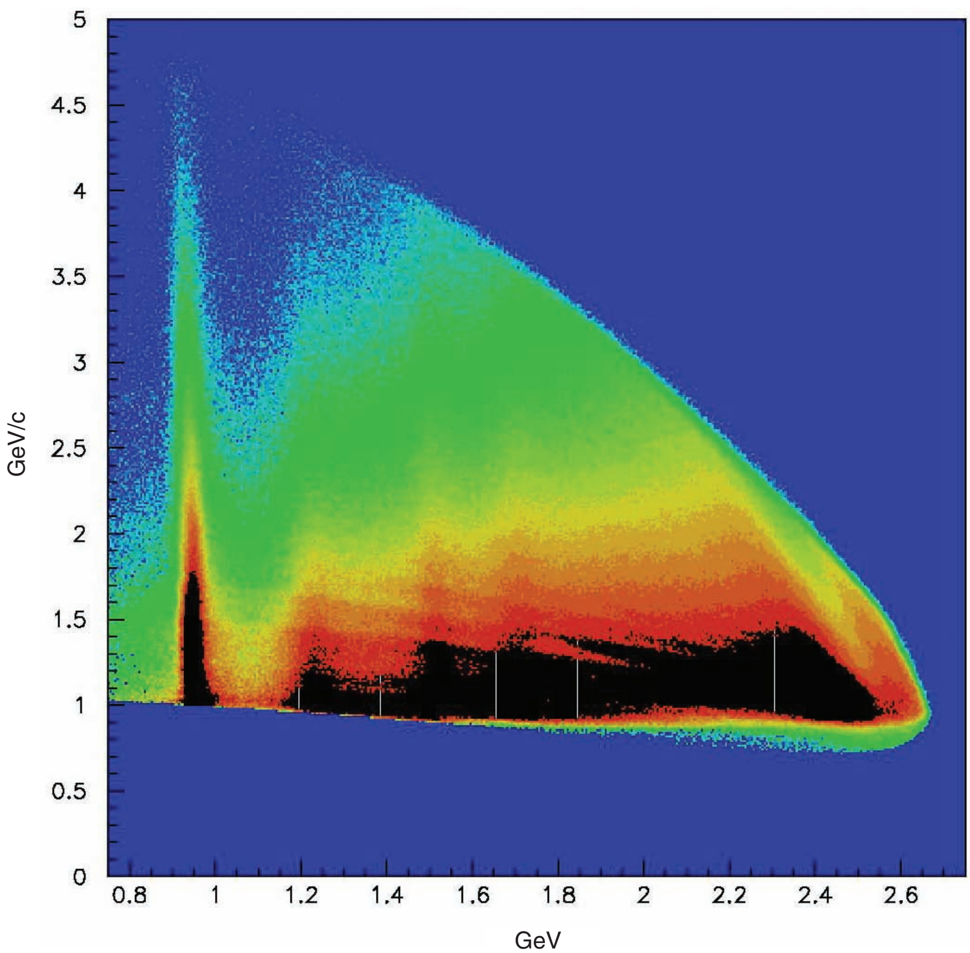

FIGURE 1.2 The response of the proton as revealed by experiments using the CEBAF Large Acceptance Spectrometer detector at the Thomas Jefferson National Accelerator Facility. The experiments measured how the proton absorbs both energy (horizontal axis) and momentum (vertical axis) from an incident electron. The features in the plot reveal certain resonances that the proton is excited to, confirming that it behaves as a complex system of quarks and gluons. Courtesy of the Thomas Jefferson National Accelerator Facility.

The QCD paradigm changed the way that nuclear physicists think about nuclear matter produced at very high temperature or density. Confinement of quarks and gluons within hadrons is regarded as a (relatively) low-energy phenomenon. At extreme pressure, hadrons overlap, the distinction between individual hadrons disappears, and a “condensed matter” of QCD is expected to be formed. At high temperatures, the identities of individual hadrons is also lost, leading to the formation of a new state of matter with very high energy and entropy density in which quarks and gluons are the relevant degrees of freedom.

A large community of experimental and theoretical nuclear physicists has launched an ambitious program to explore this very dense, hot, strongly interacting form of matter, often referred to as the quark-gluon plasma (sometimes called QGP). It is certain that in the early universe, some microseconds after the "big bang," strongly interacting matter would have gone through such a phase in which it consisted of quarks and gluons that cooled to protons, neutrons, and photons and subsequently deuterons and alpha particles. Indeed, the relative amount of these light nuclides produced in the early universe is part of the evidence supporting the big bang hypothesis.

Conditions similar to those of the early universe can be re-created in the laboratory by colliding heavy nuclei together at extremely high energies. Collisions between oppositely directed beams are much more efficient at reaching high energy than are collisions of one beam on a stationary target, so oppositely directed beams of energetic nuclei are typically required in studies of the QGP. Early experiments at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) were followed by higher-energy experiments at the European Organization for Nuclear Research (CERN). The results from the experiments at CERN provided tantalizing although not fully conclusive evidence for the formation of a new state of matter in such collisions. The U.S. quest in this area began in earnest in 2001 with the completion and operation of the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory. In a head-on collision of two gold nuclei, each carrying 100 GeV per nucleon, over 10,000 particles may emerge. Figure 1.3 shows the particles emerging from such a collision. The total energy in such collisions, 40 TeV, is the highest energy achieved to date in any human-made particle collision.

How should this quark-gluon phase manifest itself if it is formed? The earliest conjectures were that it would be plasma of locally free quarks and gluons whose interactions would be weak enough that its properties could be extracted relatively easily from the experiment and could be calculated with some reliability from QCD theory. Results from the experiments at RHIC pointed in a different direction. Much excellent data on a variety of phenomena has been gathered and analyzed from collisions of a variety of nuclei at various energies. The most recent experiments suggest that the material formed in the first instant of these collisions is best characterized as a strongly interacting quark-gluon liquid. Indeed it has been termed a perfect liquid, because the hot, dense material flows with very little viscosity, and the distance between collisions of the liquid's constituents is extremely short. This is quite different from earlier theoretical expectations; further

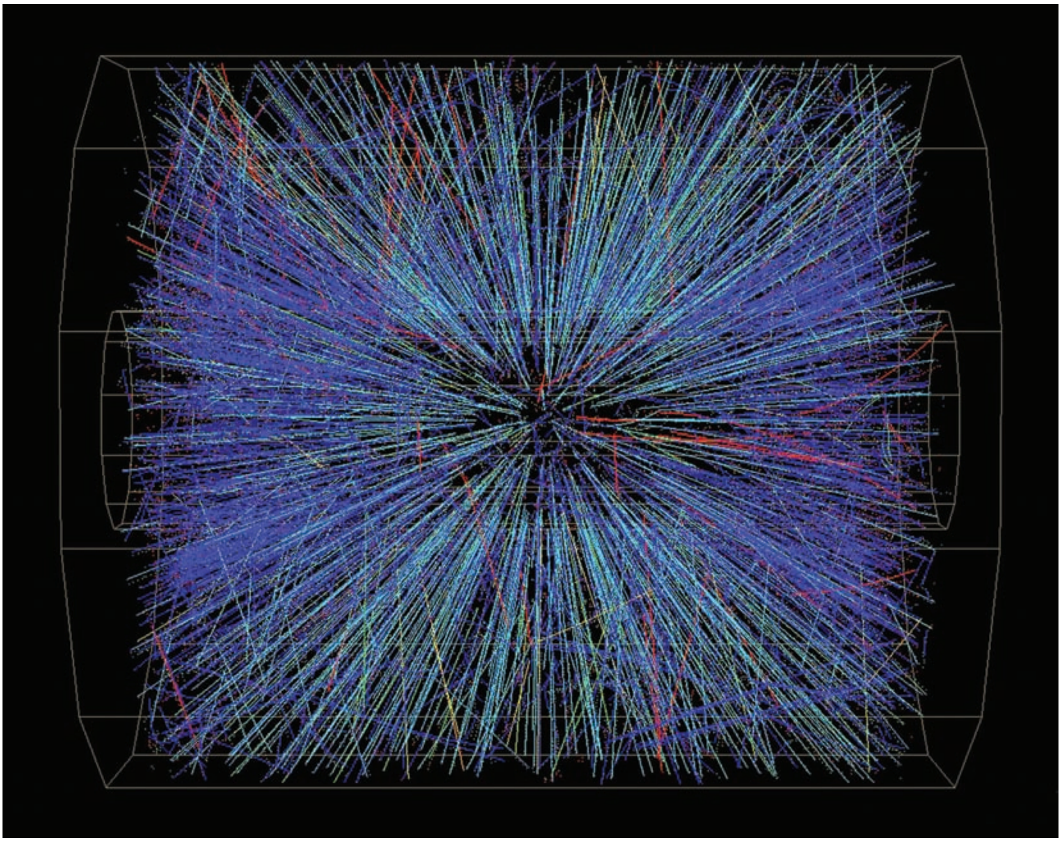

FIGURE 1.3 An example of the outgoing particles from a collision of two gold nuclei at the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory. Courtesy of the Brookhaven National Laboratory, Solenoidal Tracker at RHIC Collaboration.

study of this matter is expected to explain much about QCD and the dynamics of the very early universe.

The connection between nuclear reactions and astrophysics goes back to Bethe's pioneering work on the energy source of stars. Later, careful measurements of solar reaction processes suggested that the observed solar-neutrino flux was too low; this "solar neutrino problem" helped cause neutrino physics to emerge as a new discipline of nuclear physics and astrophysics. The past few decades have seen an explosion in the quality and quantity of astrophysical data. Satellite- and ground-based telescopes operating over a wide range of photon energies have revealed much about the behavior of ordinary stars, white dwarfs, neutron stars, black holes, galaxies, dark matter, and dark energy. There is every reason to believe that this flow of data will continue and, indeed, increase.

Initially, stellar evolution by hydrogen and helium burning is driven by proton- and alpha-capture reaction sequences on stable nuclei. Subsequent late-evolution phases from carbon to silicon burning are characterized by more complex reaction processes triggered by heavy-ion fusion or photodisintegration processes near the line of stability. Many of the most interesting, powerful, and important stellar phenomena such as supernova explosions and gamma-ray bursts that occur at the end of a star's life continue to challenge understanding. These explosive phenomena are important, since they create the bulk of the chemical elements above Fe and often lead to the formation of neutron stars or black holes. In these explosive events, an enormous flux of neutrons is created and subsequently captured by nuclei within a time short compared with the nuclear beta-decay lifetime. This is known as the rapid neutron capture process, or r-process. Thus, the nuclei experiencing the r-process are heavy and extremely rich in neutrons. Little knowledge and no data on the properties of such nuclei exist.

In addition to the relevance of nuclear structure to astrophysics, there is widespread interest in the nuclear physics community in investigating the many phenomena encountered with large neutron excesses and nearly unbound systems. Until the 1990s it was not clear that it might be possible to create a viable experimental program to investigate these issues. However, a number of technical advances in the development of high-charge-state ion sources, the availability of superconducting acceleration structures, and the fast and efficient collection of radioactive ions as well as the construction of large acceptance detectors have made such a program possible and attractive. Proposals for the construction of facilities incorporating these advances are now under consideration, with some already in development or operation. Significant advances have also made nuclear structure theory steadily more quantitatively reliable. Particularly notable among these are increases in available computing power and the accompanying formalisms and algorithms that take advantage of the increased capability. Building on these achievements, theoretical and experimental nuclear physicists, working in conjunction with astrophysicists, observational astronomers, and large-scale modelers, have the opportunity to greatly advance the understanding of stellar processes that map out a significant and critical portion of the history of the universe.

Over the period covered in this brief history of nuclear physics, many important discoveries were made without the use of any accelerator at all. Far and away the most significant has been the study of neutrinos from the Sun. This research, originally suggested by the Italian physicist Bruno Pontocorvo and undertaken in the United States by Raymond Davis, Jr., was viewed as a unique way to investigate the nuclear processes that occur at the center of the Sun and hence are responsible

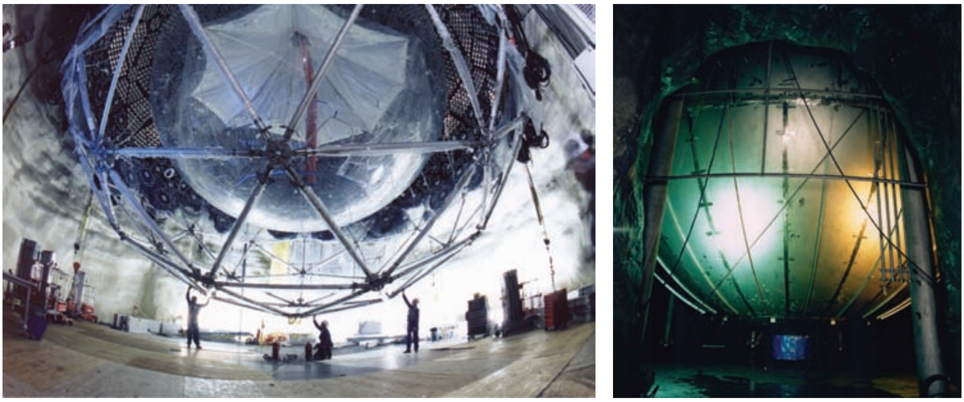

FIGURE 1.4 (Left) Photographic view from underneath the Sudbury Neutrino Observatory experiment in Canada showing the large acrylic vessel and its phototubes; image courtesy of the Sudbury Neutrino Observatory. (Right) Photographic view of the Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND) experiment in Japan; image courtesy of Hamamatsu Photonics K.K.

for its energy generation. Neutrinos interact so weakly that they readily escape from a stellar interior, allowing observation of interior nuclear processes. Early on in this research, Davis noted that fewer neutrinos than expected had been detected. Subsequent research in Japan and Canada (see Figure 1.4) has confirmed this deficit, showing that it is due to neutrino oscillations and that the characterization of the nuclear reactions driving the Sun is correct. The study of neutrino oscillations has since become an important element in nuclear and particle physics with active worldwide participation. Ray Davis shared the Nobel Prize in physics in 2002 with Masatoshi Koshiba for their work on neutrinos. Davis was recognized for his observation of solar neutrinos—his work to confirm Bethe's theory of solar-energy generation proved to be an unexpected window on a new area of fundamental physics.

Nuclear physics has also played a leading role in discoveries of fundamental symmetry violations. When the idea was first proposed that parity (symmetry under space inversion) could be violated in weak interactions, few people took it seriously until the dramatic observation of this effect in beta decays of spin-polarized ^{60}Co by C.S. Wu, R.W. Hayward, R.P. Hudson, and D.D. Hoppes. This discovery launched the experimental field of fundamental symmetry tests, leading to the eventual fall of time-reversal symmetry and a series of ever-more-precise tests for several symmetries whose violations have not yet been detected.

A variety of other measurements carried out by nuclear and particle physicists have further set strong limits on various processes that would require new physics beyond the Standard Model of electroweak interaction. Examples include the limits on electric dipole moments, the existence of second-class currents, and the lepton-flavor-changing decays of the muon. These measurements have also provided positive evidence for such particle physics landmarks as conserved vector currents, the unitarity of the Cabibbo-Kobayashi-Maskawa matrix that describes the interactions of quarks, and parity conservation by the strong interactions.

The past decade has witnessed significant developments in experimental studies of nuclei and nuclear astrophysics, driven largely by qualitative advances in technology, including high-resolution particle separators, large arrays of gamma-ray or particle detectors, a variety of traps, storage ring and laser spectroscopy techniques, and especially the development of first- and second-generation facilities for the production and use of nuclei far from stability. These technical developments have boosted experimental sensitivities by many orders of magnitude. They have led to results that have challenged long-held beliefs on many topics. Examples include the robustness of shell structure (e.g., magic numbers), nuclear geometries and density regimes in weakly bound systems (e.g., in halo nuclei), and evidence for new collective modes and many-body symmetries. Similarly, these developments enabled the creation of new superheavy nuclei. In nuclear astrophysics, experimental results from radioactive-beam facilities have provided improved knowledge on the ignition conditions for novae and x-ray bursts. These experiments also explored the far-from-stability reaction processes in explosive nucleosynthesis scenarios such as the r-process and the rapid proton capture (rp)-process in terms of reaction path and process timescales. These first results also showed that the theoretical basis of existing nucleosynthesis simulations for such processes is more than unsatisfactory and that the predictive power on the basis of these simulations is limited. Improvements in computational capabilities permit new theoretical approaches, giving rise to more realistic calculations for nearly all nuclei.

Thus, nuclear physics has expanded its scope considerably beyond its origins in nuclear structure and radioactivity (see Figure 1.5). It now investigates the properties of strongly interacting matter at a deeper level and contributes to knowledge of objects as diverse as the Sun and neutrinos. On the applied side, nuclear physics plays a significant role in energy, defense, and medicine, and its instruments are spread throughout modern technology. Nuclear physics is now deeply involved in many areas at the frontiers of human knowledge and development.

Looking into the future from today's perspective, there appear to be several clear avenues for world-class research in nuclear physics. One direction probes the consequences of QCD for hot and cold strongly interacting matter at length scales ranging from the subhadronic level to that of neutron stars. Another uses electro-

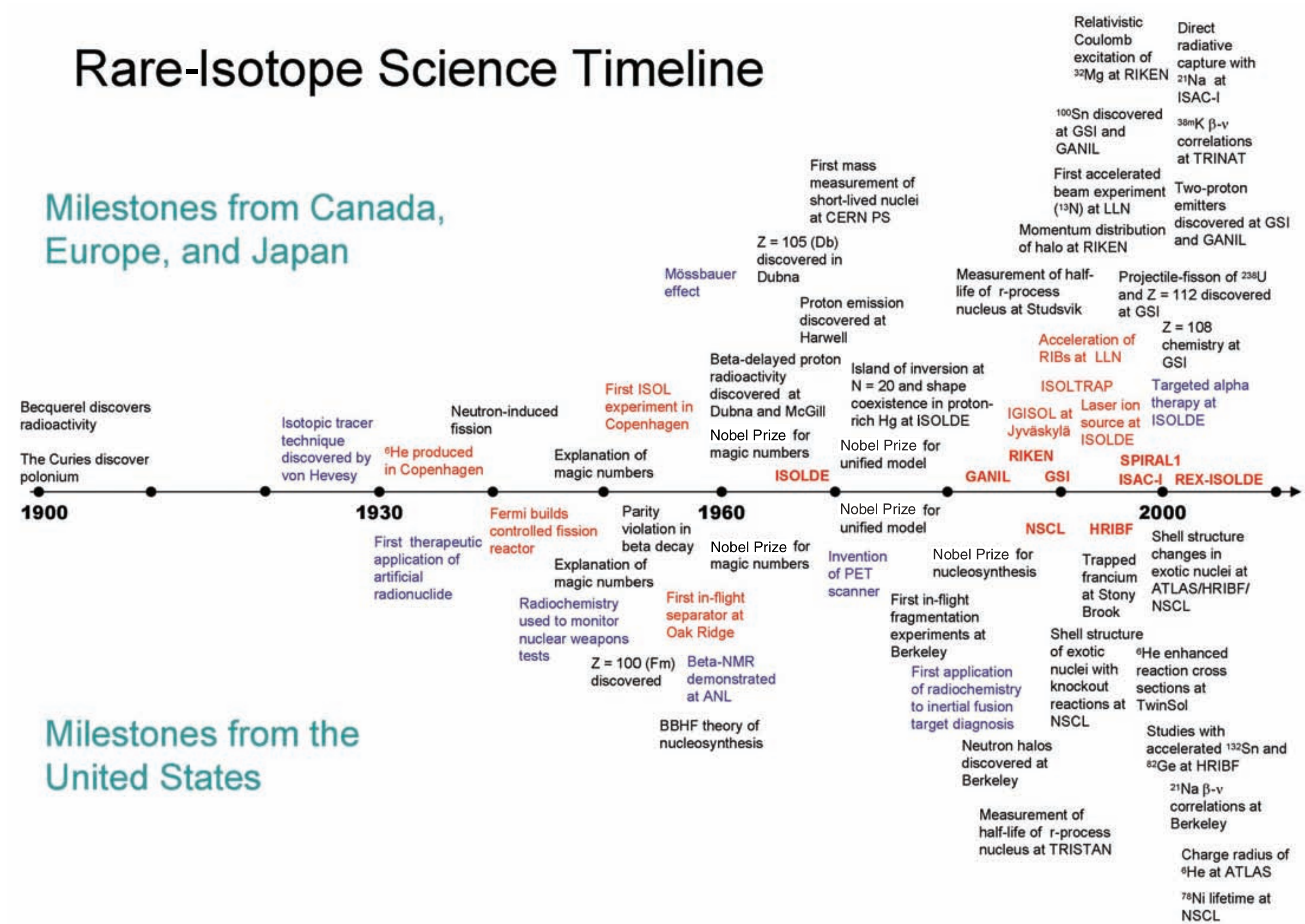
Rare-Isotope Science Timeline
Milestones from Canada, Europe, and Japan
Milestones from the United States
1900
1930
1960
2000
Becquerel discovers radioactivity
The Curies discover polonium
Isotopic tracer technique discovered by von Hevesy
^{6}He produced in Copenhagen
Neutron-induced fission
Explanation of magic numbers
First ISOL experiment in Copenhagen
Mössbauer effect
Z = 105 (Db) discovered in Dubna
First mass measurement of short-lived nuclei at CERN PS
Proton emission discovered at Harwell
Beta-delayed proton radioactivity discovered at Dubna and McGill
Nobel Prize for magic numbers
ISOLDE
Island of inversion at N = 20 and shape coexistence in proton-rich Hg at ISOLDE
Nobel Prize for unified model
Measurement of half-life of r-process nucleus at Studsvik
GANIL
IGISOL at Jyväskylä
RIKEN
GSI
Acceleration of RIBs at LLN
ISOLTRAP
Laser ion source at ISOLDE
Momentum distribution of halo at RIKEN
First accelerated beam experiment (^{13}N) at LLN
^{100}Sn discovered at GSI and GANIL
Relativistic Coulomb excitation of ^{32}Mg at RIKEN
Direct radiative capture with ^{21}Na at ISAC-I
^{38m}K β-ν correlations at TRINAT
Two-proton emitters discovered at GSI and GANIL
Projectile-fisson of ^{238}U and Z = 112 discovered at GSI
Z = 108 chemistry at GSI
Targeted alpha therapy at ISOLDE
SPIRAL1
ISAC-I
REX-ISOLDE
First therapeutic application of artificial radionuclide
Fermi builds controlled fission reactor
Explanation of magic numbers
Radiochemistry used to monitor nuclear weapons tests
Parity violation in beta decay
Z = 100 (Fm) discovered
First in-flight separator at Oak Ridge
Beta-NMR demonstrated at ANL
Nobel Prize for magic numbers
BBHF theory of nucleosynthesis
Invention of PET scanner
Nobel Prize for unified model
First in-flight fragmentation experiments at Berkeley
First application of radiochemistry to inertial fusion target diagnosis
Nobel Prize for nucleosynthesis
Neutron halos discovered at Berkeley
Measurement of half-life of r-process nucleus at TRISTAN
NSCL
Shell structure of exotic nuclei with knockout reactions at NSCL
HRIBF
Trapped francium at Stony Brook
Shell structure changes in exotic nuclei at ATLAS/HRIBF/NSCL
^{6}He enhanced reaction cross sections at TwinSol
Studies with accelerated ^{132}Sn and ^{82}Ge at HRIBF
^{21}Na β-ν correlations at Berkeley
Charge radius of ^{6}He at ATLAS
^{78}Ni lifetime at NSCL

FIGURE 1.5 A chronicle of some of the major events (by no means all-inclusive!) in the history of rare-isotope science (RIS). Scientific milestones in the studies of nuclei, nuclear astrophysics, and physics of fundamental interactions appear in black; technological advances and facilities appear in red; and applications are shown in blue. In order to illustrate the worldwide context, the upper portion displays the milestones from Canada, Europe, and Japan, while the U.S. milestones are shown below the timeline axis. This display of many leading examples of RIS in a single graph allows one to view couplings between basic science, technology, and applications as well as the steady increase in the activity in RIS and the high degree of competitiveness in the field. The only dedicated radioactive ion beam facilities in the United States are the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (1989; in-flight separation) and the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory (first Isotope Separator On-Line [ISOL] beam in 1997). The figure is based on input solicited from a number of leading scientists representing the worldwide RIS effort.

NOTE: ANL—Argonne National Laboratory; ATLAS—Argonne Tandem Linear Accelerator System; BBHF—Burbidge Burbidge Hoyle Fowler, referring to a team of scientists who wrote a landmark paper on nucleosynthesis; CERN—European Organization for Nuclear Research; GANIL—Grand Accélérateur National d'Ions Lourds (Great Heavy-Ions National Accelerator); GSI—Gesellschaft für Schwerionenforschung mbH; HRIBF—Holifield Radioactive Ion Beam Facility; IGISOL—Ion Guide Isotope Separator On-Line; ISAC—Isotope Separator and Accelerator; ISOL—Isotope Separator On-Line; ISOLDE—On-Line Isotope Mass Separator, a facility at CERN; ISOLTRAP—Tandem Penning trap mass spectrometer at ISOLDE; LLN—Laboratoire Louis Néel; NMR—nuclear magnetic resonance; NSCL—National Superconducting Cyclotron Laboratory; PET—positron emission tomography; PS—proton synchrotron; REX-ISOLDE—Radioactive Beam Experiment at ISOLDE; RIBs—rare-isotope beams; SPIRAL—Système de Production d'Ions Radioactifs en Ligne; TRINAT—TRIUMF Neutral Atom Trap; TRISTAN—Terrific Reactor Isotope Separator to Analyze Nuclides; TRIUMF—Tri-University Meson Facility.

magnetic and weak processes to probe more delicately inside hadrons and nuclei to see how quarks and gluons give rise to nuclear phenomena and to test the Standard Model of particle physics. Many of these tests of the Standard Model will employ nonaccelerator sources ranging from astronomical objects to radioactive nuclei. A third direction, the one central to the concept of a rare-isotope facility, seeks to investigate nuclear structure at the extreme limits of particle stability, which is crucial for investigating new nuclear phenomena and for achieving a better understanding of the evolution of stars and the creation of the chemical elements.

TECHNOLOGICAL CONTEXT

Frequently there is a synergy between a new scientific direction and recent technological developments that enable groundbreaking research. Rare-isotope science is in a position to exploit recent technical developments that promise much more intense, high-quality beams of short-lived isotopes.[4] However, even with the promised increase of many orders of magnitude, the intensities of a next-generation FRIB will still be low compared with what is traditionally available at a stable-beam nuclear physics facility. Fortunately there has also been significant progress in the development of new and more efficient detector systems, which, when combined with the new accelerator developments, significantly expand the reach of new experiments.

The experimental study of exotic nuclei involves three separate stages: *production* and *preparation* of the rare isotopes for research and the *observation* of the final products by means of the end-station instrumentation. Broadly speaking, there are two basic approaches to producing radioactive beams for use in nuclear physics experiments; they are called the in-flight technique and reacceleration. The techniques are complementary, and each has an important role in the study of exotic nuclei. Figure 1.6 shows the various stages of production, preparation, and experimental utilization of exotic nuclei.

In the in-flight technique, a production target is bombarded with a beam of a heavy stable nucleus. On interacting in the production target, the incident nucleus is fragmented into a variety of lighter exotic nuclei that travel with approximately the velocity of the incident beam. These exotic nuclei are then directed onto the

[4]In this report, the committee refers to as “high-quality beams” those with controlled characteristics such as good energy resolution, small transverse emittance, high duty factor, isotopic purity, and reasonable intensity. Of course, beams that are of sufficiently high quality for one experiment may not be optimized for another.

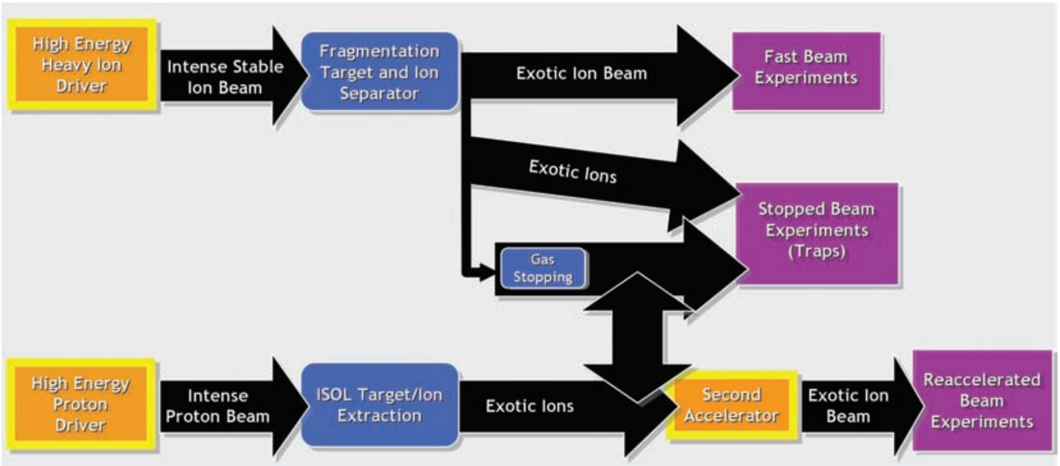

FIGURE 1.6 The different techniques for creating and utilizing beams of rare isotopes. The purple boxes represent the final stage, in which the nuclei are ready for use in experiments.

experimental target. This preparation technique is fast (less than 10^{-6} sec), direct, and independent of chemistry. These prepared beams typically have rather high energies (typically 50 to 500 MeV per nucleon), which means that they can be used to then bombard thick secondary targets giving the highest yields of the most exotic nuclei farthest from stability. These in-flight beams can also be inserted into devices called storage rings, which allow them to circulate continuously for mass measurements, or they can be used to enhance yields by being repeatedly recirculated through a given (thin) target. It is, however, very difficult to produce high-quality lower-energy beams by slowing down the fragments of the initial beam; thus, fragmentation is not suitable for many classes of experiments.

The second approach, reacceleration, takes the exotic nuclei formed in the production target and prepares a beam by bringing the exotic nuclei to rest and then injecting them into a second accelerator. This method produces high-quality, reaccelerated beams at the lower energies traditionally used for nuclear structure and nuclear astrophysics experiments, so these well-tested and well-understood techniques can be exploited in investigating their subsequent interaction with the target. There are two versions of this method of exotic-beam preparation—the "gas catcher" and the Isotope Separator On-Line (ISOL) techniques.

The gas catcher approach uses the same fragmentation process as the in-flight method, but in this case the exotic nuclei produced in the target are slowed in an absorber and then stopped in a gas catcher (typically He gas). The fragments remain ionized because of the large binding energy of electrons in the He atoms.

These ions are then fed into the second accelerator. This technique is also chemistry-independent, works for essentially all elements, and is fast. Its applicability for the most intense beams of exotic nuclei is still under investigation.

In the ISOL technique, a beam of light projectile nuclei bombards a thick target of a heavy element. The exotic nuclei are produced by a process called spallation, in which the target nucleus is fragmented into pieces, many of which are exotic. These exotic nuclei stop in the hot, thick target and diffuse from the target into an ion source where they are prepared for injection into the second accelerator and reaccelerated. This technique can often produce the highest intensities of certain isotopes and has a long history of technological development, but the extraction process depends on the atomic chemistry and surface properties of the target, is generally not useful for (refractory) elements with low vapor pressure at high temperatures, and is often slow so that short-lived isotopes are not obtained. Typically, considerable research and development are required to establish a useful beam for the first time that a new element is required.

In all three techniques, the exotic nuclei can be stopped to study their radioactive decay or injected into traps for fundamental studies or measurements of their properties such as their mass or charge radius.

Significant technical advances have been made in the development of superconducting radio-frequency linear accelerators. Improvements in cavity design and material preparation have led to higher field gradients, leading to more efficient acceleration. Independent tuning and phasing of the individual RF modules allow ion acceleration over a wide range of velocities and charge-to-mass ratios. Continuing ion source development has led to the production of large quantities of highly charged heavy ions ideal for energetic heavy-ion drivers. All this technology is also applicable for the reacceleration phase of an exotic-beam facility in which collection efficiency and beam quality are more important than high energy or beam power. Appropriate proton drivers have been available for some time, and the ISOL technique is now well developed.

An essential additional development in facilitating the study of exotic nuclei is advances in experimental instrumentation that now allow measurements to be carried out with beams as weak as a few hundred particles per second or, in special cases, as low as 1 particle per day, whereas traditionally, nuclear structure and astrophysics experiments have usually been carried out with beams on the order of 10^8 to 10^{13} particles per second.

Thus, it appears that the technological advances are now available to allow the construction of rare-isotope facilities of enhanced capability that would permit the execution of experiments unimaginable a decade ago.

2

Key Science Drivers for a Rare-Isotope Beam Facility

Chapter 1 presented a quick tour of nuclear physics, but more importantly it characterized the roots of some of the intellectual and technological drivers toward the future. This chapter explores the present-day investigations that would most directly be impacted by a facility for rare-isotope beams (FRIB)—and therefore would also most likely set the minimum performance requirements.

THE SCIENCE DRIVERS

A facility capable of producing intense beams of a wide variety of radioactive nuclei would clearly impact many areas of science and technology. This chapter presents the committee's view of the principal scientific drivers in nuclear structure physics, nuclear astrophysics, fundamental symmetries, and some important technical applications. However, it is often the case with new world-class facilities that their most important scientific discoveries are not foreseen. The science drivers are briefly presented below, and each is then discussed in a more expanded presentation.[1] A facility capable of executing the indicated research is referred to here as a FRIB.

[1]The Glossary in Appendix D provides additional discussion of key scientific terms.

Nuclear Structure

- *Testing new nuclear structure concepts.* A quantitative understanding of nuclear structure is important to problems ranging from the origin of the elements to the use of nuclei as laboratories for probing new interactions. The nuclear many-body problem—strongly interacting, with two kinds of particles (protons and neutrons), and with competing effects due to short-range multiple scattering and long-range collectivity—is also of broad intrinsic interest. The phenomena that arise—shell structure, pairing, superfluidity, collective motion and its connections with many-body symmetries, and spectral transitions from order to chaos—and the methods that nuclear physicists employ are also fundamental to fields such as atomic and condensed-matter physics and quantum chemistry. Nuclear structure theory has made significant progress in recent years by adapting numerical techniques for high-performance computing and through conceptual advances such as effective field theory and improved density functionals. However, the reexamination of old paradigms and subsequent development and validation of new nuclear models require data. This is a role for a FRIB: to test the predictive power of models by extending experiments to new regions of mass and proton-to-neutron ratio and to identify new phenomena that will challenge existing many-body theory. A FRIB's rare-isotope beams of unprecedented intensity and its sophisticated detector arrays would allow experimentalists to explore the limits of nuclear stability. A FRIB's technological developments would allow nuclear physicists, for the first time, to study nuclei that previously could be found only in the billion-degree explosions of distant supernovae.
- *Production and properties of superheavy nuclei.* Theory predicts that superheavy nuclei that do not exist anywhere else in the universe can be assembled. The nuclei would contain in excess of 120 protons; hence their stored Coulomb energy would be huge. However, with a large number of excess neutrons and an appropriate geometry, the attractive nuclear force could allow such a unique system to exist for times exceeding a day. The synthesis of such nuclei and their proper identification constitute an experimental challenge, but an advanced exotic-beam facility such as a FRIB is required if any meaningful search is to be carried out. These superheavy systems will provide great insight into the nuclear reactions and structure and, if they possess sufficient lifetimes, may reveal unusual chemical properties.
- *Probing neutron skins.* Very-neutron-rich nuclei that can be reached by a FRIB offer the only laboratory access to matter made of pure neutrons. The

outer layer of those exotic nuclei consists of a neutron skin, which dramatically impacts their structure, reactions, and decays. Neutron skins can result in novel collective modes. Vibrations with respect to the inner proton-neutron core, for example, can impact neutron-capture rates, which are key to the astrophysical rapid neutron-capture process (r-process). With an improved understanding of strongly interacting matter in finite nuclei with large neutron excesses, scientists will be better equipped to model neutron stars: giant reservoirs of neutron matter.

Nuclear Astrophysics

- *The origin of the heaviest elements.* At the extreme temperatures and pressures of fiery stellar explosions, new elements are forged by enormous fluxes of free neutrons (the r-process), energetic protons (the rapid proton-capture process, or rp-process), and gamma rays (the gamma process, historically referred to as the p-process). On timescales of seconds and less, these fluxes drive the original element abundance to the neutron or proton drip lines where even the most basic nuclear properties—binding energy and half-life—are, for the most part, unknown. Yet more than half of the elements in nature—mostly the ones heavier than iron—have been created this way. These same nuclear processes also power stellar thermonuclear explosions observed as classical novae and Type I x-ray bursts. They also provide the signatures for the diagnostics of core-collapse supernova explosions. The measurement of the properties of these exotic short-lived nuclei in the pathway of these "extreme" processes therefore provides the key to a better understanding of nucleosynthesis and the conditions, timescales, and mechanism of stellar explosions.
- *Explosive nucleosynthesis.* For nuclei in the iron group and lighter, nucleosynthesis also frequently proceeds through exotic parent nuclei. The iron in our blood and the calcium in our bones were produced by many generations of supernovae occurring since the big bang, in which these elements were originally formed as radioactive nickel and, in part, as radioactive titanium. Only about 10 percent of the isotopes in a typical modern calculation of explosive nucleosynthesis are stable. The rates for most of the key reactions are estimates based on uncertain extrapolation of theory. An exotic-beam facility would be able to measure many of the most critical rates and constrain the theoretical prediction of the rest.
- *Composition of neutron stars.* There are roughly a billion neutron stars in the Milky Way Galaxy, yet their internal structure and the composition of their crusts are poorly understood. Produced by the explosive deaths of

massive stars, neutron stars are only a few times larger in size than the event horizons of black holes of the same mass. They produce a variety of high-energy phenomena—pulsars, x-ray bursts, some types of gamma-ray bursts—and are laboratories for general relativity. While an exotic-beam facility would not directly probe the high densities of neutron stars, it would be able to constrain the isospin dependence of the nuclear equation of state that determines neutron star structure. Moreover, using charge-exchange reactions on the most critical neutron-rich nuclei along the electron-capture chains that produce the critical nuclei in the crusts of neutron stars, a FRIB could enable the study of the central questions concerning the composition and energetics of their upper mantles.

Fundamental Symmetries

- *Tests of fundamental symmetries with rare isotopes.* The Standard Model of particle physics has been extraordinarily successful but has long been believed to be incomplete. The incompleteness is now demonstrated by the discovery of neutrino mass; modifications to the Standard Model are required. The Standard Model also leaves mysteries, failing to explain, for example, the asymmetry between matter and antimatter in the universe. Solving this problem seems to demand large effects of time-symmetry (T) violation, and there is little guidance from the Standard Model on this question. Among many experimental approaches for finding a new source of T violation, the search for a permanent electric dipole moment (EDM) is consistently cited as one of the most promising. While most particles have a finite magnetic dipole moment, a finite EDM violates time-reversal symmetry and has not yet been observed. The size of a possible EDM is expected to be dramatically enhanced in a few heavy radioactive nuclei with unusual pear-shaped deformations. Large numbers of such nuclei could be produced at a high-intensity FRIB, improving the sensitivity to an EDM by several orders of magnitude over existing experiments. Such measurements, free from backgrounds and many systematic effects, would be sensitive to the existence of physics at energy scales even higher than those that can be studied at the new Large Hadron Collider at the European Organization for Nuclear Research (CERN).

Other Scientific Applications

- *Applications from stockpile stewardship, materials science, medical research, and nuclear reactors.* Applications in these areas have long relied on a wide variety of radioisotopes. At the present time, each of these areas would be significantly advanced by a facility with high isotope production rates capable of producing high specific-activity (pure) samples for experimental use. In addition, the parallel advances in low-energy nuclear theory driven by a properly organized FRIB experimental program would provide better models for needed nuclear reactions in areas now beyond direct experimental reach.

—In the case of *stockpile stewardship,* the complex nuclear reaction networks needed for understanding device performance would be greatly clarified.

—Many *materials science applications* typically require high-purity radioactive isotopes for implantation to diagnose subtle but important phenomena at the few-atom level. Here, the growing demand, the relatively short half-lives, and the required purity of the desired range of isotopes argue strongly for a new high-production-rate facility.

—Similarly, *medical applications,* such as the development of new alpha- and beta-emitter tagged antibodies that target and destroy cancer cells, have unmet requirements for high isotope production rates.

—Lastly, in *the reexamination of the nuclear fuel cycle* as part of the "global nuclear energy partnership," improved cross sections for neutrons on unstable fission fragments and actinides are required for the design of better fast-neutron reactors. The contributions of a FRIB to these questions would, in large part, be greatly enhanced by the availability of a suitable neutron source at the site.

NUCLEAR STRUCTURE

A quantitative understanding of nuclear structure is important in problems ranging from the origin of the elements to the use of nuclei as laboratories for probing new interactions. Yet a general theory of nuclear structure remains elusive: the classical formulation of this problem, protons and neutrons interacting through a strong, short-range potential, is difficult to solve except for the lightest nuclei. Nor is it understood in any detail how such a formulation emerges from the underlying theory of quantum chromodynamics (QCD). For this reason, many of the tools for describing nuclei are based on models constructed to explain observations—such as quantum mechanical tunneling, symmetry breaking, both ordered and chaotic spectral properties, and rotations and vibrations—rather than being derived from fundamental theory. Thus, these tools are of limited utility in terms of both extrapolating power and predicting new phenomena.

However, much progress is being made. The first calculations of nucleon-

nucleon scattering properties have recently emerged from lattice QCD, and effective field theory, also motivated by QCD ideas, has provided controlled expansions for observables in few-body nuclei. The classical nuclear many-body problem can now be solved exactly through 12 nucleons, owing to the growth in computing power. There are methods for heavier nuclei being formulated that make direct connections with the underlying nucleon-nucleon interaction by defining how that interaction must be modified when used in model calculations.

The validation of improved models requires data. While a considerable body of information about nuclei at or near stability exists, a FRIB would test models by providing data in entirely new mass regions. This new information would stimulate further improvements by revealing the shortcomings of current models and uncovering new phenomena requiring conceptual advances in theory.

Figure 2.1 illustrates some of the progress that has been made in solving the classical nuclear physics problem, protons and neutrons interacting through a potential derived from two-nucleon scattering data, augmented by three-nucleon forces also constrained by experiment. The results were obtained from computationally intensive variational and Green's function Monte Carlo calculations. This figure shows that in cases where the classical nuclear many-body problem can be solved, quantitative agreement with experiments is obtained for nuclear ground states and low-lying excitations. Significant in this figure is the important role of three-body forces. They are seen to provide approximately 15 percent of the binding energy, a uniquely large effect in physical systems.

A goal of nuclear structure theory is to extend such successes to the heavier nuclei that would be the focus of FRIB research. Such extensions cannot come about through growth in high-performance computing alone. The combinatorial growth of the complexity of the nuclear many-body problem with increasing nucleon number is too steep and the accuracy requirements too severe: typical nuclear binding energies may be 1 percent of the size of the canceling vector and scalar potentials operating within the nucleus. But there are paths forward that promise to combine exact techniques and present knowledge of the two- and three-nucleon potentials with models, thereby making model-based calculations far more reliable.

Much is known about the qualitative physics governing the structure of heavy nuclei. Nuclei exhibit a shell structure analogous to that found in atoms, despite the much stronger interactions among the nuclear constituents. Mass measurements show that nuclei with special "magic" numbers of neutrons or protons—2, 8, 20, 28, 50, 82, and 126—have particular stability. A spherical potential—representing the "mean field" that influences nucleon motion owing to the nucleon's interactions with the rest of the nucleus—can reproduce this pattern and account for simple excitations of nuclei near magic numbers. But unlike in atoms, impor-

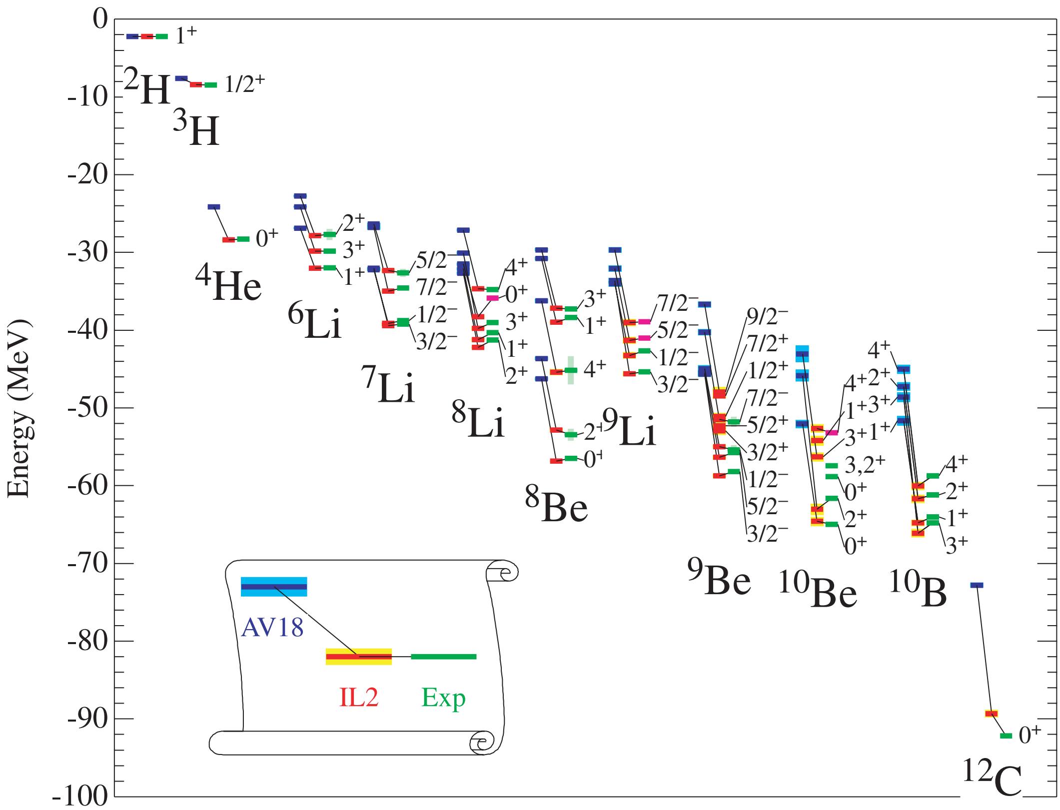

FIGURE 2.1 The results for calculations of the energy levels of nuclei up through A = 12 using Green's function Monte Carlo predictions of the binding energies of ground and excited states of light nuclei. These calculations are based on two- and two-plus-three-nucleon interactions determined from experiment combined with an essentially exact solution of the resulting nonrelativistic nuclear many-body problem. The agreement with experimentally determined energies is approximately 0.5 MeV out of 95 MeV for the two-plus-three-nucleon interaction. Courtesy of Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

tant correlations between the nucleons arise from "residual" strong interactions beyond the mean field. The nuclear shell model, perhaps the most widely used microscopic nuclear model, superimposes such correlations on the shell structure, thereby directly accounting for that part of the residual interaction most important to the long-distance structure of the nucleus. The effects of short-distance correlations can also be treated, though indirectly.

The shell model, however, still requires solution of the nuclear many-body problem for many active valence nucleons occupying the quantum states between the magic numbers. This problem also becomes numerically challenging for nuclei beyond nickel (56 nucleons). Thus, other models are needed in which only the most important degrees of freedom are identified and retained, so that a full treatment of all interactions among the valence nucleons can be avoided. This kind of approach to many-body quantum physics can be found in many other fields, such as condensed-matter physics, atomic and molecular physics, and quantum chemistry. Examples of nuclear physics models that have had success include those describing collective motion such as rotations and vibrations, those that simplify the interactions among valence nucleons by limiting interactions to small clusters of nucleons, and those that replace interactions among many nucleons by a density functional describing conditions locally around each nucleon.

One dramatic example of collective behavior is the breaking of spherical symmetry by deformation of the nuclear shape into a football or a pancake and the subsequent restoration of that symmetry by the collective rotation of the deformed nucleus, producing a spectrum characteristic of a rigid rotor. Models have been developed to describe the conditions for such shape changes and the resulting nuclear spectra characteristic of rotation.

The understanding of such phenomena is limited by the at-present restricted view of all possible nuclei. Most nuclear experiments are conducted with stable nuclei, a group of about 300 species that exist naturally on Earth. These nuclei can be viewed as forming the floor of a valley—called the valley of stability—in a two-dimensional landscape in N and Z (see Figure 2.2). That is, the stable nuclei are a one-dimensional path in (N,Z) through this two-dimensional landscape. Many properties of the stable nuclei have been measured, and most nuclear models have been designed to reproduce these properties. Thus, the important test of understanding nuclear structure will be the extent to which nuclear properties can be predicted in new regions of the landscape—properties of nuclei away from the valley of stability.

The effort to understand the broad spectrum of nuclei, stable and unstable, has important implications for other fields. In astrophysics, unstable nuclei play crucial roles in explosive environments such as supernovae and colliding neutron stars. In fact, it is believed that roughly half of the stable nuclei heavier than iron were synthesized as unstable nuclei in the core of an exploding supernova, then ejected into the interstellar medium. The stable r-process nuclei found on Earth are the "daughters" of these unstable parents, formed when the parents decayed back to the valley of stability after the supernova explosion.

Nuclear physicists would like to understand how far the nuclear landscape extends beyond the valley of stability: how exotic can a nucleus be while still remaining bound to strong interactions? The valley of stability follows a path that

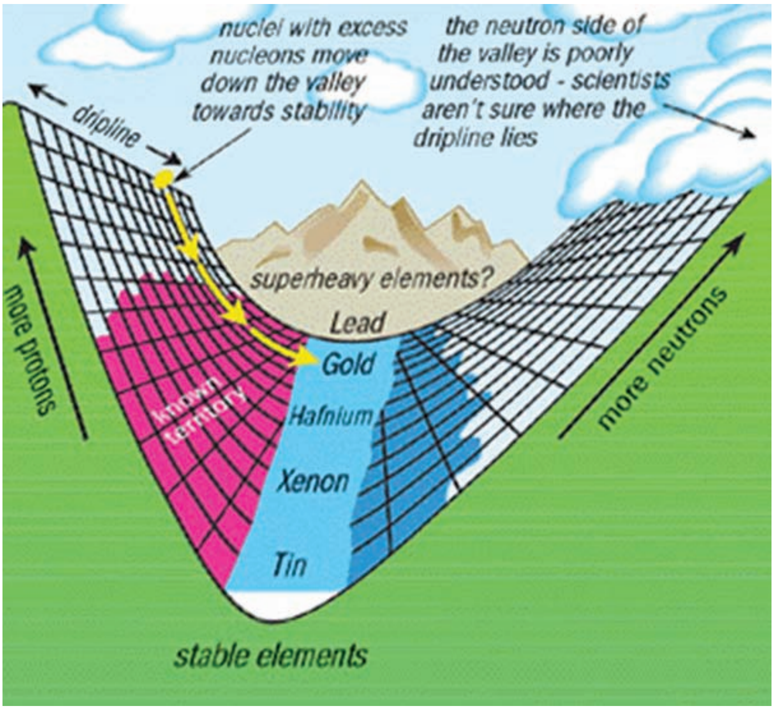

FIGURE 2.2 An artist's conception of the valley of stability. The valley walls are actually asymmetric: as one adds neutrons the valley wall rises less quickly than when one adds protons, owing to the repulsive Coulomb interaction between protons. This repulsion grows as the square of the number of protons.

begins, for light nuclei, with N ~ Z, then later veers toward nuclei with N > Z as the repulsive Coulomb force begins to favor heavy nuclei with fewer protons than neutrons. The walls of the valley are quite asymmetric (see Figure 2.2). Owing to the Coulomb force, only a few protons can be added to a heavy stable nucleus before the nucleus breaks apart. Thus, the valley walls on the proton-rich side are steep, and the proton drip line is not far from the stable valley floor. For this reason, experimentalists have already succeeded in "mapping" the "limit" of stable, proton-rich nuclei through bismuth (Z = 83). In contrast, the valley walls on the neutron-rich side are much less steep: many neutrons can typically be added to a nucleus without causing the nucleus to break apart immediately. Until the advent of radioactive-beam facilities, only relatively few of these neutron-rich nuclei at or near the drip line could be explored. A FRIB is an instrument designed to produce these nuclei, determine their masses, and measure their decay modes. Major surprises could result. For example, theory suggests that there may be an undiscovered island of superheavy nuclei, significantly heavier than the most massive stable nucleus, uranium, lying beyond current experiments, but potentially accessible to a FRIB.

This description captures the essence of a FRIB's role in nuclear structure physics: this facility would allow the mapping of a far greater region of the (N,Z) landscape than is currently accessible, thus testing the predictive power of nuclear models and provoking improvements in those models. The measurements from a FRIB would be immediately relevant to explosive environments important to astrophysics and could reveal unexpected nuclear properties, such as unusually long-lived superheavy nuclei. The following discussion expands on these points.

Testing Nuclear Structure Concepts

Several examples are discussed below to illustrate how a FRIB might probe aspects of nuclear structure not readily accessible with only stable nuclear beams.

Probing the Disappearance of Shell Structure

Perhaps the most important early advance in microscopic nuclear structure theory was the recognition that the observed regularities in nucleon separation energies with so-called magic numbers could be ascribed to properties of a mean field, despite the very strong short-range repulsion known to exist between nucleons. The shell structure of nuclei with N or Z near the magic numbers is manifested by gaps in the energy spacing and angular momentum of low-lying levels. But robust shell structure, or at least the familiar magic numbers, may prove to be a property only of nuclei near the valley of stability. Theory suggests that some of the known shell gaps close significantly as nuclei become very neutron-rich and/or extended in radius, as illustrated in Figure 2.3. If this behavior is confirmed by experiment, it will influence the distribution of heavy elements produced in the neutron-rich environment of a supernova.

One important goal of a FRIB is to produce new neutron-rich, doubly magic nuclei, that is, unstable nuclei where N and Z are both magic. If the shell gaps are unusual, this will demonstrate that the mean field, and thus the interaction of valence nucleons with the rest of the nucleus, differ from that of stable nuclei. Such nuclei are particularly simple probes of the effective internucleon interaction. Specifically, a FRIB is expected to produce the short-lived, doubly magic species ^{48}Ni, ^{56}Ni, ^{78}Ni, ^{100}Sn, and ^{132}Sn and to allow the exploration of their single-particle structure through one-nucleon transfer and knockout reactions for testing if they exhibit the magic shell-structure behavior.

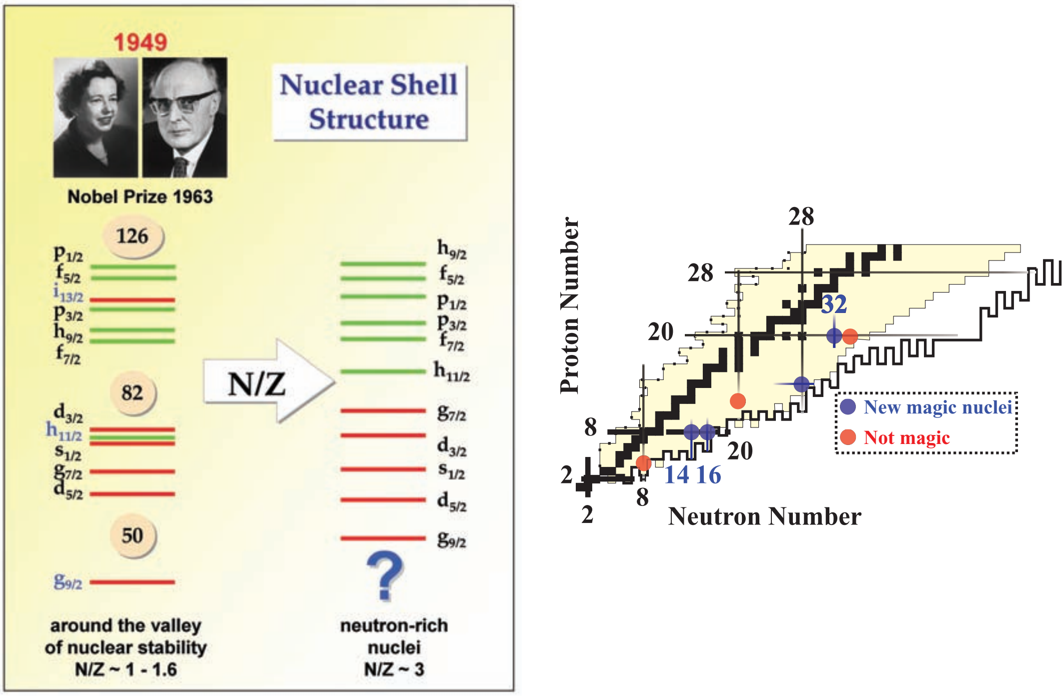

FIGURE 2.3 (Left) The shell structure description of nuclei may not apply as readily to nuclei outside the valley of stability. Nuclei may exhibit a very different structure pattern near the neutron drip line. (Right) New radioactive ion beam measurements have extended knowledge of light nuclei away from the valley of stability. Some magic numbers predicted in neutron-rich systems do not appear, while others not expected have been found in such measurements. The study of nuclei having high neutron or proton imbalances will help improve understanding of how to generalize mean-field concepts that are important to shell structure. Courtesy of TRIUMF.

Pairing and Superfluidity

Any attractive interaction between fermions (above the degenerate Fermi sea) at sufficiently low temperatures generally leads to fermion pairing and, therefore, to superfluidity, analogous to the Cooper pairing of electrons in superconducting metals. It is not surprising, therefore, that pairing plays an important role in nuclear structure. As the number of nucleons can be precisely controlled at a FRIB, exotic nuclei accessible with a FRIB would offer many new opportunities to study pairing, including its influence on the structure of the diffuse, neutron-rich skin found in nuclei far from the valley of stability. Such studies are of potential importance to an understanding of the cooling of nature's ultimate neutron-rich "nucleus," the neutron star. In extremely-neutron-rich nuclei and in heavier nuclei (A > 60) with an equal number of neutrons and protons, different superfluid phases may appear, characterized by nucleonic Cooper pairs carrying different isospin, spin, and total angular momentum. Pairing can be probed at a FRIB through a variety of reactions that add or subtract pairs of nucleons. Two-nucleon transfer studies to probe pairing properties could be carried out at a FRIB within a week, given beam intensities of 10^4 ions per second. Thus, experiments with ^{56}Ni, ^{64}Ge, ^{72}Kr, and the heavier N = Z nuclei up through ^{88}Ru and probably ^{92}Pd would likely be possible. An important probe of proton pairing, the (^{3}He,n) reaction, might be possible for species up to ^{88}Ru. Two-nucleon knockout reactions could be performed with beams as modest as 10 ions per second.

The Evolution of Collective Motion in Complex Nuclei

The number of distinct nuclear configurations increases as a combinatorial of the number of interacting nucleons. A remarkable feature apparent in nuclear spectra is that, in spite of such complexity, heavier nuclei exhibit novel collective properties that may not be as readily apparent in few-body systems. Similar simplicity also arises in the complex systems of other fields, such as atoms, molecules, and materials. In many cases, these regularities arise from underlying symmetries that govern the systems, from which the relevant and usually simple collective coordinates can then be deduced. The goals of nuclear structure physics include identifying the relevant collective coordinates, understanding their connections to the approximate symmetries governing nuclear motion, and then understanding how these symmetries arise from the underlying microscopic theory based on the degrees of freedom of nucleons.

One example is the sharp structural change in nuclear ground states that occurs in certain mass regions under seemingly small changes in mass, such as the addition of a pair of neutrons. The nucleus may respond by altering its shape from spherical to deformed ellipsoidal. This phenomenon (see Figure 2.4) can be understood in terms of quantum mechanical tunneling, a transition between nearly degenerate minima in the energy corresponding to distinct shapes, or deformations. The resulting coexistence of distinct shapes determines the excitation spectra of such transitional nuclei. These excitations are governed by symmetries: the spherical symmetry that is destroyed by deformation is restored by the associated collective modes (rotation of the ellipsoid).

While such phenomena are seen in chains of isotopes near the valley of stability, FRIB experiments could map nuclear phases over a much larger region, including cases in which the valence protons and neutrons occupy very different shells. Key questions that could be addressed by looking at the extreme nuclei far

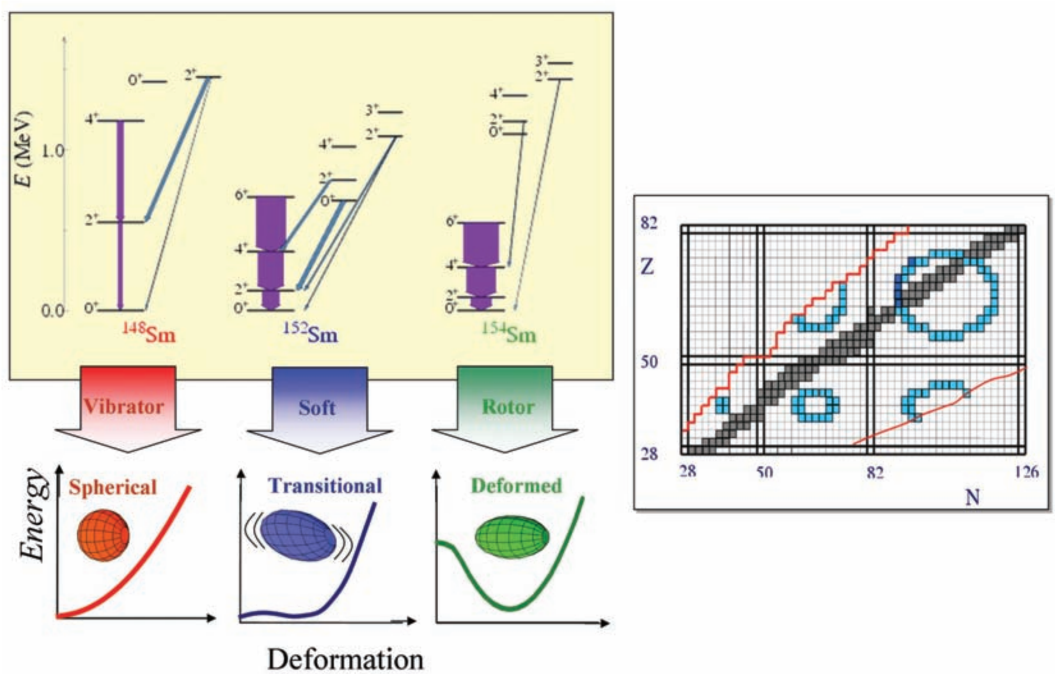

FIGURE 2.4 Illustration of the dramatic evolution of structure across the Sm isotopes, characterized by a transition between spherical and deformed shapes. Below the experimental-level schemes (top left) are sketches of how the nuclear energy evolves with shape deformation. The right panel shows the expected locus of this class of transitional nuclei (indicated by blue contours) in a section of the nuclear chart. Most of these regions lie off the valley of stability. With the new data from a facility for rare-isotope beams, one could hope to attain a deeper microscopic understanding of how shape transitions in finite systems occur and how these transitions are influenced by large neutron-to-proton asymmetries.

outside the valley of stability include what the consequences of the extended neutron radii (skins) in such nuclei are, whether the effective interactions will be weaker in this density regime, and what the effects of the large isovector densities in these species will be. It is unclear whether new candidate regions for spherical-to-deformed-shape transitions—regions exemplified by the neutron-rich nuclei ^{112}Zr, ^{96}Kr, and ^{156}Ba or the proton-rich nucleus ^{134}Sm—will exhibit the same kind of sharp shape transitions seen nearer the valley of stability. These nuclei, and their neighbors in the expected transition regions, would be available for study at a FRIB, given beam intensities ranging from a few to 10,000 ions per second. Such beams would allow experimenters to determine masses and lifetimes, and, for the more intense beams, to study Coulomb excitation, nucleon transfer, and highly inelastic collisions of these nuclei.

The study of such shape transitions would be just one element of a FRIB program to map out the collective behavior of exotic nuclei. The data from a FRIB would span very large isotopic sequences, often covering several major shells. The proposed experiments would help improve the understanding of how the critical elements of nuclear collective motion—pairing, all possible kinds of deformation, vibrations, and associated decays such as fission—evolve as one alters the neutron-to-proton ratio and the aspects of the effective interaction that this ratio controls.

Probing Neutron Skins

It was noted previously that nuclear and electrostatic forces conspire to push the neutron drip line far from the valley of stability. Nuclei with large neutron excesses are known to exhibit distinctive properties, such as the extended neutron densities (see Figure 2.5) that develop as neutrons occupy weakly bound quantum levels. Such extended neutron halos and skins have consequences for the effective interaction, weakening the coupling of outermost neutrons to the rest of the nucleus. To the extent that the understanding of strongly interacting matter with large neutron excesses is improved, it will also be more possible to model the exotic neutron-rich environment of neutron stars.

One expects to find new collective modes that are a consequence of this extended neutron skin. One of these, a low-energy isovector vibrational mode, could alter neutron-capture cross sections important to r-process nucleosynthesis. The beam intensities at a FRIB would allow experimenters to study a range of neutron skins several times greater than it is currently possible to do.

Production and Properties of Superheavy Nuclei

The elements that are found naturally on Earth end with uranium. But others may be synthesized either in the laboratory or during stellar explosions. The question of what the heaviest nuclei are that can exist, particularly ones that might live long enough to be studied, is an intriguing one in nuclear physics. Will a FRIB be able to synthesize long-lived superheavy nuclei and allow experimenters to study their chemistry? Owing to the large electrostatic energy of superheavy nuclei, one would naively expect them to be highly unstable and to spontaneously fission. However, quantum mechanics enters here in a dramatic way: individual nucleon orbits in specific nuclear shapes can lead to reductions in energy that can overcome disruptive Coulomb effects, thus binding these nuclei. Theoretical predictions indicate that the short alpha-decay lifetimes (millisecond or less) of known

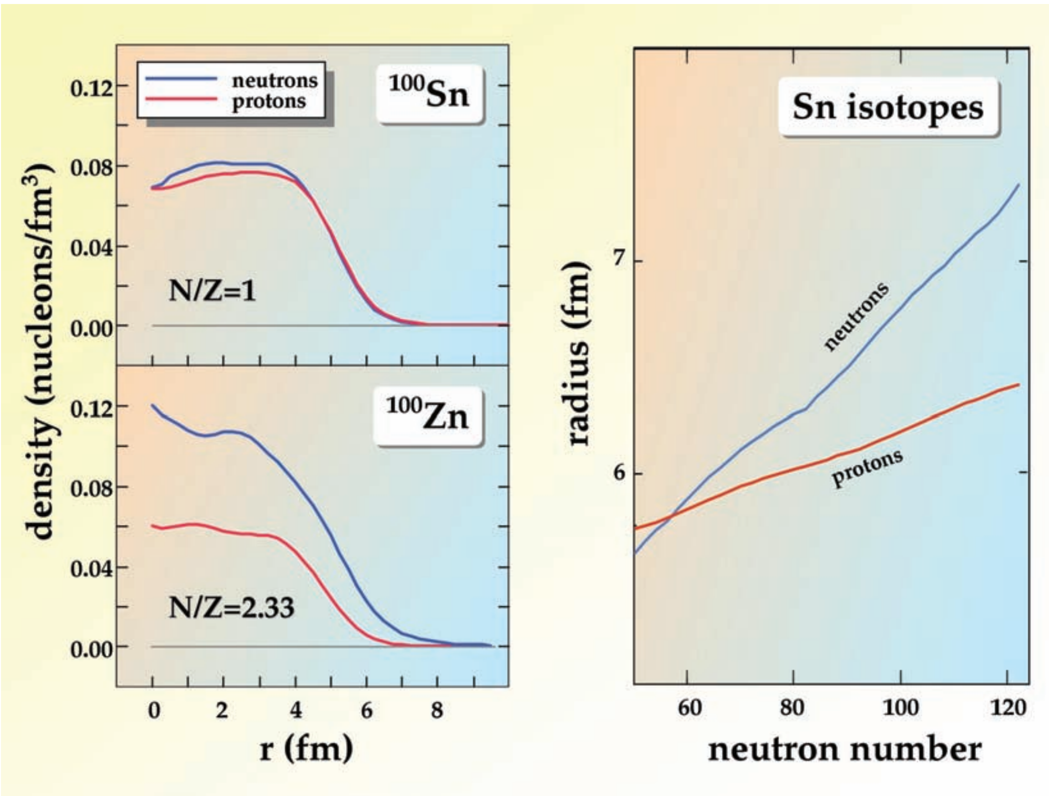

FIGURE 2.5 (Left) Calculated densities of protons and neutrons in two extreme nuclei, each with 100 nucleons. The top panel shows the proton-rich nucleus ^{100}Sn (Z = 50, N = 50), the bottom shows the neutron-rich nucleus ^{100}Zn (Z = 30, N = 70). Note how the neutrons extend much farther out in ^{100}Zn (neutron skin). The small excess of neutrons in the interior of ^{100}Sn is compensated by the small excess of protons in the surface region. (Right) Calculated neutron and proton radii in the even-even tin isotopes. The neutron skin is clearly seen in the neutron-rich nuclei; it gives rise to a neutron radius that is significantly larger than a proton radius. The calculations were done in the framework of density functional theory.

superheavy nuclei are due to a neutron deficiency, and that more-neutron-rich isotopes of the same elements might have very long lifetimes. However, theories disagree in their predictions for the location and extent of the region in (N,Z) where superheavy nuclei might exist.

A FRIB could play a crucial role in identifying such nuclei because the mechanisms by which superheavy nuclei can be produced in the laboratory have not been thoroughly explored. A FRIB would provide a range of options for synthesizing superheavy elements. One could collide two nuclei with a combined number of protons and neutrons very near that of a potential superheavy candidate and look for the requisite fusing. Alternatively, and perhaps more likely of success, would be the collision of neutron-rich nuclei. The resulting compound system could decay into the superheavy ground state via evaporation of the excess neutrons. As an example, no target-projectile combination of stable isotopes will directly lead to the center of the expected region of long lifetimes, thought to be around $Z = 112$ and $N = 184$ (see Figure 2.6). Intense beams from a FRIB would therefore complement studies of the heaviest nuclei with stable beams in at least two ways. First, in favorable cases, that is, instances in which the intensity of the rare isotope is large (^{90,92}Kr, ^{90,92}Sr $>10^{11}$ ions per second), fusion reactions become feasible with reaccelerated beams of high intensity and precise energies. Second, there is also interest in exploring the chemistry and atomic physics of the longer-lived elements, in cases in which the heavy isotope is produced in sufficient quantity. The atomic and chemical properties of superheavies are likely to be novel because of the highly relativistic behaviors of the inner-shell electrons, which in turn would affect the overall density of states.

Summary

A FRIB would extend research in nuclear structure from the domain of stable or near-stable nuclei familiar in everyday life to nearly the full range of nuclei that exist in nature's most exotic stellar environments. With its access to many new species, a FRIB would allow experimentalists to select beams that most readily map out how nuclei change as a function of N, Z, and binding energy.

The identified goals for a FRIB include testing the limiting values of N and Z in nuclei, determining properties of neutron skins, and searching for new superheavy systems at the limits of mass and charge. A FRIB, by enabling the exploration of the unknown regions of the nuclear landscape, would also have the potential to discover completely unanticipated phenomena in nuclear structure physics.

NUCLEAR ASTROPHYSICS

The nuclear physics of unstable nuclei is fundamentally important in three astrophysical contexts: in making determinations of the abundances of the elements and isotopes produced in stars and stellar explosions; in generating and releasing energy in such environments; and in helping develop the understanding of the behavior of matter at the extremes of neutron excess found in neutron stars and supernovae. Each of these areas poses robust problems in nuclear physics that have eluded solution for decades.

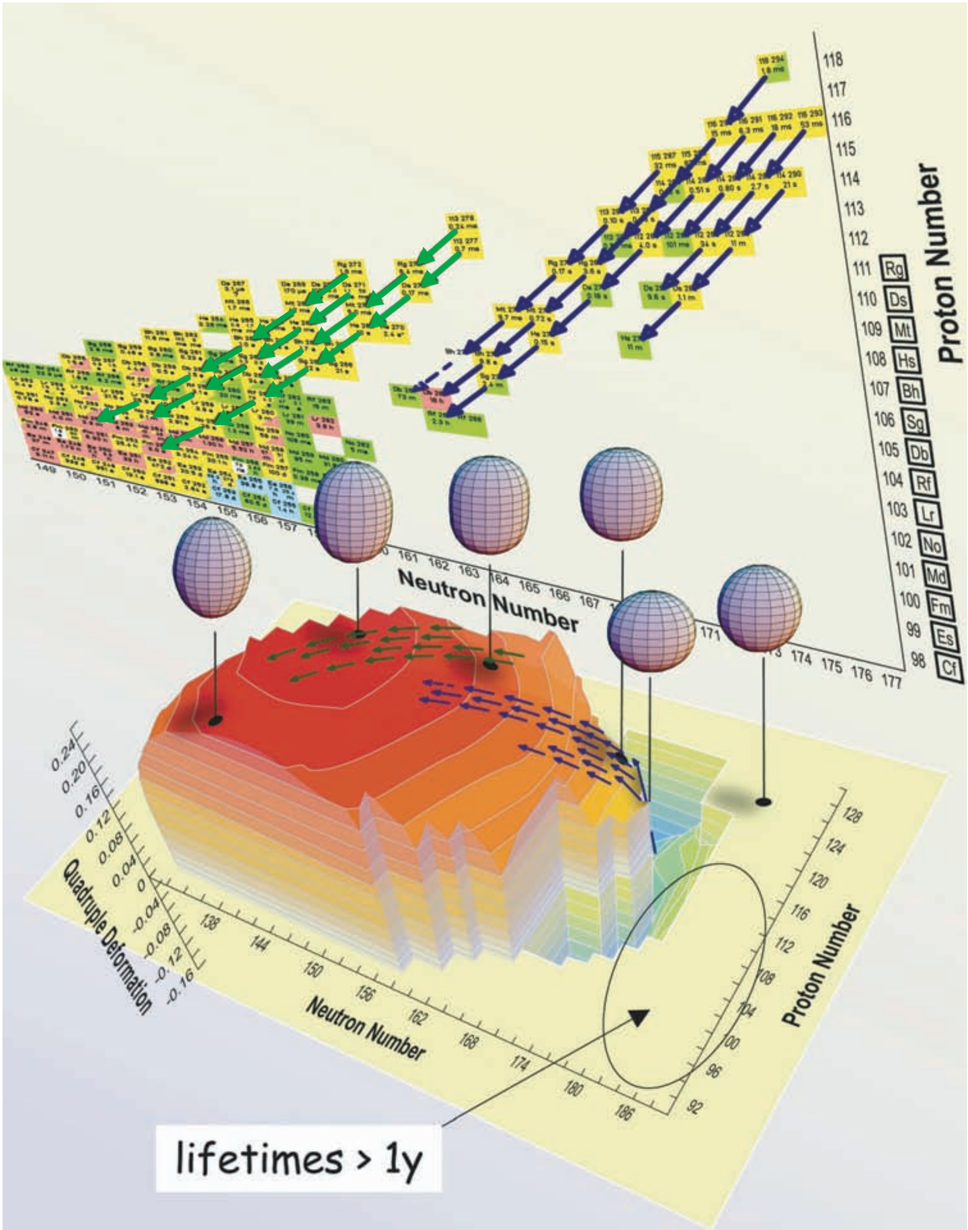

FIGURE 2.6 Deformations and shapes for the heaviest nuclei calculated in nuclear density functional theory. The Z = 110-113 alpha-decay chains found at Gesellschaft für Schwerionenforschung (GSI) and RIKEN (green arrows) go through prolate shapes (red-orange), while the Z = 114-118 chains reported at the Joint Institute for Nuclear Research (blue arrows) start in a region of oblate shapes (blue-green).

How Were the Elements from Carbon to Uranium Created?

The chemical elements and isotopes observed today were produced by nuclear processes from the big bang through star generations by a multitude of nuclear burning processes (see Figure 2.7). A complete understanding of the origins of the elements in the universe requires not only mastery of the observed current populations but also mastery of the plethora of nucleosynthesis processes that have taken place over time within the different families of stars within the universe.

The central problem of nucleosynthesis is that the elements found on Earth, the ones stable against weak decay, are only a small fraction of those transiently produced in stars along the reaction chains that create them. Nature frequently chooses paths that pass through the unstable isotopes for making the stable isotopes. Hence, to date it has been possible to study in the laboratory only a small fraction of the isotopes encountered in stars, particularly those created in key explosive events. The iron in our blood, for example, was made in supernovae as radioactive ^{56}Ni, a doubly magic nucleus that is an abundant product of explosive burning whenever the reactants have equal numbers of neutrons and protons. Gamma rays from the decay of ^{56}Co (the daughter of ^{56}Ni) to iron were detected coming from Supernova 1987A. Similarly, theory predicts that part of potassium was made in supernovae as radioactive calcium, manganese from cobalt, cobalt from copper, and so on.

Explosive events such as novae, supernovae, and x-ray bursts tend to produce unstable nuclei either because they quickly fuse fuels that have equal numbers of neutrons and protons (as in the ^{56}Ni example), or because they provide situations with large abundances of free protons or free neutrons at high temperature. A typical modern calculation of nucleosynthesis in a supernova carries 1,500 isotopes (only 10 percent of which are stable), coupled by about 15,000 possible reactions involving neutrons, protons, alpha particles, gamma rays, and neutrinos in entrance or exit channels. Such a calculation still does not include the larger set of nuclei and reactions needed to study the r-process (see below). As a result, perhaps the most challenging aspect of a quantitative theory of nucleosynthesis is the sheer volume of data it requires. The rates for most of these reactions are estimates from theory, and many will never be measured, but the most critical ones need to be measured to confirm the predicted reaction patterns and to provide a basis set for calibrating the theory of the rest.

One area in which a FRIB could contribute greatly is in terms of the understanding of nucleosynthesis of heavy elements by the r-, gamma-, and rp-processes (see Figure 2.8). Here “r” stands for rapid neutron addition, “rp” for rapid proton addition, and “gamma” for a series of photodisintegration reactions proceeding through unstable neutron-deficient nuclei. These rapid processes occur in nature

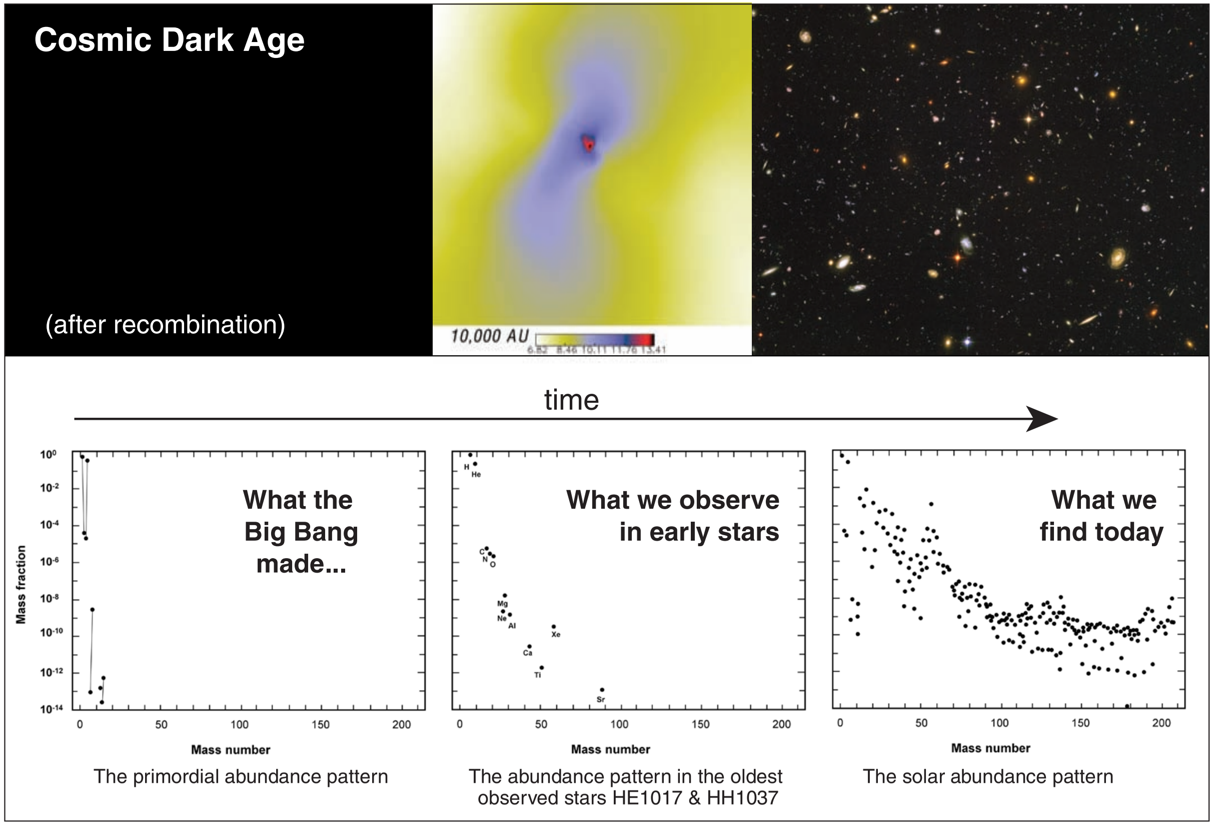

FIGURE 2.7 The history of the universe is depicted in this time sequence, starting from the Cosmic Dark Age (top left panel), displaying the formation of the first galaxies as breeding grounds for the first stars developing to the first supernovae (top center panel), and, finally, showing the universe today, as seen by the Hubble Deep Field mission (top right panel). The lower row exhibits correspondingly the results of the nucleosynthesis of elements from the big bang ($A < 12$), through the early star generations ($A < 90$), to what is observed today in the Sun ($A < 240$). Top center panel courtesy of NASA and the Space Telescope Science Institute. Lower row courtesy of the Australian National University and the University of Texas at Austin.

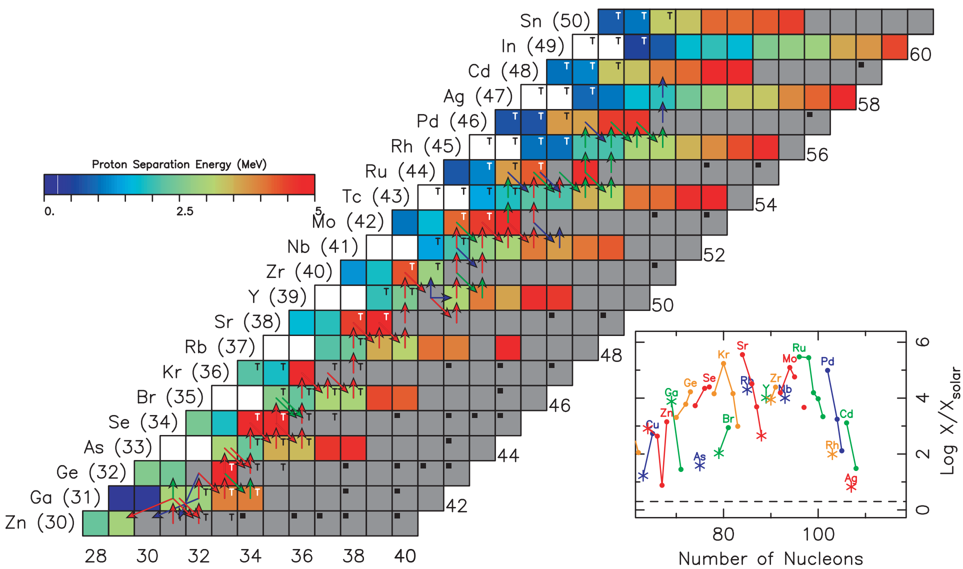

FIGURE 2.8 Nuclear flows by the rapid neutron-capture process occurring in a proton-rich wind blowing from a nascent neutron star inside a Type II supernova. A proton excess is created in the wind by neutrinos charge-exchanging on neutrons. Shown are the net nuclear flows from krypton to palladium that produce rare neutron-deficient nuclei in nature—for example, ^{96,98}Ru shown in the inset. Nuclei are color-coded according to their proton separation energies, with blue being zero and green, 3 MeV. The strong red flows, mostly (p,γ), increase the nuclear charge, and (n,p) reactions bypass the waiting points. Stable nuclei have a small black indicator in the upper left of the box. The arrows depicting nuclear flow are color-coded according to the relative rates of reaction, with red being the strongest and blue the weakest. From J. Pruet, R.D. Hoffman, S.E. Woosley, H.-T. Janka, and R. Burns, "Nucleosynthesis in Early Supernovae Winds II: The Role of Neutrinos," *The Astrophysical Journal* **644,** 1028-1039, 2006.

when there is a sufficiently large density of free neutrons, gamma rays, or protons at high temperature. Together, these processes are responsible for making over half of the isotopes heavier than iron—the r-process making the neutron-rich isotopes, the rp-process making some of the more abundant neutron-deficient ones from mass 60 to 120, and the gamma-process making the heavier neutron-deficient nuclei up to A ~ 200.

Each of these rapid processes occurs in an explosive environment. The r-process is believed to occur in the matter ejected by a merging binary pair of neutron stars, and in the "wind" blown by neutrinos from the surface of a neutron star when it first forms inside a supernova (the duration is only a few seconds). The rp-process can also occur in that neutrino-powered wind and additionally is the power source for Type I x-ray bursts on the surfaces of accreting neutron stars.

BOX 2.1
Rare Isotopes in Astrophysics—Example 1

The primary control points along the r-process path are the nuclei that are thought to possess closed neutron shells (N = 50, 82, and 126 are the most important). At these points, beta decay dominates neutron capture, which has been brought to a standstill by photoneutron ejection. The r-process slows down here and produces the prominent abundance peaks seen in observations. Access to these r-process nuclei, their masses, and half-lives is essential to the timescale of the entire process. An exotic-beam facility would enable measurements of the half-lives of the N = 126 r-process nuclei ^{192}Dy, ^{193}Ho, ^{194}Er, ^{195}Tm, and ^{196}Yb, which are, according to current r-process models, the most important bottlenecks. Such lifetime measurements would be feasible with relatively limited intensities, perhaps on the order of 10 particles per second. Most of the important branchings for beta-decayed neutron emission and the related nuclear mass measurements are also within reach. With these measurements, astrophysical models would have a solid nuclear physics underpinning for investigating the synthesis of r-process nuclei in the region of the A ~ 195 peak and beyond to explain the production of the heaviest nuclei found in nature.

The rp-process may also play a role in classical novae. In both the r- and the rp-processes, temperatures of 0.5 billion to 2 billion K and neutron or proton densities of 100 to 10^6 gm cm^{-3} drive the composition to the neutron or proton drip line, respectively. The production of heavier nuclei depends on the binding energies (which determine the "waiting point"[2] for a given capture chain), beta-decay lifetimes, and cross sections of nuclei so unstable that they are very difficult to produce in the laboratory. The gamma-process happens as the shock wave passes through the heavy-element shells of a supernova raising the temperature to 2 billion to 3 billion K. Neutrons, protons, and alphas are knocked off of heavy isotopes present in the star since its birth, changing them into a rarer, more neutron-deficient collection of species. Unlike the rp-process, the flows here do not reach the proton drip line, but proceed through unstable heavy nuclei whose neutron separation energies are large, that is, where (γ,p) and (γ,a) occur at rates comparable to (γ,n) (see Box 2.1).

A rare-isotope beam facility would provide access to the vast majority of the neutron-rich nuclei involved in the r-process for measurements of decay lifetimes, masses, and other properties—all of the essential information for reliable theoretical modeling of r-process nucleosynthesis. In particular, such a facility is needed to

[2]As the nuclei synthesized by the r-process increase in mass, they occasionally become "waiting-point nuclei," at which further progression is inhibited by either a relatively long half-life or an inability to capture another neutron.

access r-process nuclei near the shell closure at neutron number 126. As a major bottleneck in the r-process, this region is an important normalization point for model predictions of the synthesis of heavy r-process elements such as uranium and thorium. Results from an exotic-beam accelerator facility, coupled with astrophysical simulations, would constrain temperature, density, timescales, and neutrino fluxes at the r-process site from observations of elemental abundances. This information would in turn help to determine once and for all the sites in nature where the r-process occurs. Using isotope harvesting, an exotic-beam accelerator facility could also enable neutron-capture cross-section measurements of long-lived unstable nuclei produced in the slow neutron-capture process (s-process). These reactions are used to monitor temperature and convective mixing in the helium shells of asymptotic giant branch stars where most of the heavy isotopes not due to the r-process are made.

How Is Energy Generated in Stars and Stellar Explosions?

Ordinary stars are gravitationally confined thermonuclear reactors, with nuclear reactions providing the necessary power to keep the star from contracting. Because stars live a long time, the most important reactions involve stable nuclei and are not a goal of an exotic-beam accelerator facility.

By contrast, nuclear energy generation in explosive events, especially novae and x-ray bursts, comes from reactions involving unstable targets. A classical nova is the consequence of a critical mass of hydrogen and helium piled up on an accreting white dwarf star and experiencing a nuclear-powered runaway. An x-ray burst is the same phenomenon, but with a neutron star substituted for the white dwarf. In both instances, temperatures from 0.3 billion to 2 billion K are reached in dense, hydrogen-rich material (the lower temperature is more relevant to novae; x-ray bursts are hotter). Energy is initially generated from the carbon-nitrogen-oxygen (CNO) cycle, but as the temperature increases above about 0.5 billion K, alpha capture on unstable oxygen and neon nuclei (^{15}O and ^{18}Ne) leads to a breakout and an ensuing chain of proton-capture sequences that can go as far as the element tin. These proton captures, augmented at the highest temperatures by (α,p) reactions, proceed along the proton drip line. The rate at which heavier elements are produced depends on the binding energies, lifetimes, and cross sections of these very-short-lived, proton-rich nuclei. Energy is generated from a combination of helium burning, hydrogen burning by the CNO cycle, and the rapid proton captures on heavy elements, with proton capture dominating in the x-ray burst case (see Box 2.2).

At present, it is uncertain if novae ever get hot enough for a substantial breakout and rp-process, but this definitely occurs in x-ray bursts where the life-

BOX 2.2
Rare Isotopes in Astrophysics—Example 2

Certain reactions are more critical than others in understanding astrophysical events. The reaction $^{15}O(\alpha,\gamma)$ results in a breakout of material from the carbon-nitrogen-oxygen (CNO) cycle and starts a rapid proton-capture (rp) process that leads to nucleosynthesis possibly as far as tin. The reaction rate determines the temperature at which breakout occurs, triggering the NeNa cycle in novae or the rp-process in x-ray bursts. Within the current range of uncertainty in this reaction, breakout for high-temperature nova explosions cannot be excluded, and the question about the on-site production of the observed Ne abundances cannot be addressed. The predictions of x-ray burst models also depend critically on this particular rate. Recent simulations suggest significant differences in the burst amplitude and sequence, depending on the present uncertainties in the rate.

An experimental verification of the predicted low-energy resonance parameters in the $^{15}O(\alpha,\gamma)$ reaction is desperately needed; these parameters can only be measured in the laboratory with a rare-isotope facility. The required intensities range from on the order of 10^6 to 10^8 particles per second for alpha scattering measurements to 10^{11} to 10^{12} particles per second for the necessary studies of resonant capture. Both this level of intensity and the requisite beam quality would be compatible with a next-generation facility.

times and binding energies of proton-rich waiting-point nuclei are reflected in the observed light curve (see Figure 2.9). In the most energetic of these, light pressure blows a wind from the neutron star surface, possibly contributing to the nucleosynthesis of some rare isotopes.

How Would an Exotic-Beam Accelerator Facility Help Improve Understanding of Neutron Star Structure, Supernovae, and Gamma-Ray Bursts?

There are roughly one billion neutron stars in the Milky Way Galaxy, yet their structures and crusts are very poorly understood. Produced in supernovae at the deaths of massive stars, neutron stars are the sites of radio pulsars, x-ray pulsars, and exotic binaries that are laboratories for general relativity. Of particular interest is the physics of the neutron star crust. The properties of neutron-rich nuclei far from stability are important to probing the thermal and electromagnetic characteristics of matter at extreme density. Material accreted onto the neutron star envelope will be buried in layers with increasing density as new material piles on. Electron capture will make the nuclei progressively more neutron-rich. The same thing happens to the ashes of x-ray bursts. Eventually neutron drip occurs at a density $\sim 4 \times 10^{11}$ g/cm^3 and internal energy is released, heating the neutron star crust. The timescale and internal energy production depends on the electron-

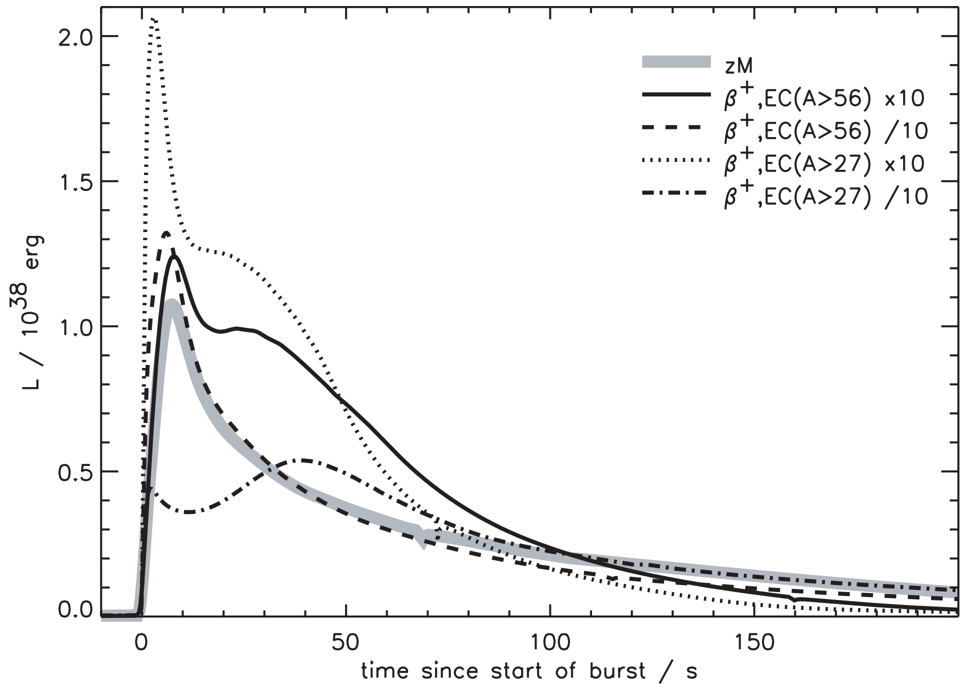

FIGURE 2.9 Light curves of a model x-ray burst with varying assumptions about the rate of uncertain weak decays along the path of the rapid proton capture process. Advanced experimental data from a facility for rare-isotope beams would play a strong role in distinguishing these different models from one another. Each curve assumes a different set of parameters (zM and different β or EC values index the complex set of assumptions). From S.E. Woosley, A. Heger, A. Cumming, R.D. Homan, J. Pruet, T. Rauscher, J.L. Fisker, H. Schatz, B.A. Brown, and M. Wiescher, "Models for Type I X-Ray Bursts with Improved Nuclear Physics," *Astrophysical Journal Supplement* **151,** 75-102, 2004.

capture rates and the neutrino losses in neutron star crust matter. These electron-capture rates can be studied with an exotic-beam accelerator facility using charge-exchange reactions on the most critical radioactive neutron-rich nuclei along the dominant electron-capture chains between A = 56 and A = 104. The measurement of the Gamow-Teller strength distribution will also provide information about the neutron release and the subsequent neutronization of neutron star crust matter.

A neutron star is, in some ways, just a huge stellar-mass-sized nucleus with a very large neutron-to-proton ratio. Unlike the case with ordinary atomic nuclei, however, gravity is important in confining the nucleons, and the central density in neutron stars is much greater than in ordinary nuclei. As a result, new aspects of the nuclear force (and particle physics) are needed to fully describe the system. A key uncertainty is the resistance to compression offered by such matter at nuclear and supernuclear densities. This uncertainty affects the maximum mass of neutron stars, the strength of the initial shock wave in the most common variety of supernovae (those derived from iron-core collapse in massive stars), and the dynamics of neutron star mergers (see Figure 2.10). Most studies of nuclear compressibility are, of necessity, carried out on stable nuclei. For neutron stars, the phases, nuclear masses, electron-capture rates, and equation of state in the outer crust (which geometrically can be quite large) are not known in the sense that there is little experimental confirmation of the physics inputs in model crusts. With an exotic-beam accelerator facility, the range of neutron excesses available would be much larger, so the neutron-to-proton ratio dependence of the nuclear equation of state could be determined.

Exotic Beams: An Urgent Need of the Nuclear Astrophysics Community

The key feature of an exotic-beam accelerator facility (such as a FRIB) for applications in nuclear astrophysics is its ability to produce high fluxes of unstable nuclei across a broad range of masses and particle-separation energies—it is the general-purpose nature of the facility that becomes its primary asset for nuclear astrophysics (see Box 2.3). Ultimately, one wants to understand the origin of *all* nuclei and then to use that understanding to diagnose stellar explosions and the chemical evolution of galaxies of all sorts. That is, in order to get leverage on the specific problem, scientists need first to sample and then understand the general case. Scientists have worked toward that goal for at least 50 years and have made some progress.

The vast majority of the elements heavier than helium are made in stars, with supernovae making the majority. The processes of nucleosynthesis have been defined, and one or more probable sites exist for each. Models agree qualitatively with the abundances seen in the Sun and in stars of varying ages in the Galaxy, but the theory is only as reliable as the nuclear data it employs. Major investments are being made in space- and ground-based observations of abundances in all astronomical environments. These measurements are carried out across the spectrum—from gamma-ray lines emitted by nuclear gamma decay in space, to infrared—and in objects nearby and at high redshift. The complexity and realism of numerical simulations on large, massively parallel machines is starting to approach the precision of the best and most recent observational data—and comparisons have yielded great insights. To enable scientists to pursue these questions fully then, an investment parallel to that in the astronomical observational facilities is necessary for expanding the nuclear data that comprise the physical basis for these simulations.

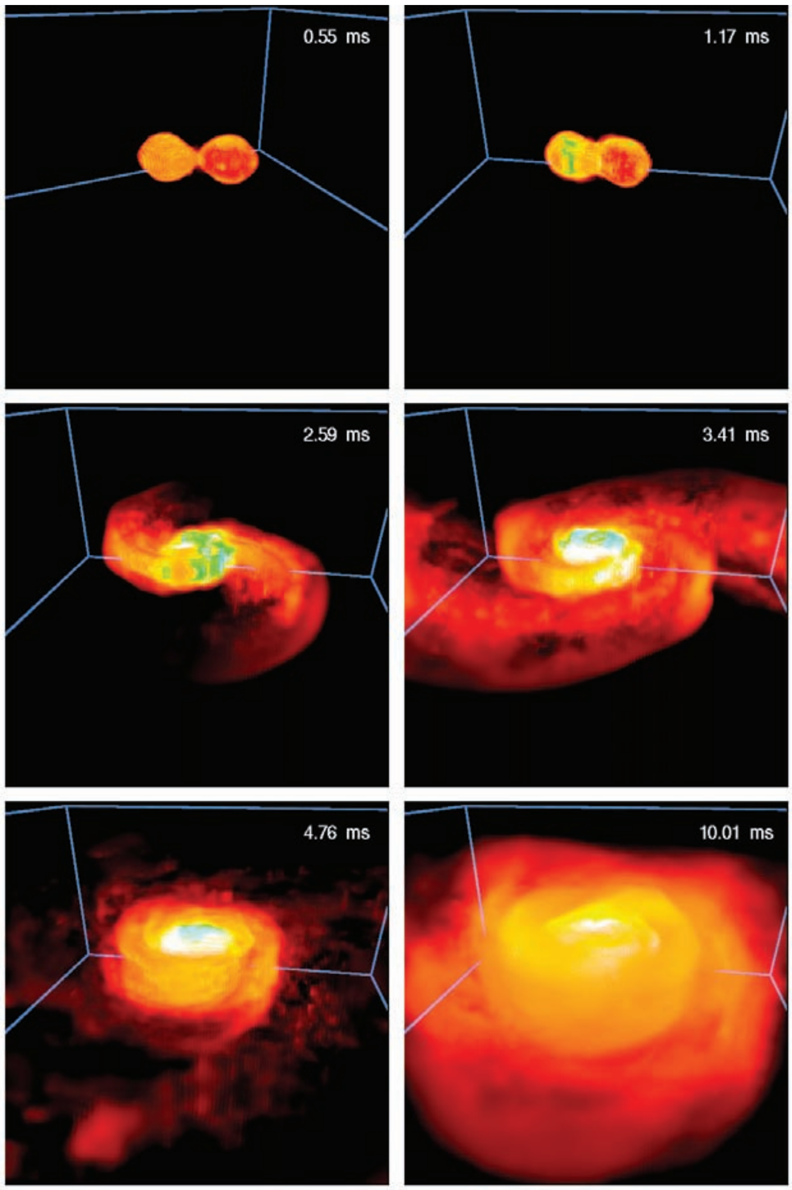

FIGURE 2.10 Three-dimensional simulation of the merger of two neutron stars in a binary system. Such systems have recently been implicated in the generation of a class of gamma-ray bursts called short-hard bursts. Careful simulation and analysis suggest that their ejecta are also rich in the nuclei produced in the rapid neutron-capture process. Courtesy of the Max Planck Institute for Astrophysics.

BOX 2.3
Specific Examples of Astrophysical Processes That a Rare-Isotope Facility Might Illuminate

Following is a list of astrophysics problems that an exotic-beam accelerator facility would uniquely address. A strength of such a facility is that as these problems are solved and new ones take their place, the same machine can address them.

- Binding energies and lifetimes for nuclei along the path of the rapid neutron-capture process (r-process) responsible for producing the most-neutron-rich isotopes from just above iron to the actinides.
- Binding energies, lifetimes, and cross sections for (p,γ) and (α,p) for nuclei from neon to tin along the path of the rapid proton-capture process (rp-process).
- Cross sections affecting the production of radioactive nuclei that are potential targets for gamma-ray line astronomy— ^{22}Na, ^{26}Al, ^{44}Ti, ^{56,57}Co (made as ^{56,57}Ni), and ^{60}Fe.
- The rate of the ^{15}O(α,γ)^{19}F and ^{18}Ne(α,p)^{21}Na reactions, which govern the breakout from the carbon-nitrogen-oxygen (CNO) cycle and the onset of the rp-process.
- The isospin dependence of the nuclear equation of state for application to neutron stars and supernovae.
- Charge-exchange reactions on unstable nuclei in the iron group to get the nuclear matrix elements for use in electron-capture rates in presupernova stars of all types.
- Proton- and alpha-capture cross sections on heavy, proton-rich nuclei up to lead for use in studies of the p-process (or gamma process), which makes the heavy, neutron-deficient isotopes above mass 130.
- Cross sections for a large variety of nuclear reactions on unstable targets across the entire range of bound nuclei from neon to lead in order to calibrate the parameters of the Hauser-Feshbach and direct-capture theories used to calculate the tens of thousands of reaction rates used in studies of nucleosynthesis. Reactions include (n,γ), (p,n), (p,γ), (α,p), (α,n), (α,γ), and their inverses.
- Neutron-capture cross sections for unstable nuclei along the path of the slow neutron-capture (s)-process responsible for the isotopes above iron that are not made by the r- or p-processes. This will also solidify the accuracy of the s-process abundance distribution derived from these data, which provides the calibration for the currently predicted r-process abundance distribution curve.

FUNDAMENTAL SYMMETRIES

Studies of fundamental interactions aim to understand the nature of the most elementary constituents of matter and the interaction forces between them. With the exception of the recent and dramatic discovery that neutrinos have mass, most of what has already been learned about elementary particles and interactions is embodied in the Standard Model of particle physics, a framework that has been astonishingly successful, with three decades of experimental tests that have supported its predictions with ever-increasing precision.[3] How much of a change in the Standard Model will be required by the discovery of neutrino mass is not yet understood. Other and perhaps related defects in the Standard Model are that it fails to account for the dominance of matter over antimatter observed in the universe, does not include gravitational interactions, and contains many parameters that must be taken from experiment. Understanding the properties of the universe at a deeper level than the Standard Model is one of the greatest challenges facing science.

Historically, many features of fundamental interactions have been discovered in nuclear physics experiments. The existence of neutrinos was first proposed by Wolfgang Pauli to explain an apparent loss of energy and momentum in nuclear beta decays. The first observation of parity violation came from studies of ^{60}Co beta decays, showing that the laws of physics are not the same if viewed in a mirror. Nuclear experiments have resulted in the first direct detection of neutrinos, the establishment of the vector/axial-vector structure of the weak interactions, the demonstration of mixing between different flavors of neutrinos, and the establishment of a 2 eV/c^2 limit on the electron neutrino mass. This limit is presumed to apply to the other neutrinos, given the small mass differences observed in the recent nuclear experiments that discovered neutrino oscillations. Experiments exploiting nuclei as laboratories can have the powerful advantage that, with a large range of different isotopes to choose from, a specific isotope can often be selected with unique properties that isolate or amplify important physical effects. For example, recent measurements at the TRIUMF laboratory at the University of British Columbia and the On-Line Isotope Mass Separator (ISOLDE) at CERN of positron-neutrino correlations in pure Fermi $0^+ \rightarrow 0^+$ beta decays put stringent constraints on a possible scalar contribution to weak interactions, while a measurement of the same correlation in $3/2^+ \rightarrow 3/2^+$ beta decays, recently completed at the Lawrence Berkeley National Laboratory, is also sensitive to tensor interactions.

Among the most striking facts that the Standard Model cannot explain is the dominance of matter over antimatter in the universe. The leading proposed explanation for this vital fact is that an asymmetry between matter and antimatter developed as the universe cooled after the big bang, owing to a violation of time-reversal symmetry of physics laws, or, equivalently, to a violation of charge-parity (CP) symmetry. While the ingredients necessary for CP violation exist in the Standard Model, the level of CP violation is far too small to account for the observed

[3]For an enhanced discussion of the Standard Model, see National Research Council, *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics*, Washington, D.C.: The National Academies Press, 2006.

amount of matter in the universe. One of the best ways to look for a sufficient source of CP violation is by searching for a permanent electric dipole moment in subatomic particles. Other methods for searching for excess CP violation in the quark section are also being actively pursued, including major efforts at B-factories at the Stanford Linear Accelerator Center (SLAC) and the High Energy Accelerator Research Organization (KEK) in Japan. The discovery of neutrino mass opens up the possibility of CP violation for the leptons.

Most particles (with spin) have a finite magnetic dipole moment in their ground state; these moments have no particular significance for fundamental symmetries. However, the presence of an analogous electric dipole moment in their ground state violates time-reversal and CP symmetry and has never been observed. At the level of present experimental sensitivity, an EDM could be a signal of the excess CP violation beyond that allowed by the Standard Model to explain the matter-antimatter asymmetry. Many searches for an EDM have been conducted over the years, putting extremely tight bounds on its possible size. The absence of an observable EDM played a role in establishing the mechanism of CP violation in the Standard Model involving the mixing of the three generations of quarks. As a result, the Standard Model predicts negligibly small EDMs, while most extensions of the Standard Model can naturally generate much larger EDMs. Present EDM experiments are already sensitive to the existence of new particles with large CP-violation at the TeV scale and place stringent constraints on many theories proposed to explain the matter-antimatter asymmetry of the universe.[4]

Existing techniques for laboratory-based EDM searches are beginning to reach their limits, although several new ideas have emerged. One of the most promising methods for expanding the reach of EDM searches is to choose nuclei with special properties that could enhance the effect of CP-violating interactions. A handful of such nuclei have been identified over the years: for example, ^{229}Pa, ^{223}Ra, ^{225}Ra, and ^{223}Rn. The CP-violating effects are enhanced in these radioactive nuclei because they have a static octupole deformation and closely spaced levels of opposite parity, increasing the mixing of quantum states due to CP-odd nuclear forces. Such pear-shaped nuclei occur only rarely and only in special regions of the nuclear chart. Several theoretical calculations have confirmed that the size of the EDM (if it exists) is expected to be enhanced in these nuclei compared with ^{199}Hg, the most sensitive stable nucleus currently used in EDM searches, by a factor of several hundred to several thousand. Developing better estimates of the enhancement

[4]For further reading, see M. Pospelov and A. Ritz, "Electric Dipole Moments as Probes of New Physics," *Ann. Phys.* **318,** 119-169, 2005.

factors is an important problem for nuclear structure physics that will become particularly crucial if a finite EDM is observed.

EDM searches with radioactive nuclei require the development of new experimental techniques. The most promising approach for Ra isotopes is based on recently developed laser cooling and trapping techniques. As recently as 2005, laser trapping of ^{225}Ra was demonstrated at the Argonne National Laboratory. For the EDM measurement, the atoms will be cooled and collected in a magneto-optical trap, spin polarized, transferred into an optical dipole trap, and placed into a region of high electric field. A permanent EDM would then result in a precession of the nuclear spin proportional to the strength of the electric field. A very different technique is being developed for Rn isotopes at TRIUMF and at the University of Michigan. It involves collecting Rn atoms in a glass cell where they are polarized by spin-exchange collisions with optically pumped alkali atoms, and their precession in an electric field is monitored using gamma- or beta-decay asymmetry.

While current EDM searches are very susceptible to various environmental noise sources and often have to contend with significant systematic effects, experiments using radioactive isotopes with large intrinsic sensitivity to CP violation will be much less affected by these problems. Therefore, there is a strong expectation that they will be able to make clean EDM measurements; optimistic forecasts suggest that these results might only be limited by the statistical uncertainty determined by the number of available atoms and the integration time. Currently, ^{225}Ra is produced from a radioactive Th source, while ^{223}Rn will be produced with an Isotope Separator On-Line (ISOL) target at TRIUMF using a 50 kW proton beam. Present sensitivity projections indicate that EDM experiments with radioactive isotopes can improve on current EDM limits by about two orders of magnitude using existing sources. As these new experimental techniques for EDM measurements mature, they will need more intense sources to realize their full potential. Existing ISOL targets are limited by thermal effects due to beam heating, but new concepts that can handle higher-power beams, such as tilted targets and beam rastering, are being developed. It will also be crucial for EDM experiments that future facilities have multiuser capabilities and allow months-long data-collection periods. To assist in advancing this frontier, a FRIB should incorporate these characteristics.

Searches for new sources of CP violation are just one example of fundamental interaction studies that can be done with radioactive nuclei. Another important interaction that is still poorly understood is the parity-violating interactions that lead to a nuclear spin distribution called an anapole moment. A nonzero anapole moment has been detected so far in only one nucleus, ^{133}Cs, and its size is not consistent with theoretical estimates. The size of parity violation is enhanced in heavy atoms, making it possible to perform anapole measurements on a string of

Fr isotopes. Additional such measurements would continue to expand the horizons of parity-violation studies in nuclear matter.

The interdisciplinary nature of fundamental interaction studies also leads to a significant stimulus for other branches of physics and science. For example, the experimental techniques for EDM and anapole-moment measurements come largely from atomic physics, while their results will directly affect theoretical particle physics. New experimental techniques developed for these measurements, such as efficient laser trapping and detection of radioactive atoms, have led to significant improvements in radioactive dating and trace-isotope detection.

OTHER SCIENTIFIC APPLICATIONS

Applications of a facility for rare-isotope beams fall into four categories: stockpile stewardship and inertial fusion, medical and biological research, materials science, and advanced fuel development for nuclear power. The chief advantages of a FRIB for these applications are very high isotopic production rates (~100 times those of existing facilities), fairly complete N,Z coverage, and high specific activity. Readers who may be unfamiliar with the material and terms covered in this section are referred to the Glossary (Appendix D).

Stockpile Stewardship

Because the nation's nuclear weapons stockpile stewardship program is aimed at maintaining confidence in the U.S. nuclear deterrent without testing, there is greatly increased emphasis on gaining better scientific understanding of all the input information and computational tools used to evaluate the status of the stockpile. In the context of microscopic physics, relevant nuclear data such as cross sections, branching ratios, and transition rates take their place along with other data including radiation opacities and material equations of state in overall detailed assessments of performance uncertainties.[5] Because of the extreme operating regimes of nuclear weapons, much of the nuclear input originates from theoretical calculations due to the difficulty in carrying out experiments on unstable nuclear species. This situation led to the consideration of the role for advanced

[5]In addition to the question of the accuracy of radiochemical inferences on device performance, there are potentially relevant nuclear data uncertainties in basic cross sections such as $D + T \rightarrow \alpha + n$. Here, however, only those nuclear physics issues addressable by exotic-isotope production are discussed.

facilities such as rare-isotope beam facilities that can give experimental access to this unique regime.[6]

In the specific arena of the application of nuclear physics to stockpile stewardship and (to some extent) inertial fusion, radiochemical analysis is a powerful tool for evaluating performance. In the analysis of the performance of devices, a wide array of nuclear species has been employed and inferences made from the recovery of samples after nuclear tests. In general, understanding the test results required the modeling of the diverse reaction pathways driven by both neutrons and charged particles spanning an energy spectrum from about 0.1 to 16 MeV. Thus, the required cross sections involve processes such as (n,γ), (n,n′), and (n,2n) on the ground, excited, and isomeric states of stable and radioactive isotopes. The yttrium neutron reaction network and its charged-particle entrance and exit branches shown in Figure 2.11 is a fairly typical example. In addition, fission and fission fragment reactions are an important area of study.

All of this is analogous to the r-process, except that (n,2n) is absent because the incident neutron energy is too low. As in astrophysics, high-leverage kinetic paths have been identified and are the subject of many investigations.

As most of the needed cross sections have not been measured, statistical reaction models such as that of Walter Hauser and Herman Feshbach are applied. Such statistical models require parameterized nuclear-level densities, angular momenta, and values for the compound-state pre-equilibration cross sections, adding further uncertainty. These parameterizations are typically obtained by fitting existing experimental data on stable species. Importantly, in many cases where the direct cross section cannot be measured, it is also possible to apply a variant of the compound nucleus ansatz using inverse kinematics on related reactions (known as surrogates), thereby allowing experimental tests of key cross sections. The surrogate method is useful in cases both in which the target lifetime is too short for practical scattering experiments and in which a neutron-scattering source is unavailable.

A facility capable of isotope production rates significantly greater than those now available could improve this situation in two powerful ways. First, rare-isotope experiments can directly measure cross sections on important radioactive

[6]A January 10, 2003, memorandum from Everet Beckner, Deputy Director of the National Nuclear Security Administration (NNSA), to Raymond Orbach, Director of the Department of Energy's Office of Science, stated, "a future Rare-isotope Accelerator (RIA) will be important to science-based stockpile stewardship. . . . While the NNSA could not build such a facility to fulfill the needs we have for nuclear data, we will be users with interest in nuclear science as well as in specific data."

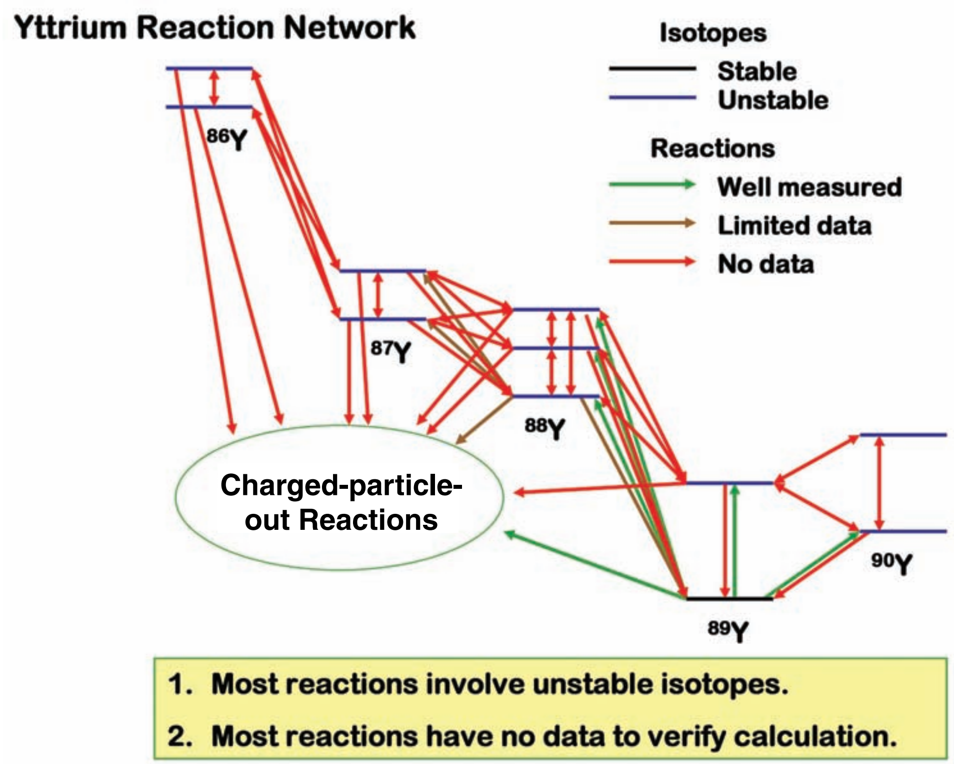

FIGURE 2.11 Important examples of neutron-induced reactions on isotopes of yttrium. Proton-number-changing charged-particle entrance and exit channels (driven, for instance, by protons or alphas) of importance to nuclear kinetics are also shown. The indicated charge-particle-out reactions are sets of nuclear reactions that alter the number of protons in the nuclei; in order to conserve electric charge, an electrically charged particle is emitted. Courtesy of Larry Ahle and of the University of California, the Lawrence Livermore National Laboratory, and the Department of Energy under whose auspices the work was performed.

species and also pin down the needed parameters in compound nucleus calculations directly on actual nuclei of interest. Second, in the event that a suitable neutron-scattering source was not available, it would still be possible to extend the surrogate method over a wider range of the relevant (N,Z) space by examining appropriate inverse reactions on unstable species. The main leverage of a high-flux exotic-beam experimental program is likely the ability to pin down a large fraction of the steps in an important network (such as the Y network and its charged particle feeders) as distinct from a few measurements on a handful of nuclei.

Real improvement in the knowledge of relevant cross sections would rely on complementary aspects of both the proposed ISOL and fragmentation options. The main issues are the production and harvesting rate of sufficient isotopes in competition with their decay, and the purity of the collected samples.

Because the stockpile stewardship reaction sets are similar to those needed to study the s- and r-processes, a parasitic collection scheme for radiochemically relevant isotopes, running in parallel with basic science experiments, is in order. As was indicated above, the addition of a monoenergetic, tunable, intense neutron source covering the full energy range would be very useful to the study of the wide variety of (n,x) reactions on the exotic species created at a FRIB. The utility of such a neutron source depends on production rates, target isotope decay times, and the development of both activation analysis and prompt diagnostics (Figure 2.12). From the low-energy (~50 keV) (n,γ) reactions to the higher-energy (n,xn) reactions unique to stewardship (≥3 to 4 MeV), with generic neutron partial (channel specific) cross sections from 0.1 to 1 barn, both high fluences and pure samples are necessary to suppress background. Therefore, for radiochemistry, in contrast to r-process astrophysics, effective experimentation requires high-purity samples relatively near the valley of stability. A neutron source would also be very valuable for s- and r-process studies.

Turning to inertial fusion, radiochemistry is applicable to the determination of the density-radius product of capsules at maximum compression.[7] These parameters are inferred from the flux and range of charged particles and neutrons that are made in thermonuclear reactions and react on tracer nuclei placed in the capsule. Because the overall level of radiochemical activation is an integrated function of the entire capsule's time history, better knowledge of the cross sections will help disentangle the details of the capsule implosion, subsequent ignition, and runaway burn.

Significantly, a FRIB's greatest impact on the broad national security arena might be through the reinvigoration of low-energy nuclear physics. At present, while stockpile stewardship has a continuing need for people conversant with the phenomenology of nuclear physics, homeland security's nuclear physics and

[7]For additional information, see E.M. Campbell, W.M. Ploeger, P.H. Lee, and S.M. Lane, "Exploding-Pusher-Tamper Areal Density Measurement by Neutron Activation," *Appl. Phys. Lett.* **36,** 965, 1980; S.M. Lane and M.B. Nelson, "A Technique for Shell Compression Measurements of Laser Fusion Targets by Neutron Activation of a Rubidium Tracer," *Rev. Sci. Inst.* **61,** 3298, 1990; M.A. Stoyer, C. Sangster, B. Hudson, R. Lougheed, C. Freeman, B.-E. Schwartz, and M. Olsen, "The OMEGA Gas Sampling System and Radiochemical Diagnostics for NIF," 42nd Annual Meeting of the American Physical Society Division of Plasma Physics, Long Beach, Calif., 2001.

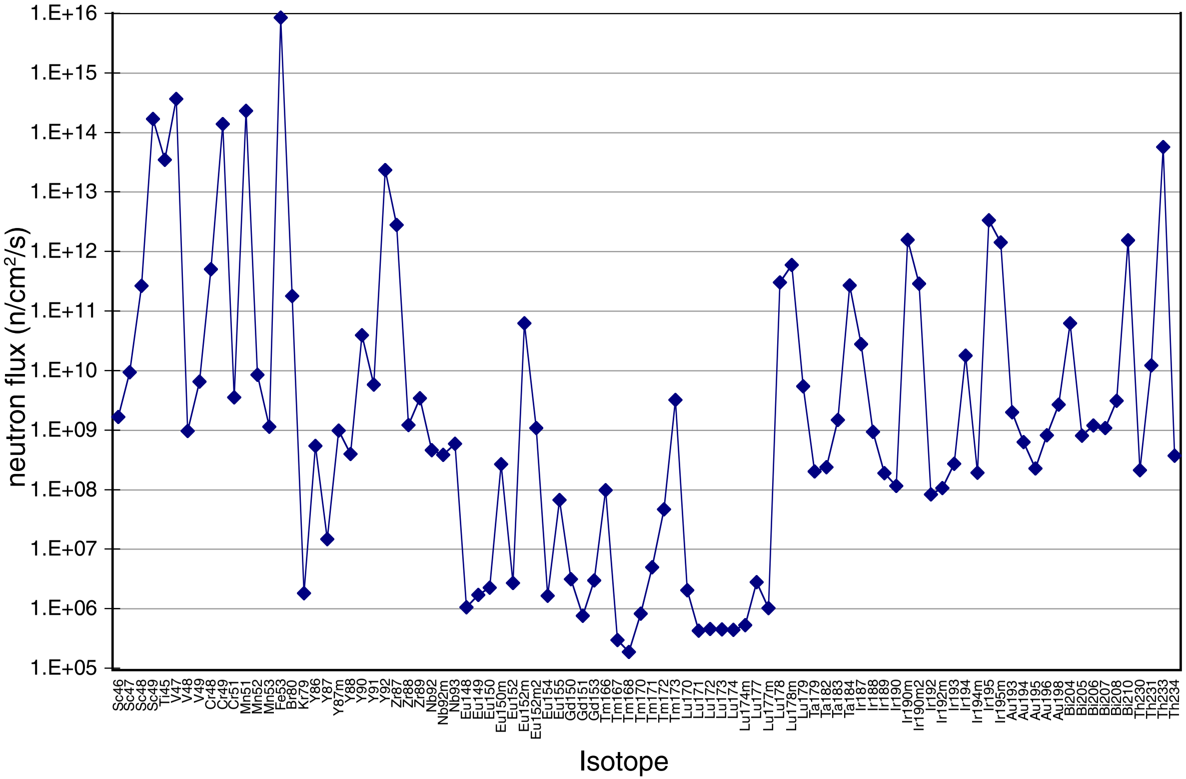

FIGURE 2.12 Required neutron flux for activation measurements on radiochemistry isotopes produced at a 400 MeV/A driver, 100 kW machine, according to Argonne National Laboratory estimates for the Rare Isotope Accelerator (RIA). Each entry on the horizontal axis is a different isotope, labeled with its chemical symbol and the number of total nucleons in it. The “m” that follows some of the isotopes is the standard nuclear physics notation for an isomer. Isomers are excited states of an isotope with a significantly long half-life. If a number follows the “m,” the isotope has more than one isomer, with the numbers going in order of increasing excitation energy. Isotopes listed without the “m” are in the ground state. Courtesy of Larry Ahle and of the University of California, the Lawrence Livermore National Laboratory, and the Department of Energy under whose auspices the work was performed.

nuclear chemistry needs are rapidly growing. The anticipated homeland-security-funded activities could absorb all of the nuclear chemists and many of the nuclear physicists trained in the United States. Unless there is an increase in the number of nuclear physicists, perhaps spurred by a new U.S. initiative in low-energy nuclear physics, there is likely to be a surge in unfulfilled demand before 2010 in the number of such applied scientists and engineers.[8]

Medical and Biological Research Applications of Radionuclides

The applications of radionuclides to the medical sciences and biological research fall into the three overlapping categories of imaging, targeted therapy, and radiotracers. In each of these areas, radionuclides offer the capability of imaging local conditions as a function of metabolism as well as delivering site-specific therapies.[9] In this subsection the committee discusses some of the broader impacts of rare-isotope science; it should be noted that a U.S. FRIB would not serve as a primary element of medical research; rather, it might advance the science of rare isotopes and that, in turn, could have implications for clinical practices.

All three applications mentioned above share the characteristic of requiring isotopes with short lifetimes (<1 day). This is because one wants the radiotracer/radiopharmaceutical to result in a low integrated dose to the patient, match the lifetime to the metabolic uptake under study, and minimize hazardous waste. Also, rapid-turnaround serial diagnostic tests of patients require short tracer lifetimes. As with other applications of short-lived radionuclides for chemically specific in situ probes, local, high specific activity is also desired, as it leads to the highest site-specific dose.

In contrast to medical imaging done with collimated, externally defined sources as in computerized axial tomography (CAT) scanning, imaging with radioactive species can track the local rate of metabolism or of a biological function. Examples of the latter are positron emission tomography (PET) and single photon

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[8]This estimate is supported in an unpublished paper from the Lawrence Livermore National Laboratory. See also a recent study by the nuclear energy industry that projected great difficulty in replacing the expected retirement of more than 23,000 skilled workers in the next decade (available at http://www.nei.org/index.asp?catnum=3&catid=1295; accessed January 26, 2007). See additional discussion in Chapter 4 of this report.

[9]For further reading, see T.J. Ruth and D.J. Schlyer, "The Uses of Accelerator Produced Radioisotopes," Ch. 2 in *Review of the Applications of Isotopes in Medicine and Biology*, forthcoming; or N. Oriuchi, T. Higuchi, H. Hanaoka, Y. Ida, and K. Endo, "Current Status of Cancer Therapy with Radio-Labeled Monoclonal Antibodies," *Ann. Nucl. Med.* **19,** 355-365, 2005.

emission computed tomography (SPECT). Typical isotopes applied to these methods are respectively ^{11}C ($T_{1/2} \sim 20.4$ minutes) for PET, and ^{99m}Tc ($T_{1/2} \sim 6$ hours) for SPECT. The very short lifetimes of the PET nuclei require on-site accelerator production, while the SPECT mainstay ^{99m}Tc is primarily made via reactor-produced ^{99}Mo ($T_{1/2} \sim 66$ hours).

These examples also typify the trade-offs between reactor and accelerator production of medical isotopes. Reactors are applied to produce radioisotopes either by (n,γ) reactions in target cells or by the harvesting of fission fragments. Their advantages of low cost and parasitic collection are weighed against several disadvantages, including contamination of samples with multiple isotopes of the same element, resulting in low specific activity; lifetime limitations on the distance to the point of application; and the inability to make some isotopes. In contrast, accelerators have long offered the possibility of using charged-particle reactions to drive production, as well as the applicability of in-flight product filtering to produce high specific activities. The main drawbacks of accelerator production are its high cost and low overall production rates. Of course, one should not assume that a FRIB would produce isotopes at a commercially viable level, but it certainly could produce specific activities that readily allow useful research on applied topics. For instance, a recent experiment in Europe using a novel radioisotope produced at the CERN ISOLDE facility showed significant enhancement in cancer-drug effectiveness; see Appendix E for details.

Moving to radiopharmaceutical therapy, there is a variety of radioactive "scalpels" in various stages of development. Beginning with Goldenberg's original work in 1978, the basic idea is to attach appropriate radionuclides to compounds that are preferentially taken up at the target site (e.g., localized lymphoma cells), and emit decay products (alpha, beta, Auger electron) with appropriate specific activities and range and energy-loss characteristics for the type of diseased tissue in question.

As with other applications, the main advantages of the proposed facility for rare-isotope beams for both imaging and radiopharmaceuticals are both the very high isotopic production rates (estimated at approximately 10 times greater than at ISOLDE or TRIUMF) at high specific activity and the complete coverage of almost all candidate nuclei. Given the enormous production rates, parasitic harvesting of appropriate radioisotopes may be attractive.

Materials Science Applications of Radionuclides

Generally speaking, rare isotopes have broad applications in condensed-matter and materials science as low-density, very-high-signal-to-noise in situ detectors of local atomic environments. Radioactive isotopes offer the synergistic virtues of chemical specificity with the emission of decay products (gamma, beta) whose angular and spectral content can carry a faithful imprint of local field gradients and crystalline anisotropy. Examples include varieties of photoluminescence of implanted ions, perturbed angular correlation gamma decays, Mössbauer spectroscopy, beta-nuclear magnetic resonance (beta-NMR; see the Glossary in Appendix D), and electron (beta) channeling.[10] Radioactive probes can give improvement of many orders of magnitude over conventional probes in detectable defect or impurity densities.

In several respects, beta-NMR exemplifies the development of this field and the key role of very high specific activity beams. It is natural to compare beta-NMR with the established technique of muon-spin-resonance (μSR). Both offer as much as a 10-orders-of-magnitude improvement in signal over conventional NMR, through the combination of high polarization and beta-decay anisotropy. They therefore can probe "rare" structures, such as superconducting vortices, local magnetic relaxation, and behaviors at nanostructure material interfaces. However, unlike muons, which are produced well polarized, in beta-NMR one usually needs to produce high-purity beams of the requisite nuclei, then polarize and implant them. This has only recently been possible with the ISOL method and has now been successfully implemented at TRIUMF.[11] Beta-NMR has the advantage over μSR because of the former's much higher intensities of implantable ions and because the nuclei have much longer lifetimes.

The study of semiconductors is another key application of radionuclides, where their potential for detecting low-density crystalline defects, impurities, and weak doping gradients is proving very important in the development of higher-performance materials.

The great potential of radioactive probes for materials science is currently limited by the capacity to produce pure isotopes. There is, potentially, a very large materials science user community for these applications. Other key issues are the polarization of the beam—it must be quite high—and the intensity requirements of 10^6 particles per second; the latter is not as challenging as the need for the availability of significant beamtime. Typical experiments require systematic stud-

[10]D. Forkel-Wirth, "Exploring Solid State Physics Properties with Radioactive Isotopes," *Rep. Prog. Phys.* **62,** 527-597, 1999.

[11]For further reading, see Z. Salman, R.F. Keifl, K.H. Chow, M.D. Hossain, T.A. Keeler, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, T.J. Parolin, M.R. Pearson, H. Saadaoui, J.D. Schultz, M. Smadella, D. Wang, and W.A. MacFarlane, "Near-Surface Structural Phase Transition of $SrTiO_3$ Studied with Zero-Field β-Detected Nuclear Spin Relaxation and Resonance," *Phys. Rev. Lett.* **96,** 147601, 2006.

ies of many samples as a function of temperature, magnetic fields, pressure, and so on and do not benefit from higher intensities. Hence, a new facility for rare-isotope beams would be of great value for these applications if it met certain requirements for multiuser capabilities and offered long run times.

Exotic-Beam Applications to Advanced Reactor Fuel Cycles for Transmutation of Waste

The transmutation of waste as a key part of future nuclear power fuel cycles is an active area of study in the United States, Japan, Western Europe, Russia, India, and China. Given the likely future growth of fission power, ideas such as fast neutron reactors and accelerator transformation of waste (ATW) for the mitigation of long-lived radioactive waste will certainly be investigated with much greater urgency. Both fast neutron reactors and ATW use high-energy neutrons either to burn or to irradiate waste, thereby favoring fission over (n,γ) processes causing the net destruction of unwanted actinides. In order to accomplish this goal, however, a wide variety of neutron cross sections, including many on unstable neutron-rich isotopes, are required for the improved designs of the detailed operating regime, determining the required levels of isotopic separation and purity. Many of the required cross sections could be measured at a rare-isotope facility in a manner analogous to needs for stockpile stewardship and astrophysics, either by using direct neutron reactions (if available) or by application of the surrogate method. For an application such as this one, the utility of a rare-isotope facility is not in its production of highly exotic nuclei but in the high-volume production of isotopes from which high-precision cross sections can be extracted.

3

Rare-Isotope Beams in the United States and Abroad

Chapters 1 and 2 have presented the background and scientific opportunities associated with the research at a rare-isotope facility. This chapter presents the existing and near-term capabilities in three regions of the world—North America, Europe, and Asia. The existing facilities in the United States and Canada are described in some detail, followed by a description of major facilities to come online in Japan, Germany, and France (see Appendix C for a broader survey of global activity). The role of these facilities in addressing the science drivers presented in Chapter 2 is described. This information frames the background for the discussion of the projected U.S. Facility for Rare-Isotope Beams (U.S. FRIB), its origins, and the associated technical developments that make such a facility possible.

EXISTING RARE-ISOTOPE FACILITIES IN NORTH AMERICA

United States: Selected Facilities

At present the United States has world-leading capabilities in the study of exotic nuclei and an active research community currently performing experiments with exotic beams here and elsewhere in the world. Appendix C presents a tabular listing of most of the operating and planned rare-isotope beam facilities in the world.

There are two major U.S. facilities running dedicated user programs primarily in exotic beams:

- The National Superconducting Cyclotron Laboratory (NSCL) located at Michigan State University (MSU), and
- The Holifield Radioactive Ion Beam Facility (HRIBF) located at the Oak Ridge National Laboratory (ORNL), Tennessee.

Other laboratories have capabilities to provide exotic beams: the Argonne Tandem Linear Accelerator System (ATLAS) at the Argonne National Laboratory (ANL), the Cyclotron Institute at Texas A&M University, the 88-inch Cyclotron at the Lawrence Berkeley National Laboratory (LBNL), and the TwinSol facility at the University of Notre Dame. The ATLAS facility and the Texas A&M laboratory are planning major upgrades of their exotic-beam capabilities, as described below. The current U.S. program is world leading, with the highest-intensity fast exotic beams available at the NSCL and a unique set of beams from actinide targets at HRIBF. The approximate size of the U.S. rare-isotope science community is 600 researchers and 150 graduate students. In addition, about 100 users from the international community come to the United States each year to conduct experiments at these facilities.

The NSCL at MSU provides approximately 4,000 hours of exotic fast-beam experiments per year. The facility is currently able to produce the most-intense fast beams of exotic isotopes worldwide through the use of two coupled superconducting cyclotrons and the A1900 fragment separator. Beams of between 20 and 200 MeV/A are available for experiments. During the laboratory's first few years of operation, more than 100 different secondary beams have been used for experiments. Key experimental equipment includes the superconducting high-resolving power, large solid angle S800 magnetic spectrograph. This device is used in approximately 60 percent of all experiments. Other equipment includes the highly segmented germanium array (SeGA), a sweeper magnet plus neutron wall system for measuring neutron unbound states, a high-resolution array (HiRA) made of silicon, and a gas-stopping and Penning trap system for precision measurements of short-lived nuclei. Near-term upgrades include the addition of a radio-frequency (RF) separator for the purification of proton-rich nuclei, gamma-ray tracking using the SeGA array, and an improved gas-stopping system based on a cyclical system. In the medium term, plans are being developed to add postacceleration and to develop a modest program of reaccelerated beams. Ion beam intensities of up to 10^8 particles per second will be possible for many species.

HRIBF at ORNL employs the Isotope Separator On-Line (ISOL) method to produce radioactive ion beams using the Oak Ridge Isochronous Cyclotron

(ORIC) as the production accelerator and a 25 MV tandem Van de Graaff as the postaccelerator. From 2003 through 2005, HRIBF, operating on a 5-day per week schedule, provided an average of 1,600 hours of rare-isotope beams per year. A facility upgrade project that will be completed in mid-2009 will expand the exotic-beam capacity by more than 50 percent. HRIBF has demonstrated the ability to accelerate approximately 175 radioactive isotopes, including 140 neutron-rich species; more than 50 of these, including ^{132}Sn, are available at intensities of 10^6 particles per second or greater. The facility's postaccelerated neutron-rich beams are unique worldwide. The tandem postaccelerator produces high-quality beams with energies up to 10 MeV/A at A ~ 40 and 5 MeV/A at A ~ 130. Experimental equipment at HRIBF includes the Recoil Mass Separator, which is used primarily for nuclear structure studies and is equipped at the target position with the Clover Array for Radioactive Ion Beams Ge detector array, near full-coverage, charged-particle arrays, and neutron detectors, along with a variety of specialized detector systems at the focal plane for decay studies. The astrophysics end station is based on the Daresbury Recoil Separator, which is optimized for very asymmetric capture reactions and is equipped with highly segmented charged-particle arrays and high-density gas targets.

Other equipment at HRIBF includes a novel setup for very-low-rate evaporation residue and fission reaction studies, a split-pole spectrograph, and a facility for unaccelerated beam studies. A 3-year project, the Injector for Radioactive Ion Species 2 (IRIS2), begun in 2006, will incorporate the newly completed High Power Target Laboratory into HRIBF as a second ISOL production station, with functionality substantially exceeding that of the present facility (IRIS1). IRIS2 will provide critical redundancy in ISOL production, substantially improving the efficiency and reliability of HRIBF. A program of improvements of the capability and reliability of ORIC is also under way, including the installation of an axial injection system to replace the existing internal ion source.

Roughly 1,000 hours per year (15 to 20 percent) of the beam time available at ATLAS at ANL involve the use of a radioactive beam. At the facility, exotic beams can be produced with two distinct approaches: the two-accelerator method and the in-flight technique. Examples of beams produced with the two-accelerator method are long-lived ^{44}Ti and ^{56}Ni, which have been provided to experiments with intensities of 5×10^5 to 6×10^6 ions per second and beam energies up to 15 MeV/A. With the in-flight technique, the desired radioactive isotope is usually characterized by a much shorter half-life. It is produced by sending a primary, stable beam through a gas cell in which the secondary beam is produced through a direct nuclear reaction. Thus far, a number of short-lived beams have been used in experiments. Examples include ^{6}He, ^{8}B, ^{12}B, ^{11}C, ^{20}Na, and ^{37}K. In the near future, further purification of the secondary beam will occur through the addition of an RF beam sweeper.

The ATLAS facility is equipped with state-of-the-art instrumentation, including two Penning traps, an atom trap, a split-pole spectrograph, and a Fragment Mass Analyzer. ATLAS is also the current home of Gammasphere, the national gamma-ray facility. A major advance in rare-isotope capabilities at ANL will be the Californium Rare Isotope Breeder Upgrade (CARIBU), at which a new source will be installed to provide beams of short-lived neutron-rich isotopes. The technique follows the gas catcher concept developed for the Rare Isotope Accelerator (RIA); it will provide accelerated neutron-rich beams with intensities up to 7×10^5 particles per second. Specifically, CARIBU will provide beams of a few hundred nuclei between Z = 34 (Se) and Z = 64 (Gd), many of which cannot be extracted readily from ISOL-type sources. In addition, it will make available reaccelerated beams at energies up to about 12 MeV/A, which are difficult to reach at other facilities.

The in-flight technique described in Chapter 1 was developed early at the University of Notre Dame's Nuclear Structure Laboratory, where it continues to be used extensively. In this case, primary beams from the FN tandem accelerator are used to produce the rare isotopes of interest through nuclear reactions. These isotopes are subsequently focused onto a target by TwinSol, a set of two superconducting solenoids. Thus far, beams of ^{6}He, ^{7}Be, ^{8}Li, ^{8}B, ^{12}B, ^{10}Be, ^{12}N, ^{18}Ne, and ^{18}F have been produced at energies typically on the order of 2 to 5 MeV/A and intensities of 10^5 to 10^7 ions per second.

The Cyclotron Institute at Texas A&M University has, for some time, employed heavy-ion beams from the K500 cyclotron along with the Momentum Achromat Recoil Separator to produce exotic beams using the in-flight method. A project is now under way to add a versatile, reaccelerated exotic-beam capability. A key element of the project is the reactivation of the mothballed K150 cyclotron for use as a production accelerator. Radioactive species produced by beams from the K150 will be stopped as 1^+ ions in He gas cells, formed into a beam by RF ion guides, transported to a charge-breeding Electron Cyclotron Resonance ion source, and finally postaccelerated in the K500. Several gas-stopping ion guide configurations are planned, with layout and geometry tailored to the production reaction. Initial effort will center on production by light-ion (p, d, α) reactions and will employ a configuration based on the existing Ion Guide Isotope Separator On-Line system at Jyväskylä, Finland. The first reaccelerated beam is expected in 2009. A broader range of rare isotopes, including neutron-rich species, will be available once a second configuration appropriate for use with various heavy-ion production reactions is operational (in about 2011). This configuration will include a large-bore superconducting solenoid as a first-stage collector and a gas cell based on the ANL design. Beam intensities up to $\sim 5 \times 10^5$ particles per second are expected in favorable cases, and reaccelerated beams with energies in the range 2 to 70 MeV/A will be available.

Complementary to these efforts using exotic beams, a number of facilities for stable beams (including a major portion of the ATLAS program at ANL, as well as LBNL, Florida State University, the University of Notre Dame, the Triangle Universities Nuclear Laboratory, the University of Washington, and Yale University) operate extensive programs in nuclear structure and astrophysics. Naturally, beam intensities at these facilities are, in general, much larger than intensities with exotic beams, allowing a more detailed investigation of the nuclei available for study. The technique of inverse kinematics, developed out of necessity for exotic-beam experiments, has been found to have many advantages in some stable-beam experiments as well. The interplay between exotic- and stable-beam research runs deep, and questions raised with one approach are often further addressed in the other. Maintaining these complementary capabilities is very desirable.

Canada: Isotope Separator and Accelerator at TRIUMF

TRIUMF, located in Vancouver, British Columbia, is Canada's national laboratory for accelerator-based science. Traditionally it has provided a sizable contingent of U.S. scientists an opportunity to carry out research. The epicenter of the TRIUMF facility is a high-intensity 500 MeV negatively charged hydrogen ion cyclotron—a proven reliable source of simultaneously extracted, high-intensity, proton beams. The Isotope Separator and Accelerator (ISAC) user community numbers a few hundred; about 20 percent of the researchers come from the United States.

ISAC, an advanced ISOL-type facility, is one of the major facilities receiving beam from the cyclotron (see Figure 3.1). The target area is shielded to permit delivery of a 100 μA, 500 MeV (50 kW) proton beam onto an ISOL target. All isotopes with an $A/q \leq 30$ can be accelerated in a continuous-wave, radio-frequency quadrupole linac from 2 keV/A, at injection, to 150 keV/A at exit. A subsequent drift tube linac allows the energy of the ion beam to be continuously varied from the initial 0.15 MeV/A to 2 MeV/A and transported to any one of the three experimental stations in ISAC-I (the first phase of ISAC). With the installation of a charge-state booster in 2007, essentially all exotic isotopes ionized in ISAC could be accelerated. In 2006, a superconducting linac was commissioned, bringing the beam to a new experimental hall (ISAC-II). Initially the ISAC accelerator will begin operation at an energy of 4.3 MeV/A (6.1 MeV/A, ^{12}C, $A/q = 4$, has been commissioned). Additional accelerating structures are being built that will increase the final energy up to a nominal 6.5 MeV/A for $A \leq 150$ by 2010.

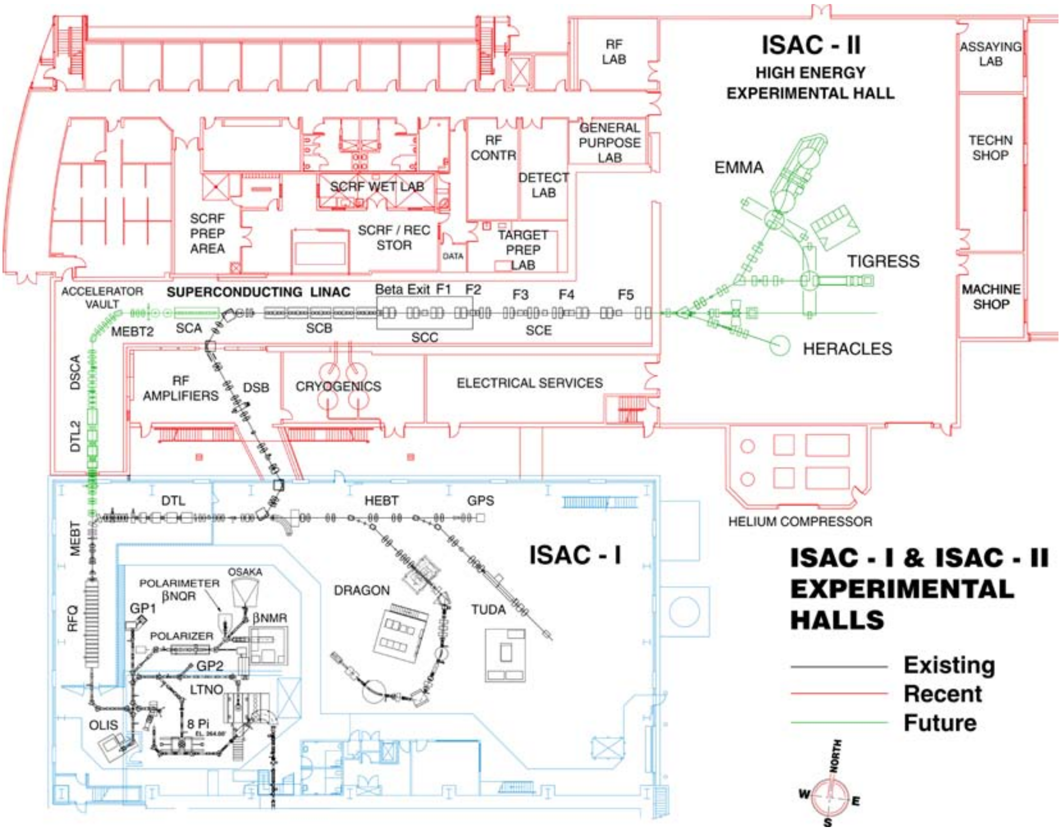

FIGURE 3.1 Layout of the accelerators and experimental stations in the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Canada. See text for additional detail.

A proposal has been developed to take advantage of the unique capabilities of the cyclotron to independently provide simultaneous high-current beams for multiple beam lines. In this proposal, a second high-intensity proton beam line would be constructed to bring a second beam to ISAC. This proposed facility would then provide a unique testing facility for high-power targets and ion sources. This concept potentially also permits the simultaneous acceleration of different isotopes from separate targets for experiments.

In addition to a complement of general-purpose experimental equipment, some of the specialized experimental equipment associated with the different beams at ISAC is listed below.

- *For the low-energy unaccelerated beams (≤60 keV):*
  —TRINAT (TRIUMF Neutral Atom Trap), a magneto-optical atom trap for electroweak precision tests of the Standard Model.
  —TITAN (TRIUMF Ion Trap Facility for Atomic and Nuclear Science), a facility optimized for high-precision mass measurements of short-lived nuclei scheduled to begin operation in the fall of 2006.
- *For the accelerated beams in the ISAC-I experimental hall:*
  —DRAGON (Detector of Recoils and Gammas of Nuclear Reactions), a recoil mass separator and associated windowless gas target built to measure the rates of proton- and alpha-radiative-capture reactions.
  —TUDA (TRIUMF UK Detector Array), an array of double-sided silicon strip detectors located in a general reaction chamber designed to study resonant reactions complementary to those from DRAGON and transfer reactions associated with explosive hydrogen and helium burning.
  —A general-purpose experimental location.
- *For accelerated beams in the ISAC-II experimental hall:*
  —A versatile, high-efficiency gamma-ray detector array, TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer), consisting of 12 "clover-type," segmented, hyperpure germanium detectors.
  —EMMA (ElectroMagnetic Mass Analyzer), a recoil mass spectrometer to detect the following: (1) the exotic heavy products of fusion-evaporation reactions, (2) elastic and inelastic scattering, and (3) transfer reactions in inverse kinematics. This facility should be available for experiments in 2010.
  —A general-purpose facility that will first be used in 2006 with the Multi-Angle Gamma Apparatus detector (on loan from Grand Accélérateur National d'Ions Lourds [GANIL]) with an accelerated ^{11}Li beam.

RARE-ISOTOPE FACILITIES COMING ONLINE IN ASIA AND EUROPE

There is global interest in the science of rare isotopes. In addition to continued significant investments in Japan, Germany, and France, countries including Belgium, Brazil, China, Finland, Italy, India, Russia, and Switzerland are pursuing beam-based facilities for rare-isotope research (see Appendix C for selected details). The three emerging facilities in Japan, Germany, and France—the Rare-Isotope Beam Factory (RIBF) at RIKEN in Japan, the Facility for Antiproton and Ion Research (FAIR) at Gesellschaft für Schwerionenforschung (GSI) in Germany, and the Système de Production d'Ions Radioactifs en Ligne (SPIRAL) 2 facility at GANIL—are described in some detail, as they represent the standard with which a

U.S. FRIB must be compared if it is to have a world-leading role in rare-isotope physics research. The considerable scope of these two facilities represents the view of the international scientific community of the opportunities of enhanced capability in rare-isotope science. Layout diagrams of these facilities are presented so that their ambitious scope can be fully appreciated.

Japan: Rare-Isotope Beam Factory at RIKEN

Construction of the Rare-Isotope Beam Factory is divided into two phases. Phase 1, which is already funded, consists of (1) a high-power heavy-ion accelerator with ^{238}U beams at 100 kW, (2) a fragment separator, and (3) a multifunction beam line spectrometer at zero degrees. The RIBF accelerator consists of three cyclotrons with K = 570 MeV, 980 MeV, and 2500 MeV, respectively. Expected beam energies will be up to 440 MeV/A for light ions and 350 MeV/A for ^{238}U. The goal for the intensity of the driver is 6×10^{12} ions per second. As of this writing, the first beam from the entire accelerator system is expected in December 2006. A diagram of the facility is shown in Figure 3.2.

Typically, rare-isotope (RI) beams at ~250 MeV/A will be used either via projectile fragmentation of stable ions or via in-flight fission of uranium ions through the fragment separator. The fragment separator consists of dipole (normal conducting) and quadrupole magnets (superconducting) for the production of fission fragments with a large acceptance. The zero-degree spectrometer is a multifunction beam transport line composed with many magnets, the structure of which is similar to that of the fragment separator. With this spectrometer, inclusive and/or semi-exclusive spectra in the reactions will be measured with particle identification by the zero-degree spectrometer. In Phase 1, the scientific agenda will include a search for halo nuclei via a transmission method, a search for any loss or birth of magic numbers via in-beam spectroscopy and beta-spectroscopy, and other searches.

In Phase 2 (2007-2010), many additional experimental systems will be installed. Studies of nuclear structure as well as astrophysics, as described in Chapter 2, will be the main focus at this RIBF facility. In addition, with the installation of a new storage ring, a high-precision mass measurement with $\Delta m/m = 10^{-6}$ is planned. Production of polarized RI beams is planned with a novel method. Also, there are plans for measurements of electron-RI scatterings, with the construction of an electron storage ring with an electron energy of 300 MeV. In addition, a new linac injector is proposed for the gas-filled recoil separator in order to enhance the efficiency of a superheavy element search. At present, the expected user community for RIBF numbers about 450 researchers, with some room for additional growth.

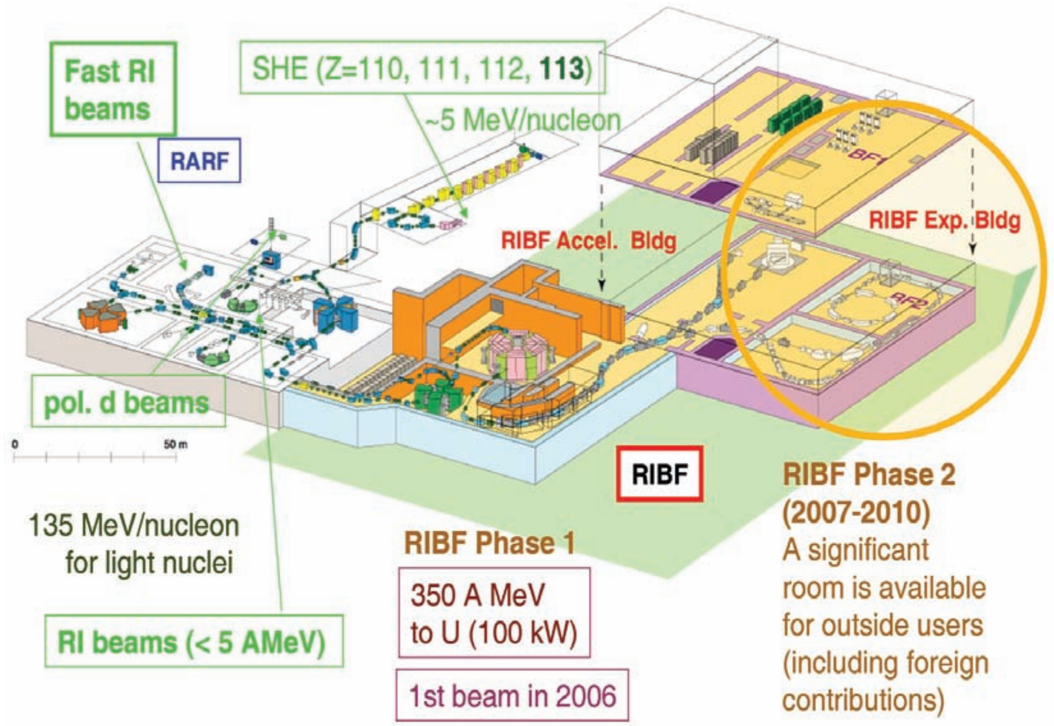

FIGURE 3.2 Present RIKEN Accelerator Research Facility (RARF) and the new, high-power Rare-Isotope Beam Factory (RIBF). The latter is under construction and is expected to begin operation in December 2006.

Germany: Facility for Antiproton and Ion Research at GSI

The central part of the Facility for Antiproton and Ion Research consists of two large superconducting synchrotrons and a complex system of storage rings that will deliver high-intensity ion beams up to 35 GeV per nucleon for experiments with primary beams of ions up to uranium, as well as secondary (radioactive) ion beams and antiprotons. A system of storage and cooler rings is foreseen in order to increase the phase-space density of the beams of rare isotopes and antiprotons. Figure 3.3 presents a schematic layout of the present and future facilities at GSI. FAIR will open up unique opportunities for a broad spectrum of research. There are to be five major programs: quantum chromodynamics studies with cooled beams of antiprotons, nucleus-nucleus collisions at the highest baryon densities, nuclear structure and nuclear astrophysics investigations with nuclei far off stability, high-density plasma physics, and atomic and materials science studies, radiobiological investigations, and other interdisciplinary studies.

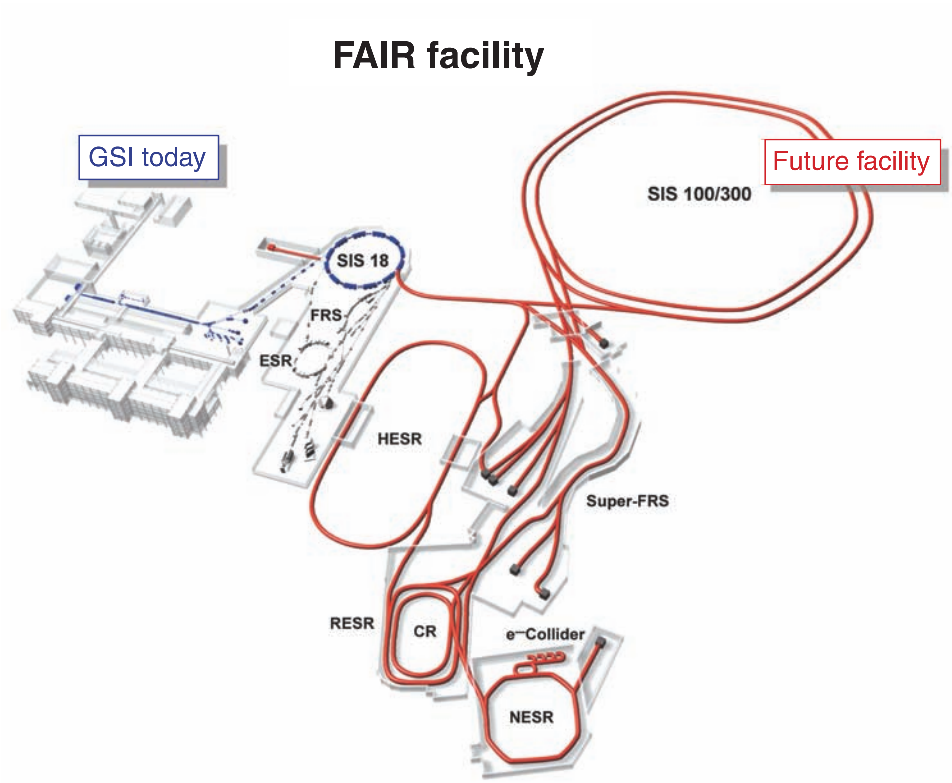

FIGURE 3.3 Layout of the present and future facilities at Gesellschaft für Schwerionenforschung (GSI). The new Facility for Antiproton and Ion Research's (FAIR's) accelerators and buildings (indicated in color on the right of the site map) are located east of the existing GSI facilities (indicated in gray). NOTE: SIS—Heavy-Ion Synchrotron; FRS—fragment separator; ESR—experimental storage ring; HESR—high-energy storage ring; RESR—accumulator/decelerator ring; CR—collector ring; NESR—new experimental storage ring. Image courtesy of H. Geissel, GSI.

The concept and design of the FAIR accelerator facility have been adapted to the requirements of the planned scientific programs. These requirements are as follows:

- *Beams of all ion species.* With FAIR, beams of all kinds of ions, from hydrogen to uranium, as well as antiprotons with a large energy range (from nearly at rest up to some 10 GeV per nucleon), will be provided.
- *Highest beam intensities.* The intensities of the primary beams are increased by a factor of one up to several hundred for the heaviest ion species relative to any existing facility. For the production of radioactive secondary beams

and also for the generation of high-power pulses for plasma research, these high-intensity beams with up to 5×10^{11} ions circulating in the SIS 100-synchrotron can be compressed to short bunches of 50 to 100 ns duration. The increases in primary intensity translate into an even higher gain factor of 1,000 up to 10,000 for radioactive secondary beam intensities, owing to the higher acceptance of the subsequent separators and storage rings.

- *Increase in beam energy.* For antiproton production, intense proton beams with an energy of around 30 GeV are needed. In order to achieve the highest baryon densities and allow for charm production in nucleus-nucleus collisions, beam energies of up to 35 GeV per nucleon for uranium 92^+ are to be provided.
- *High-quality beams.* By exploiting beam manipulation methods such as stochastic cooling and electron cooling, the momentum spread and transverse emittance of primary and secondary beams can be reduced by several orders of magnitude. These cooled beams will allow novel precision experiments on the structure of matter and the fundamental interactions and symmetries on which it is based.
- *Running of parallel programs.* By special coordination of the time sequence of acceleration and transfer between the various synchrotrons and storage rings, all five major scientific programs will be running in a highly parallel mode.

The FAIR project is funded at a total cost of 1,187 million euros (M€) (1,001 M€ in investments, 186 M€ in personnel). Construction is projected to start in the fall of 2007. FAIR will be constructed in three phases until 2014. The full performance with parallel operation of all experimental programs is planned for 2015. FAIR will serve a user community of about 2,500 researchers, about 25 percent of whom are primarily interested in the rare-isotope beam capabilities of the facility.

France: SPIRAL 2 Facility at GANIL

In 2005, the Nuclear Physics European Collaboration Committee (NuPECC) —an advisory committee of the European Science Foundation—prepared a roadmap for the construction of nuclear physics research infrastructure in Europe. The committee recommended the construction of two next-generation rare-isotope beam facilities that were under discussion in the region: FAIR at GSI, using in-flight fragmentation, and the GANIL/SPIRAL 2 radioactive-beam facility employing ISOL techniques. The document acknowledged the interest of the scientific community in pursuing an "ultimate" ISOL facility for Europe, termed EURISOL—European Isotope Separator On-Line. This facility is not envisioned to begin for at least another 10 years, however. Because of the timeline for this project, NuPECC recommended the construction of an intermediate-generation facility that would continue research and development efforts and provide much-needed rare-isotope beams to the user community of about 700 physicists. Among the intermediate facilities that have been proposed, SPIRAL 2 met all of the criteria that NuPECC supplied (scientific agenda, site evaluation, and level of investment).

In March 2005, the European Strategy Forum on Research Infrastructure published its "List of Opportunities." FAIR and SPIRAL 2 were among the selected projects. In May 2005, the French Ministry of Research announced its intention to build SPIRAL 2. Its construction cost, estimated to be 130 M€ (including personnel and contingency), will be shared by the French funding agencies, the authorities of the locality of Basse Normandie, and other European partners. The construction will last about 5 years, with full operations planned for 2012. The facility will serve a community of about 700 users.

SPIRAL 2 is an upgrade planned for the SPIRAL facility at the French laboratory GANIL in Caen, France. The SPIRAL 2 project is based on a multibeam driver in order to allow both ISOL and low-energy in-flight techniques to produce rare-isotope beams (see Figure 3.4). A superconducting light-/heavy-ion linac with an acceleration potential of about 40 MV capable of accelerating 5 mA deuterons up to 40 MeV and 1 mA heavy ions up to 14.5 MeV/A will be used to bombard both thick and thin targets. These beams could be used for the production of intense beams by several reaction mechanisms (fusion, fission, transfer, and so on) and technical methods. The production of high-intensity beams of neutron-rich nuclei will be based on fission of a uranium target induced by neutrons, obtained from a deuteron beam impinging on a graphite converter (up to 10^{14} fissions per second) or by a direct irradiation with a deuteron, ^{3}He, or ^{4}He beam. The postacceleration of beams in the SPIRAL 2 project would be obtained using an existing cyclotron. An important aspect of this project is that it will allow GANIL to provide beams in parallel to up to five different experiments.

A review of the scientific agenda for SPIRAL 2 shows that several domains of research in nuclear physics at the limits of stability will be covered by this project, including the study of the rapid-neutron-capture-process (r-process) and rapid-proton-capture-process nuclei, and shell closure in the vicinity of magic numbers, as well as the investigation of very heavy elements. The high-intensity stable and radio-active heavy-ion beams will also be available for interdisciplinary research in atomic physics and materials science. An intense flux of fast neutrons produced by SPIRAL 2 might find additional important applications, such as in a program for studies of the astrophysical slow-neutron process. Within this niche, SPIRAL 2 will be a very attractive facility.

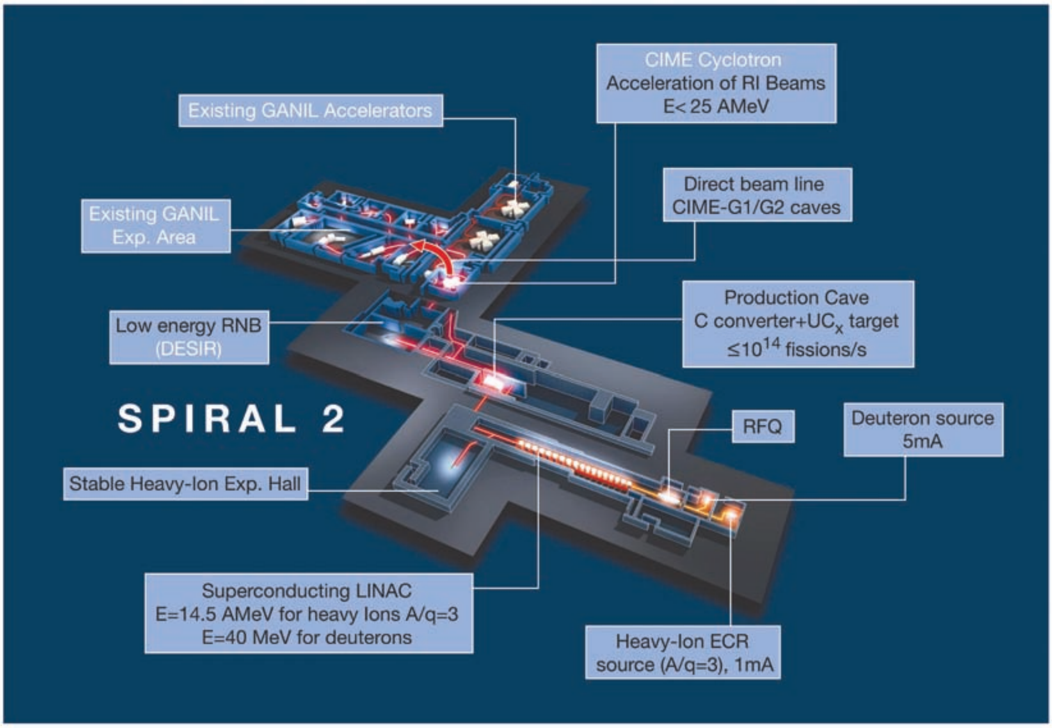

FIGURE 3.4 Conceptual overview of the proposed Système de Production d'Ions Radioactifs en Ligne (SPIRAL) 2 radioactive-beam facility at GANIL in France. NOTE: GANIL—Grand Accélérateur National d'Ions Lourds; CIME—Cyclotron pour Ions de Moyenne Energie; RI—rare-isotope; RNB—radioactive nuclear beam; DESIR—low-energy RNB; RFQ—radio-frequency quadrupole; LINAC—linear accelerator; ECR—Electron Cyclotron Resonance. Image courtesy of GANIL/APRIM.

INTERNATIONAL COMPARISONS

First-generation rare-isotope beam facilities have been operating in the three regions of the world where nuclear physics is most actively pursued, Europe, North America, and Asia, and several laboratories have undertaken significant upgrades to prepare second-generation facilities (GSI, TRIUMF, RIKEN, and the SPIRAL facility at GANIL in France). These facilities continue to produce important results, and ambitious experiments are planned with them in the next few years. However, major breakthroughs toward the ultimate scientific goal of a comprehensive understanding of atomic nuclei will only be achieved by the next generation of rare-isotope facilities.

In order to better understand the capability and advantages of facilities that would be sharing the world stage with a future U.S. facility, the Department of Energy/National Science Foundation (DOE/NSF) Nuclear Science Advisory Committee (NSAC) established a subcommittee in 2003 to compare the relative capabilities of FAIR at GSI and the then-proposed facility concept RIA. The subcommittee generated a detailed, 45-page report examining all aspects of the issue.[1]

The NSAC subcommittee compared the energies, intensities, rarity, and quality of the rare-isotope beams projected to be achieved at both FAIR and RIA. Since the time of the subcommittee's report, U.S. plans have been revised. The reduction in scope and budget from RIA to a potential FRIB is estimated[2] to result in a rare-isotope beam intensity that ranges from being 0 to 20 percent reduced for ions near the valley of stability to being more than 90 percent reduced for certain elements nearer the neutron drip line compared to what could have been achieved with a 400 MeV/A driver. Larger reductions are offset by retaining the same beam power at 200 MeV/A energy and hence having twice the beam current. On the basis of these estimates, the committee conducted some approximate comparisons among a potential implementation of a FRIB, GSI's FAIR, and RIKEN's RIBF. Rather than repeating the NSAC's detailed flux comparisons for RIA and GSI, this committee provides an evaluation relative to the science questions identified in Chapter 2. Thus, this committee reviewed several of the key comparisons of RIA and GSI made in the NSAC report and comments on the applicability to a FRIB.

For instance, in the area of nuclear structure research, the NSAC subcommittee found the following with respect to the relative strengths of GSI and RIA:

- *RIA strength:* RIA's generally higher intensity of unstable nuclei, especially at the limits of existence, will provide it with across the board advantages even in the capabilities it shares with GSI. The flexibility of the RIA concept allows the choice of production methods to be optimized for particular rare-isotope species that will, for example, have a major impact on studies of very heavy elements. The re-accelerated beam capability at RIA, which is unique to that facility, will enable the application of a wide range of classical nuclear structure studies to nuclei with extreme N/Z ratios that will be a focus of the nuclear structure program.
- *GSI strength:* GSI has unique capabilities of stored and cooled unstable beams that make possible broad-range measurements of large numbers of masses at moderate precision (~50 keV).* Colliding-beam eA studies of nuclear charge distributions will also be possible for species produced at relatively high inten-

[1]U.S. Department of Energy, *NSAC Subcommittee on the Comparison of RIA and the GSI Project Opportunities and Capabilities,* Washington, D.C., February 2004.

[2]These estimates are the product of work undertaken by the National Superconducting Cyclotron Laboratory and the Argonne National Laboratory and displayed in presentations to this committee.

sity (>10^6 ions/s). The availability of thin internal targets of hydrogen and helium isotopes will facilitate hadron scattering studies of the radial distributions of mass in nuclei, and may allow an extension of knowledge of isoscalar giant modes into the regime of neutron-rich unstable nuclei.[3]

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*Note recently that masses with A~200 have been measured with an accuracy of 30 keV, e.g., Nucl. Phys. A756, 3 (2005).

The most interesting masses are those farthest from the valley of stability, and they will be much less abundantly produced. The present committee heard testimony that mass resolutions of ~100 keV would be achieved in these instances—still an impressive and useful feat.

With respect to the projected impact on addressing the nuclear physics aspects of the r-process, the NSAC subcommittee concluded as follows:

- *RIA strength:* The higher intensities allow more sensitive and higher quality structure and life-time measurements, identification and study of halo effects, and shell quenching signatures. In particular, determinations of half-life and the probability for β-delayed neutron emission are very intensity dependent. RIA also provides deeper access (on average by 2-3 neutrons compared to GSI) into the neutron rich regions of the nuclide chart. The proposed (d,p) transfer studies to probe (n,β) reaction rates can also be performed without major difficulty over a wide energy range. Because of the fast beam option, (γ,n) Coulomb break-up experiments are also possible, but face similar uncertainties as at GSI.
- *GSI strength:* The storage ring allows global mass measurement for many masses at the same time. This is a good technique for testing mass models and promises to provide mass information with uncertainties less than 100 keV/c^2. The fast beam capability allows measurements of Coulomb break-up, but the method may only be useful for light isotope systems because of the complexity in structure and gamma-decay pattern of the resonance states.[4]

These comparisons, 10 in all, by the NSAC subommittee show unique advantages for both facilities in addressing a set of scientific issues rather similar to those listed in Chapter 2 of the present report. Moreover, FAIR will be a facility focusing on a broader set of issues than rare-isotope science, as it has relativistic stable ion beams, kaon beams, and antiproton beams, as well as rare-isotope beams.

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[3]U.S. Department of Energy, *NSAC Subcommittee on the Comparison of RIA and the GSI Project Opportunities and Capabilities*, Washington, D.C., February 2004, p. 12.
[4]U.S. Department of Energy, *NSAC Subcommittee on the Comparison of RIA and the GSI Project Opportunities and Capabilities*, Washington, D.C., February 2004, p. 14.

Thus, not to belabor the issue further but to quote from the conclusion of the NSAC subcommittee:

> There have been numerous previous studies that have made a strong science case associated with the study of rare-isotopes and we reaffirm those findings. The RIA and GSI facilities are largely quite distinct in their strengths and are indeed, as the proponents claim, complementary. RIA clearly has a much larger reach as a rare-isotope facility, and hence the better facility to address the science associated with rare-isotopes. The existence of an upgraded GSI facility does not, by itself, constitute justification for de-scoping the rare-isotope capability of RIA as there is only modest overlap in their rare-isotope capabilities. However, the rare-isotope capability at the future GSI facility is only one part of a remarkably versatile and multifaceted accelerator complex. We expect the U.S. research community to have a strong interest in several of the GSI capabilities.[5]

The present Rare-Isotope Science Assessment Committee is in accord with the findings of this NSAC subcommittee and further notes that since FAIR will be pursuing a broad program of which rare-isotope beams are only a part, significant annual operations would make a FRIB quite competitive. That is, beam-time availability for exotic species would be a key determining factor in the success of a FRIB over FAIR.

No such complete study exists comparing the capabilities of RIA to RIKEN's RIBF, let alone for a U.S. FRIB. However, the following observations can be made. RIKEN is currently designed as a heavy-ion-fragmentation facility. It aims for a heavy-ion driver power of somewhat less than 100 kW for a 350 MeV/A ^{238}U beam. The suite of experimental systems planned for installation in the second phase of construction is impressive. The planned storage ring (with a mass resolution $\Delta m/m = 10^{-6}$) will be an important capability for measurements of masses approaching the neutron drip line. The addition of a 300 MeV electron storage ring to investigate the charge distribution of radioactive ion species will be a unique capability unmatched at any other facility.

There are no plans for a light-ion ISOL capability. The goal for the RIBF primary accelerator requires a tenfold improvement in the performance of the cyclotron-ion source and proof of performance for the stripper foil technology at these intensities. With the considerable investments being made and the sharp focus on physics with rare ions, RIKEN's RIBF will be the leading facility in the region and a major facility in the world with several unique features.

[5]U.S. Department of Energy, *NSAC Subcommittee on the Comparison of RIA and the GSI Project Opportunities and Capabilities,* Washington, D.C., February 2004, p. 30.

4

Assessing the U.S. Position

This chapter presents the background and current status of developments progressing toward a U.S. Facility for Rare-Isotope Beams (U.S. FRIB) and places the facility in the broader context.

RECENT HISTORY

In 1999, the joint Department of Energy/National Science Foundation (DOE/NSF) Nuclear Science Advisory Committee (NSAC) convened a task force that unanimously concluded that there was a scientific imperative for the United States to build a next-generation rare-isotope beam facility (termed the Rare Isotope Accelerator, or RIA) and recommended a unique technological solution that included both the in-flight and Isotope Separator On-Line (ISOL) isotope-production capabilities.[1] The main feature of the recommended facility was a novel accelerator (driver) capable of accelerating any stable ion from hydrogen to uranium. The driver would have delivered primary beam powers up to 400 kW for the production of unparalleled yields of rare isotopes from both ISOL targets and fragmentation targets. Other major

[1]DOE/NSF Nuclear Science Advisory Committee, *ISOL Task Force Report*, Washington, D.C.: U.S. Department of Energy, 1999.

components of the proposed facility included isotope separators for isotopic separation of in-flight fragmentation-produced exotic beams, a gas catcher/ion guide for preparing these in-flight beams for subsequent injection into an accelerator, and a postaccelerator facility for varying the energy of these rare isotopes.

The 1999 report recommended conducting modest preconstruction research and development (R&D) on key elements of the facility to enhance the predicted performance and to reduce costs. The subsequent R&D has enhanced the concept, verified that the concept is robust, expedited the readiness to proceed to detailed engineering, and reduced the need for large financial contingencies. Key developments were made in the areas of ion source technology, superconducting cavity design, accelerator design, beam target and stripper technology, and gas catcher technology. The baseline concept design for the accelerator now includes about 1,200 major elements (300 radio-frequency [RF] resonators, 90 solenoids, 100 quadrupoles, and 16 magnetic dipoles) to achieve at least an energy of 400 MeV/A for all ions. The final energy for an ion depends on its charge-to-mass ratio (that is, hydrogen, with a charge-to-mass ratio of 1, will reach more than twice the energy/mass unit of the heaviest ions). The lower-energy (200 MeV/A) driver, proposed for a FRIB, would merely be a shortened version of this existing design.

At the time of the NSAC task force, there was no ion source that had demonstrated the heavy-ion current to realize the 400 kW specification for the heaviest ions. To reach this specification required nearly an order-of-magnitude improvement in uranium ion current. Subsequently, with DOE-supported R&D, a group at the Lawrence Berkeley National Laboratory demonstrated that its Electron Cyclotron Resonance Ion Source meets the required specifications. The ion source is shown in Figure 4.1. Beam dynamics calculations have shown that the beam characteristics from the ion source are, in fact, so excellent that it is even possible to accelerate two charge states simultaneously. A unique radio-frequency quadrupole (RFQ) linac that accommodates the acceleration of multi-charge-states has been prototyped at the Argonne National Laboratory (ANL). The ability to simultaneously accelerate ions of different charge-states is important for reaching high beam powers.

The velocity of the accelerated ions varies considerably over the length of the accelerator, and the technology to accelerate these ions has been optimized to achieve cost-efficient acceleration. The concept design is unique in that it proposes to use superconducting RF cavities throughout the acceleration process. To reduce the size and cost of the accelerator, various cavity structures have been proposed and prototyped. The cavity structures are grouped into several accelerator sections according to the respective betas (β [beta] = v/c, ion velocity/speed of light) and resonating frequency. The structures include fork, quarter wave, half wave, triple

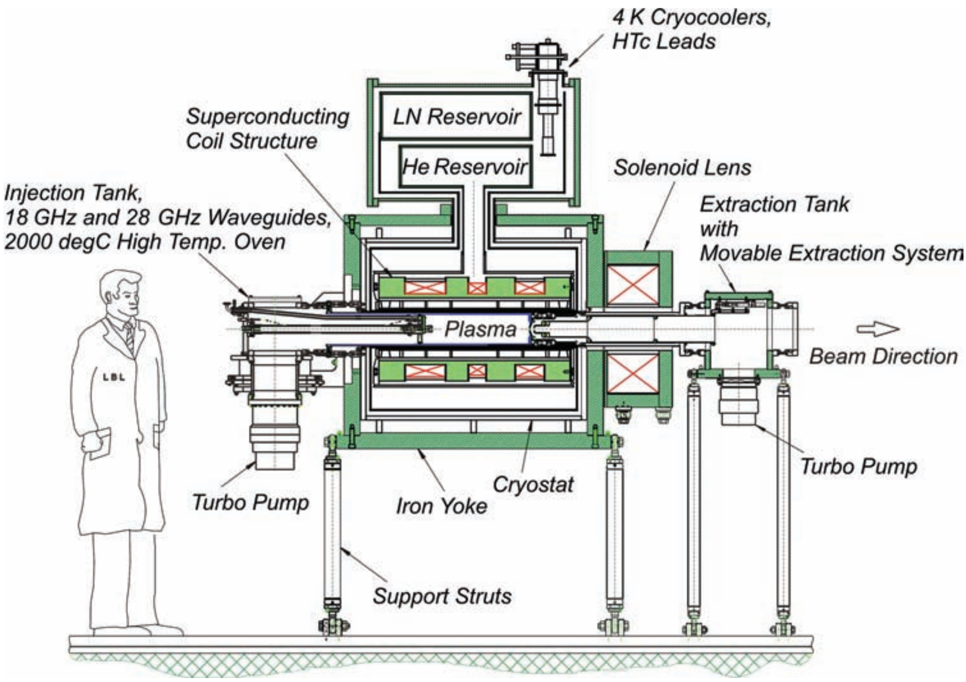
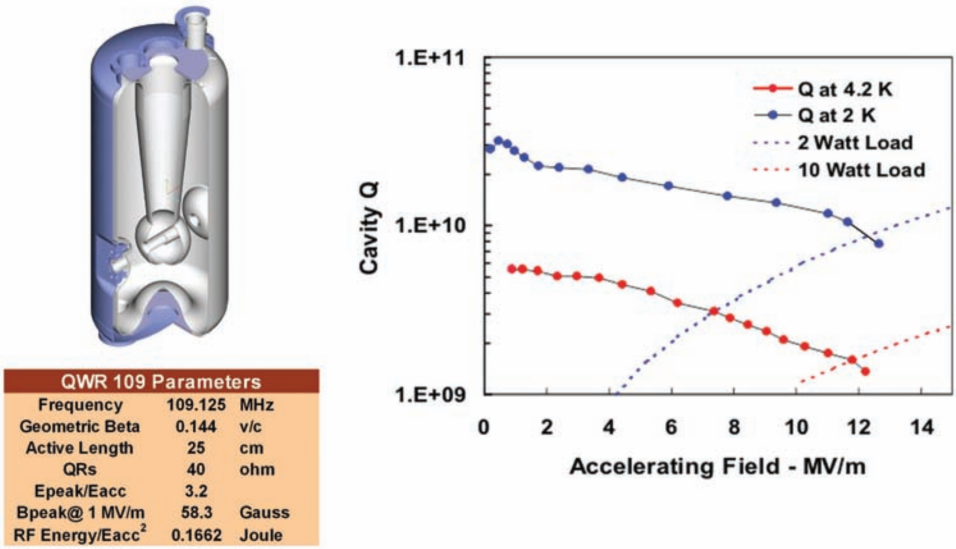


FIGURE 4.1 The ion source developed for the Rare Isotope Accelerator (RIA). It has delivered 8×10^{12} of Bi in charge state +30. Courtesy of the Lawrence Berkeley National Laboratory.

spoke, and elliptical cell resonating structures. All proposed resonator structures have been either prototyped or tested. Figure 4.2 shows the design and prototype performance of a quarter wave resonator.

For a given energy, the length of the accelerator affects the overall cost of the facility; a lower total number of accelerating RF cavities results in a lower total accelerator cost. For RIA, and presumably also for a FRIB, the cost of the driver accelerator has been minimized through the use of electron strippers at optimal points in the accelerator chain. At these locations, the charge state of an ion is increased by removing electrons from the ions. The total energy gain in crossing a voltage gap of an RF cavity is enhanced, since the energy gain is proportional to the charge of ion. A technological challenge for next-generation rare-isotope facilities has been to develop electron strippers that have manageable lifetimes at the power densities of the uranium beams. Graphite foils are commonly used in accelerators but can only tolerate relatively low beam power deposited in the foil. Initially, large rotating graphite wheels were proposed to deal with the required increased power deposition. Recently, a thin, high-speed, liquid-lithium film has been proposed as



QWR 109 Parameters		
Frequency	109.125	MHz
Geometric Beta	0.144	v/c
Active Length	25	cm
QRs	40	ohm
Epeak/Eacc	3.2	
Bpeak@ 1 MV/m	58.3	Gauss
RF Energy/Eacc^2	0.1662	Joule

FIGURE 4.2 Design and performance of a prototype superconducting quarter wave resonator (QWR). Courtesy of Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

the preferred solution and has successfully undergone initial testing to confirm some of the basic requirements. This development comes as a by-product of the R&D on a liquid-lithium fragmentation target. The liquid-lithium "foil" designs and a photograph of their operation is shown in Figure 4.3.

For exotic beams produced by the fragmentation technique, a focused, 400 kW, high-energy high-mass beam from the driver accelerator impinges on a windowless liquid-lithium target. Fragments from the collision reaction of the high-energy beam and the lithium atoms are captured and transported to a mass separator. The liquid-lithium target must be capable of withstanding approximately 4 MW/cm^3. A windowless lithium jet has been assembled, tested in vacuum with an electron beam, and confirmed to be stable with a uranium-beam-equivalent deposited beam power.

A major novel element of the proposed design for RIA is a gas catcher system that permits mass-separated isotopes formed via fragmentation to be stopped and reaccelerated. The output of the gas catcher would be a low-energy cooled beam of isotopes in a single-charge state. To meet scientific requirements, the gas catcher must be efficient, universal, and fast. Of particular interest are the small quantities of very-short-lived isotopes at the extremes of the nuclear landscape. Tests have

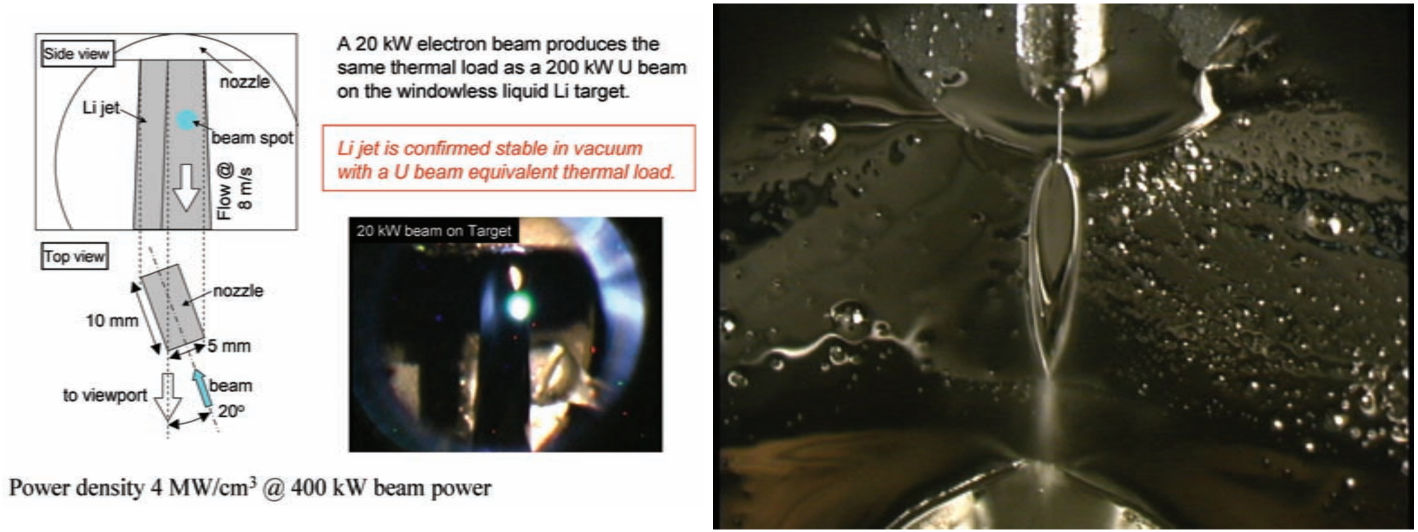


FIGURE 4.3 Layout of the liquid-lithium "foils" that serve as fragmentation targets for the heavy-ion beam from the accelerator. The foil on the left is 1 cm thick and 0.5 cm wide; it has been shown to be capable of serving as a target in a 400 kW beam. The foil on the right is the object in the center of the photograph. It is ~10^{-3} cm thick and has a high mass flow rate of 2 g/s. It is to be used to strip electrons from 10 MeV/A heavy-ion beams and should be able to handle the power deposition. Courtesy of Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

confirmed that a large gas catcher capable of operating at these energies can be built and that it operates essentially as predicted. In a test of the U.S.-built gas catcher at the Gesellschaft für Schwerionenforschung (GSI) accelerator complex in Germany, a remarkable 50 percent of the radioactive ions stopped in the gas catcher were extracted as a singly-ionized low-energy radioactive ion beam.[2] Figure 4.4 shows the focusing forces in a gas catcher and lists some observed performance levels. As of this writing, a final test to verify the upper operating intensity limit for the beam into the gas catcher is imminent. In spite of this one unanswered question, it is clear that the gas catcher already meets expectations for a majority of the scientifically interesting rare isotopes.

The driver can also accelerate the light ions required to produce exotic isotopes through the ISOL technique. Isotopes of interest are created via the process of spallation or by fission. The isotopes diffuse from the target material and effuse to an ionizer. Both processes are enhanced if the target is maintained at elevated temperatures. A major technological challenge is to develop targets that are small enough to release short-lived exotic isotopes rapidly and yet capable of operating with the 400 kW beam power that the driver accelerator can provide and which the scientific program requires. For optimal operation, it is essential that regardless of the beam power, the target material be maintained at an elevated temperature (typically 1200 to 1600°C) in order to speed diffusion of the ISOL-induced rare isotopes; high efficiency requires good thermal conductivity in the target to maintain a uniform temperature. The yield of exotic isotopes is proportional to the intensity (power) of the driver beam. Target developments at the Isotope Separator and Accelerator (ISAC) have shown that the technology exists to handle 50 kW beam powers effectively.

DOE-funded R&D has modeled various target-design concepts that could potentially operate at these substantially higher powers. One of the schemes is being tested and offers significant advantages for both the production of neutron-rich exotic beams and the suppression of unwanted isotopes. In this approach the exotic isotopes are created by the ISOL technique via two-step neutron-induced fission. In essence there are two targets combined into one unit. A primary target is used to produce neutrons. A secondary target, an actinide compound, uses the neutrons to produce the exotic beams by a fission reaction. The beam power from the driver accelerator can be deposited in a target that is adequately cooled to handle the power. The secondary target has much less deposited power and can be

[2]Unpublished; private communication to the committee from Jerry Nolen, Argonne National Laboratory, February 11, 2006.

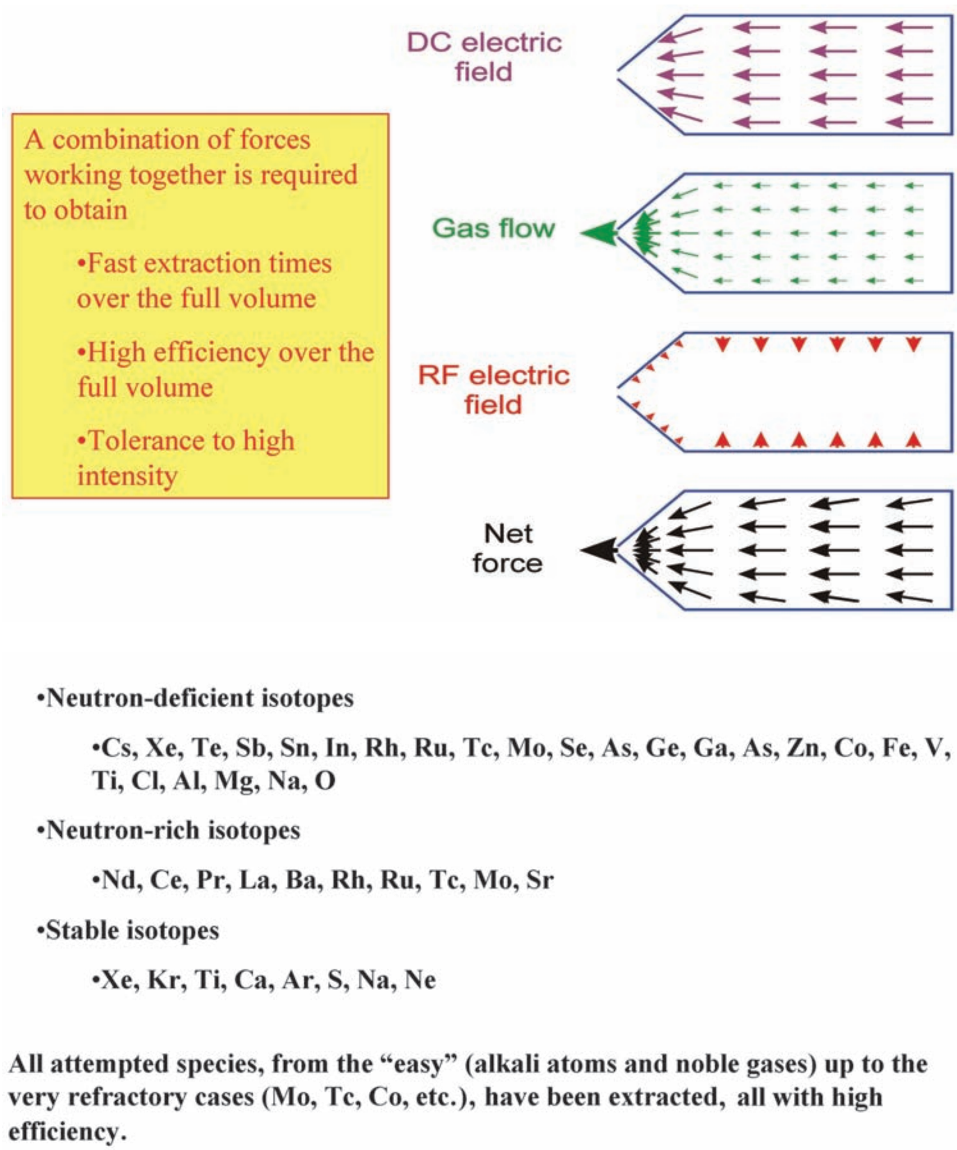


FIGURE 4.4 Composite figure showing the various force fields at play in a gas catcher design and a list of the various ions that have been extracted. The principal uncertainty in gas catcher performance is its efficiency when a high flux of ions is present in the catcher. Courtesy of Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

maintained at the required elevated temperatures using conventional ISOL target-heating techniques.

Radiation control, activation reduction, contamination control, and remote handling are essential considerations for a FRIB facility. The end-to-end simulations developed for the RIA accelerator have been effectively addressing these issues. In spite of the large currents, beam loss in the driver accelerator, with the exception of the stripper and target locations, has been minimized to permit hands-on maintenance. Remote-handling procedures have been considered where required. Initial layouts of target servicing have included consideration of how best to address these issues.

A postaccelerator concept has been developed that would efficiently capture and accelerate the broad range of scientifically interesting isotopes (from lightest to heavy masses) that could be produced in the FRIB. The requirements as a whole dictate a novel design. The accelerator must accept singly-charged isotopes (large charge-to-mass ratio range), operate in a continuous-wave mode, and provide an output energy that can be continuously varied over the entire energy range. Ongoing developments at the U.S. rare-isotope beam facilities are developing and using the accelerator beam diagnostics that are required to monitor the beam characteristics over the large dynamic range of currents that will be used.

As mentioned in the beginning of Chapter 1, in the course of this committee's deliberations the scope of RIA was reduced and the start of construction delayed. Fortunately the technology under development for RIA appears to be directly applicable to the reduced-scope FRIB. The significant technical advances are listed below.

The technical concepts to go into the U.S. FRIB have evolved and been strengthened through a vigorous national R&D program that has been ongoing for about 10 years at several national laboratories and universities in the United States,[3] in many cases leading to strong, multi-institutional collaborations. In recent years, the RIA R&D program of the DOE's Office of Nuclear Physics has been funded at the level of $2.8 million, $4 million, $6 million, $6.5 million, and $4 million in fiscal years (FY) 2002 through 2006, respectively. The current plan is to continue with R&D for advanced exotic-beam facilities at roughly the present level in the coming years. The direct DOE programmatic funding of RIA/FRIB R&D has been leveraged with significant contributions via discretionary programs at several of these institutions.

[3]Primarily Argonne National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Colorado School of Mines, Los Alamos National Laboratory, Michigan State University, Oak Ridge National Laboratory, and Texas A&M University.

Major milestones achieved through this R&D program include the following:

- *Electron cyclotron resonance ion source*—The necessary intensities of heavy ions have been demonstrated.
- *Driver linac beam dynamics*—The multiple-charge-state, high-intensity mode of operation of the driver linac has been simulated in detail.
- *Superconducting RF resonators*—Prototype resonators to cover the necessary velocity regime from 0.02 c to 0.8 c have been demonstrated at the gradients required for the driver.
- *Driver linac front end*—Engineering concepts have been developed for the room-temperature injector including the low-energy bunching and RFQ for two-charge-state operation.
- *High-power production targets*—The liquid-lithium target concept for uranium beams has been demonstrated at equivalent power using an electron beam. Detailed production rates and thermal simulations have been completed for a high-power two-step ISOL target.
- *Large-acceptance fragment separators*—Concepts for optical solutions and physical layouts for both the in-flight and gas catcher branches have been developed.
- *Gas catcher for rare isotopes*—The gas catcher concept has been demonstrated at a range of energies, including the full-energy test at GSI.
- *Radiological issues and concepts in the production areas*—Preliminary concepts for the physical layouts and remote-handling options, including proposals for high-power beam dumps for both the ISOL and fragmentation areas have been developed.
- *Rare-isotope postacceleration*—Alternatives for postacceleration with emphasis on high efficiency and beam quality have been worked out.
- *Experimental facilities*—User workshops have led to tentative layouts that incorporate the necessary instruments for rare-isotope research in the four required energy regimes.

Ongoing R&D needs include further development of engineering prototypes in many of these areas in order to address issues such as radiation resistance, accelerator diagnostics, instrumentation, and fast controls necessary for fail-safe high-power operations; stripper foil development; further development and demonstration of gas catcher operation at higher intensities; and more detailed concepts for advanced instrumentation for research with rare isotopes.

As mentioned in Chapter 1, the Department of Energy decided not to address the construction of a facility for rare-isotope beams for 5 years and reduced the budget of the facility by roughly half. The two proponents for the facility, the

Argonne National Laboratory and Michigan State University (MSU), provided the committee with quick-turnaround presentations on how they would reduce the cost of the facility to meet the new DOE target. Both parties chose to reduce the energy of the driver accelerator by a factor of two, so that the new driver would provide approximately 500 MeV protons and 200 MeV/A uranium. The ANL presentation focused on complementing the main driver with an extensive ISOL program, while the MSU presentation favored the use of fast beams from fragmentation of the heavy ions from the driver with a small ISOL component. These presentations to the committee of course were not formal proposals, but they included some data on the projected reduced performance that were used in making the comparisons presented in the following section, "Global Context for a U.S. FRIB."

The committee examined the reduction in scope given that a FRIB was defined to cost only about half as much as RIA. The central issue revolves around what one means exactly by "scope." If it is taken to mean simply the reduction in the number and intensity of rare isotopes that can be produced, then the options initially shared with the committee (by ANL and MSU, the former proponents of and hopeful sites for RIA) of cutting the maximum energy of the heavy-ion accelerator back to 200 MeV/A (from 400 MeV/A) have the following consequences. For the production of many isotopes, typically those not far from stability, there is only modest reduction (0 to 20 percent) in production rates. However, for those isotopes farthest from the valley of stability, which are produced by in-flight fission, the loss is much larger. In these cases, the production rates for a 400 MeV/A, 400 kW driver are more than an order of magnitude higher than a 200 MeV/A, 400 kW driver because yields for ions far from the beam (particularly for fission fragments) drop rapidly with the available beam energy owing to overall collection efficiency and secondary production in thick targets. In terms of scientific impact, the study of very-neutron-rich nuclei near the drip line in the mass 70 to 120 range would be most significantly affected. There would appear to be no way to develop a technical solution to this shortcoming without increasing the driver energy and the cost.

Analyzing the two strawman proposals further, however, the committee observed that the proponents had tried to preserve as much of the isotope-production capability as possible, in exchange for cutting back the experimental capabilities—research space, multiplicity of end stations, and overall flexibility. These factors are critical to research productivity and user "throughput."

Given the ambiguity and uncertainty that this issue entails together with the limited information and time available, the reduction in scope (and its impact) is uncertain. Based on information from ANL, reducing the driver energy by a factor of 2 accounts for about 60 percent of the $600 million cost reduction. Savings were also assumed by proposing that a larger acceleration gradient be used in the accelerator, thereby recovering some of the energy while still "shortening" the accelerator. The other reductions were in the experimental areas, so the reduced-scope facility could only provide beam to one user at a time, and the budget for experimental equipment would be reduced from $100 million to $30 million.

The committee also considered the DOE-proposed delay in schedule for a U.S. FRIB. Understanding and predicting the consequences of a delayed start date are even more difficult than anticipating the effects of budget reduction because of all the uncertainties that the future holds for any area of science. There are both advantages and disadvantages to a later schedule. For instance, on the one hand an extreme precautionary stance would argue that all delays ultimately result in a more technologically advanced facility. On the other hand, prolonged delays in starting a project can eventually render it meaningless because the expert community could wither away, the scientific objectives could be achieved elsewhere, or the global perception of the United States as a credible and serious partner in the field could crumble.

GLOBAL CONTEXT FOR A U.S. FRIB

The primary impact of the proposed schedule delay for a U.S. FRIB relative to the original RIA timeline is shown in Figure 4.5. As illustrated, the reduced scope for a FRIB will also have an effect on the U.S. capabilities in the global effort: instead of arriving early on the science scene with a new facility, the United States might arrive last with a FRIB, although the facility could have unique capabilities compared to other facilities available at that time. Clearly, the major national user facilities in the United States (the National Superconducting Cyclotron Laboratory at MSU and the Holifield Radioactive Ion Beam Facility at the Oak Ridge National Laboratory) are now competitive with the world's other leading facilities and thus are extremely important. Worldwide coordination of the use of all these facilities by the United States and its partners should be pursued to optimize science outcomes. Exemplifying the need for such coordination, the NSAC subcommittee, comparing RIA and the Facility for Antiproton and Ion Research (FAIR) at GSI and placing a special emphasis on the U.S. and German communities that it studied, found that the upgraded facilities at GSI would not be sufficient to meet the combined global demands for access to such rare-isotope beams.

The geographical, representative distribution of projected major rare-isotope beam facilities is seen in Figure 4.6. In the report by the Working Group of Nuclear Physics of the Organisation for Economic Co-operation and Development (OECD) Megascience Forum, published in January 1999, the major recommendations stated, "the Working Group recognizes the importance of radioactive nuclear

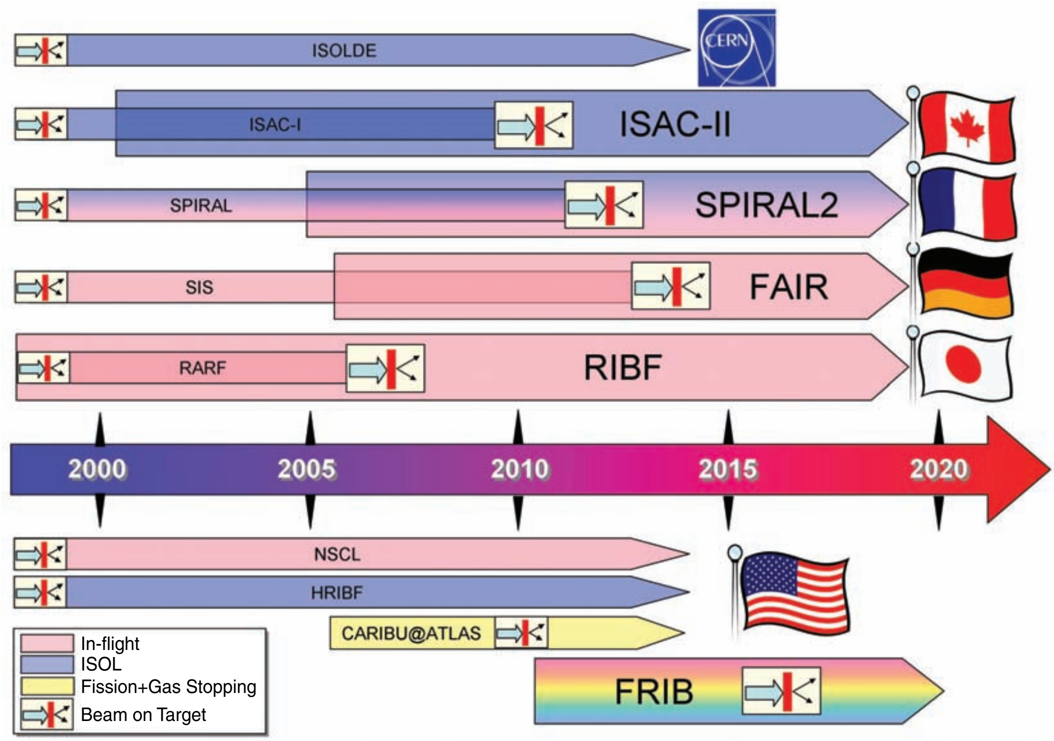


FIGURE 4.5 Timeline for the global development of dedicated rare-isotope beam facilities; the unique capabilities of each facility are slightly oversimplified to allow for this cartoon comparison. The "beam-on-target" date approximates the date on which the facility began (or is scheduled to begin) operations. To a certain extent this diagram is misleading because it portrays only the largest facilities. The fact that countries such as Brazil and India are building small, dedicated facilities is perhaps a better demonstration of the worldwide interest in rare-isotope beam physics. They may not be able to compete in the short term, but they have recognized the relevance and are working to invest a substantial fraction of their resources into the development of their own facilities. NOTE: ISOLDE—On-Line Isotope Mass Separator; ISAC—Isotope Separator and Accelerator; SPIRAL—Système de Production d'Ions Radioactifs en Ligne; SIS—Heavy Ion Synchrotron; FAIR—Facility for Antiproton and Ion Research; RARF—RIKEN Accelerator Research Facility; RIBF—Rare-Isotope Beam Factory; NSCL—National Superconducting Cyclotron Laboratory; HRIBF—Holifield Radioactive Ion Beam Facility; CARIBU—Californium Rare Isotope Breeder Upgrade; ATLAS—Argonne Tandem Linear Accelerator System; FRIB—Facility for Rare-Isotope Beams; ISOL—Isotope Separator On-Line.

FIGURE 4.6 Representative distribution of projected major facilities for rare-isotope beams. The location of a facility for rare-isotope beams within the United States has not been determined and is therefore placed arbitrarily in the center of the country. NOTE: FRIB—Facility for Rare-Isotope Beams; HRIBF—Holifield Radioactive Ion Beam Facility; NSCL—National Superconducting Cyclotron Laboratory; ISOLDE—On-Line Isotope Mass Separator; GANIL—Grand Accélérateur National d'Ions Lourds; GSI—Gesellschaft für Schwerionenforschung; TRIUMF—Tri-University Meson Facility.

beam facilities for a broad program of research in fundamental nuclear physics and astrophysics, as well as applications of nuclear science. A new generation of radioactive nuclear beam facilities of each of the two basic types, ISOL and In-flight, should be built on a regional basis."[4] This conclusion was based on the recognition that, unlike a field such as particle physics in which facilities can be targeted and optimized for finding answers to a specific question (or two), nuclear science requires a very large number of systematic studies.[5] Hence, progress in this

[4]OECD Megascience Forum, *Report of the Study Group on Radioactive Nuclear Beams to the Working Group on Nuclear Physics*, Paris, France: OECD Megascience Working Group on Nuclear Physics, 1999, p. 39.

[5]The reader may recall from the section entitled "Technological Context" in Chapter 1 that the ISOL method provides high-quality beams from low up to, in principle, high energies. However, it has a limitation for the acceleration of short-lived isotopes owing to the finite release time of radioactive nuclei from the production target and transfer time to the ion source. The present practical limit is on the order of 10 to 100 milliseconds. The in-flight method provides the fastest separation time, on the order of 100 nanoseconds, that is, the flight time of the radioactive nuclei in the fragment separator. Therefore, not only drip-line nuclei but also many isomers can be produced by

field is limited not only by the range ("exoticity") of nuclei available but also by the beam time available for experiments.

Rare-isotope science (and even nuclear physics in general) is no stranger to the march toward globalization—and the efforts to coordinate worldwide plans to address and exploit the most compelling scientific opportunities.[6] Indeed, as discussed above, considerations about global coordination and cooperation in nuclear physics have infused recent meetings of the OECD Global Science Forum (formerly the Megascience Forum) and the European Science Foundation's Research Infrastructure Council.[7] As the U.S. nuclear science community undertakes the next cycle of its long-range planning process through NSAC, it will have to address these issues carefully.

The original RIA design was intended to be a world-leading facility in nearly every regard. If a FRIB were constructed in the United States, however, the facility could be world leading in several areas, thereby adding value to both the regional and the global portfolios. Nevertheless, as described above, the usage of the other regional facilities included in Figures 4.5 and 4.6 should be investigated until a new U.S. rare-isotope facility would be in operation (approximately 10 years from now). The U.S. rare-isotope research community, in concert with the DOE and NSF, needs to establish an appropriate balance of usage of domestic and overseas facilities.

The committee briefly examined global "supply" of and "demand" for rare-isotope beams. As noted above, at face value the demand for rare-isotope beams seems strong, given the new large investments being made in Europe and Asia as well as the many smaller projects (described in Appendix C). Within the United

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this method. However, the quality of the beams is limited, and in particular, a low-energy beam of high quality is difficult to obtain at all. This problem can be circumvented if one applies accumulation and cooling techniques, but the cooling process takes time, thereby limiting the usable lifetime above about 1 second with the present techniques. Therefore, at the present time, both types of beam-preparation techniques are in use around the world.

[6]For a general discussion, see National Academy of Sciences (NAS), National Academy of Engineering (NAE), and Institute of Medicine (IOM), *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, Washington, D.C.: The National Academies Press, 2007; for an example of a specific analysis, see National Research Council, *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics*, Washington, D.C.: The National Academies Press, 2006.

[7]Nuclear Physics European Collaboration Committee of the European Science Foundation, *Roadmap for Construction of Nuclear Physics Research Infrastructure in Europe*, Strasbourg, France: European Science Foundation, 2005.

States, the anticipated user community for RIA numbers about 800 researchers; as noted above, FAIR, Système de Production d'Ions Radioactifs en Ligne (SPIRAL) 2, ISAC, and the Rare-Isotope Beam Factory at RIKEN together will serve a community of more than 2,000 users. Although these populations often overlap, the committee observes that the facilities in Asia and Europe are not likely to be able to provide access to the full U.S. community.[8] In general terms, the NSAC subcommittee comparing RIA and GSI came to a similar conclusion.[9] Finally, the committee notes that the ISAC facility in the American region reports an "oversubscription" rate that forces many users with approved proposals to wait more than a year to obtain access to conduct their experiments.

AN OPPORTUNITY FOR THE UNITED STATES

The technical developments at many of the laboratories cited make construction feasible for a FRIB with a flexible driver that can accelerate ions from protons to uranium nuclei. Those same developments would also permit the effective reacceleration of stopped charged radioactive ions. This combination with supporting technology, such as a gas catcher capable of efficiently extracting exotic ions at high incident beam-power levels, would make a FRIB potent and flexible. The higher intensity of beams created by heavy-ion fragmentation would allow the investigation of nuclei closer to the neutron drip line. The lower energy of a FRIB relative to RIA could use the gas catcher technique more easily (if the technique can handle the higher intensity).

To be more specific, consider the utility of a FRIB for addressing the scientific drivers discussed in the following subsections. Making specific predictions about the advance of scientific progress is fraught with uncertainty (especially 10 years into the future when a FRIB might come online), but it is the committee's judgment that the scientific agenda outlined in this report is likely still to be viable at that time.

[8]Indeed, a 1998 Nuclear Science Advisory Committee estimate of the full rare-isotope beam community suggested the following breakdown: about 700 in North and South America, 500 in the European Union, 600 in Central and Eastern Europe, 700 in Japan, China, and India, and several hundred from other parts of the world.

[9]U.S. Department of Energy, *NSAC Subcommittee on the Comparison of RIA and the GSI Project Opportunities and Capabilities*, Washington, D.C., February 2004, p. 28.

Nuclear Structure

A FRIB has a variety of applications for nuclear structure science.

- *Single- and two-nucleon transfer reactions for studying shell structure.* This research traditionally needs beams (in inverse kinematics) corresponding to light projectile energies (p, d, He . . .) of typically 15 to 20 MeV and so historically has not easily been performed at in-flight facilities; in recent years, however, many experiments have been successful with higher energies. The whole area of study of shell structure is best done with well-focused beams with precisely controlled energies, especially if the strength is fragmented and the detailed structure is important.

  The intensities expected at a FRIB for beams such as ^{100}Sn, ^{48}Ni, ^{78}Ni, and ^{132}Sn are on the order of 35, 0.5, 40, and 2×10^{10} ions per second, respectively. These are typically two to three orders of magnitude above what is currently available.
- *Research in pairing.* Two-nucleon transfer studies to probe pairing properties can be carried out at a FRIB within a week, with beam intensities of 10^4 ions per second. For specifically N = Z nuclei, experiments with ^{56}Ni, ^{64}Ge, ^{72}Kr, and the heavier N = Z nuclei up through ^{88}Ru and probably ^{92}Pd will be possible.
- *Researching collectivity.* Collective motion in nuclei can be investigated in a variety of ways. Some aspects of collective behavior require fragmented beams, while others require low-energy reaccelerated beams. For example, collective modes of excitation near the ground state are often best studied with single or multiple Coulomb excitation. Multiple Coulomb excitation requires beams of $\sim 10^3$ to 10^4 ions per second in inverse kinematics and is better suited to a reaccelerated beam. This kind of experimental data is an excellent way to deeply map out nuclear structure along long iso-chains.
- *The heaviest nuclei.* For example, intense beams of ^{132}Sn on neutron-rich targets at controlled energies of, and slightly below, the Coulomb barrier could be used to study the reaction mechanisms governing fusion and multineutron transfer. In favorable cases in which the intensity of the rare isotope is large (^{90,92}Kr, ^{90,92}Sr $>10^{11}$ ions per second), fusion reactions become feasible with reaccelerated beams of high intensity and precise energies.
- *Neutron skins.* The measurements of nuclear matter radii will involve optical model analysis of the (quasi) elastic scattering data. Those scattering experiments (involving protons or alpha particles) often require reaccelerated beams of high intensity and precise energies.

Nuclear Astrophysics

Accretion-induced thermonuclear explosions, such as novae and x-ray bursts, are driven mainly by the hot carbon-nitrogen-oxygen cycles and/or the rapid proton-capture process (rp-process). Most of these reaction sequences are based on theoretical model predictions and assumptions regarding the associated nuclear reaction processes. These assumptions may lead to significant uncertainties in reaction path, reaction flow, energy production, and timescales. Most important to measure are nuclear structure parameters far off stability, such as masses, level-densities, half-lives, decay branchings on rp-process to rapid-neutron-capture-process (r-process) nuclei, but also critical are particular reaction rates for so-called waiting-point nuclei, which in many cases are not uniquely identified yet. The field is haunted by these underlying uncertainties, which make it difficult to pinpoint the "key reaction" clearly at this time.

Measurements in nuclear astrophysics at a FRIB would mostly be associated with explosive stellar processes at timescales less than or comparable to typical beta-decay lifetimes. At these conditions, reaction sequences are far off stability and depend critically on the timescales of the associated nuclear processes.

Shock-front-induced explosions (such as those anticipated for core collapse supernovae) are expected to be important sites for the r-process and possibly antineutrino production. The latter would be generated by charge-exchanging on protons to build up elements on the neutron-deficient side of the line of stability, complemented by the neutron-induced r-process and the gamma-induced p-process.

Fundamental Interactions

There is not a readily envisioned program of research on fundamental interactions but rather a series of experiments, each of which addresses some aspect of fundamental physics at the existing limit of knowledge at the time of the different experiments. Fundamental interaction studies usually involve the measurement of very weak effects in very specific nuclei. Thus, the critical requirement is intensity and purity, that is, a maximum yield of the isotopes of interest and the absence of contaminants. Precision tests of fundamental symmetries are often limited by statistical uncertainties, and therefore experiments need to collect high volumes for data, typically running for extended periods of time. Thus, multiuser beam-sharing and isotope-harvesting facilities would be needed to enable efficient use of accelerator time. These applications also usually require specialized instrumentation, such as laser facilities.

The highest intensities always come from isotopes that can be extracted by the ISOL technique, not from gas stopping. For those species, the FRIB concept yields intensities higher than any other facility and a broader range of isotopes because of the variety of production beams available.

If gas stopping is required, the number of incident particles generating the exotic species of interest is always the main issue. In this area, the driver of a FRIB always surpasses any other existing or proposed driver, certainly when heavy-ion beams are considered. The lower energy is also an advantage over facilities such as FAIR, since less energy per particle is lost in the gas catcher, which allows it to operate at higher intensity without space-charge limitations.

For most of the periodic table, a FRIB would have instantaneous intensities that were at worst 70 percent of the RIA intensities (in most cases they would be the same). Only in the region where in-flight fission dominates production would the yield be lower (~30 percent of RIA).[10] This is the region of neutron-rich nuclei around ^{132}Sn where no case for fundamental interaction studies has been identified thus far.

Applications of Rare-Isotope Science

It is likely that much of the nuclear physics currently desired for stockpile stewardship and inertial fusion will remain unknown until dedicated experiments at a FRIB-like facility are conducted. Other current U.S. facilities have neither the low-energy exotic beams nor the motivation to measure the important cross sections relevant to these processes. This may also hold true for some of the measurements relevant to the advanced nuclear fuel cycle where the reach of the surrogate method at a FRIB may provide some of the needed cross sections on short-lived isotopes.

As indicated in Chapter 2, the impact of a FRIB on medical research and industrial processes has considerable potential. However, the actual incorporation of FRIB science results into these endeavors depends on so many external factors that it is impossible to predict the outcomes.

PROGRAMMATIC CONSIDERATIONS

The Context of the Nuclear Physics Portfolio

The scientific agenda of nuclear science in the United States contains a diversified portfolio with a triad of research frontiers: (1) quantum chromodynamics

[10]These estimates of FRIB capability were presented by proponents from ANL and MSU in presentations to the committee and were judged adequate by the committee.

(QCD) and its implications for the state of matter in the early universe, quark confinement, the role of gluons, and the structure of hadrons; (2) the study of nuclei and astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) the Standard Model and its possible extensions as they bear on the properties of neutrinos, neutrons, and other subatomic particles.

U.S. nuclear scientists employ a broad range of facilities to carry out the research programs described above. The two major facilities, the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and the CEBAF Large Acceptance Spectrometer detector at the Thomas Jefferson National Accelerator Facility, are dedicated to probing the consequences of QCD for hot and cold strongly interacting matter. These two relatively new world-class facilities are likely to remain at the forefront of nuclear physics for the foreseeable future.

At present, individual DOE and NSF low-energy facilities carry out the program in nuclear structure and astrophysics. A community of nuclear physicists proposes to build a world-class FRIB to strengthen and focus the present activities and to exploit new scientific opportunities. Complementary to this activity is a set of new and challenging experiments in fundamental physics carried out at a variety of facilities—some of which are abroad. Within the United States, the advent of the Spallation Neutron Source and the prospect of building the Deep Underground Science Engineering Laboratory offer new opportunities for nuclear physicists pursuing these lines of research.

The construction of a U.S. FRIB of the capability discussed in this report would align the national nuclear science agenda with world-class facilities in each of its three frontiers. This is a sound strategy for maintaining a balanced program and one that would likely put the U.S. nuclear science agenda in a unique leadership position worldwide. For the United States to effectively utilize its investment in world-class facilities, support for nuclear science at U.S. universities must be strengthened to increase the participation of young researchers. Otherwise, the cost of operating world-class facilities could put additional pressure on the already-tight research budget in nuclear physics, which creates and develops the needed young researchers.

Education, Training, and Workforce in Nuclear Science

An NSAC subcommittee on education recently issued a comprehensive report entitled *Education in Nuclear Science,* after a 2-year study that included extensive surveys among undergraduate and graduate students, postdoctoral fellows, and recent Ph.D.'s 5 to 10 years after receiving their doctorates. One of its key recommendations deals with Ph.D. production of nuclear physicists: "We recommend that the nuclear science community work to increase the number of new Ph.D.'s in nuclear science by approximately 20% over the next five to ten years."[11] This recommendation was based on an analysis of the current demographics of the field and a projection of future demand using expected retirements and growth in university and laboratory staff with expertise in nuclear physics. These general expectations, however, are difficult to connect with the specific case of a U.S. FRIB.

The demand for increasing the production of nuclear scientists and engineers comes at a time when much of the existing basic-research and applied-technology nuclear workforce is approaching retirement. Indeed, *Nuclear Regulatory Commission News* reported that an estimated 76 percent of the nuclear engineering workforce (in industry) will be at retirement age during the period from 2000 to 2010.[12] This projection does not directly affect the anticipated U.S. basic-research community for a FRIB, but it does highlight the important leverage that nuclear physics graduate-training programs have on the much larger industry of nuclear energy. For instance, the aforementioned NSAC report found that up to two-thirds of the recipients of recent nuclear physics Ph.D.'s were employed outside the university and national laboratory system of basic research.

As exciting forefront research opportunities attract the best young minds, the construction of a world-class FRIB in the United States would certainly enhance the nation's capability for attracting Ph.D. candidates to low-energy nuclear physics. It would allow for the training of scientists with hands-on experience in experimental nuclear science at a time when many accelerator facilities at universities have been ramped down or closed. The committee notes that the construction and operation of a large facility is not, in general, a recipe for revitalizing the education and training aspects of a basic-research program. The future NSAC long-range planning committee will need to evaluate how best to maintain the vitality of the U.S. nuclear physics community while best deploying it to address the most compelling science.[13] Without a forefront facility at which nuclear physicists are engaged in exciting research, it will be hard to attract able students to the field.

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[11]DOE/NSF Nuclear Science Advisory Committee, *Education in Nuclear Science: A Status Report and Recommendations for the Beginning of the 21st Century*, Washington, D.C., 2004, p. vii.

[12]Speech by the Honorable Greta Joy Dicus, Commissioner, U.S. Nuclear Regulatory Commission, "Keynote Address on Structural Mechanics in Reactor Technology," at the 2001 U.S. Women in Nuclear Science Annual Workshop, St. Pete Beach, Florida, August 20, 2001.

[13]The nuclear physics community is not alone in facing this issue. Elementary-particle physics has embraced one solution, described in the National Research Council report *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics* (Washington, D.C.: The National Academies Press, 2006). The U.S. fusion science community is addressing this issue in a planning process described in an unpublished report of the U.S. Burning Plasma Organization: *Plan for U.S. Fusion Community Participation in the ITER Program.*

Moreover, students trained in the science that drives a new FRIB fill an important niche in the national need for nuclear scientists. These scientists have already made innovative contributions in many areas such as nuclear medicine, stockpile stewardship, homeland security, and nuclear energy.

In a final note, the committee considered the broader impact of a U.S. FRIB in light of the national attention on economic competitiveness, recently highlighted in a report by the National Academies—*Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.*[14] The report argued that strong public support of basic research can help fuel the national economic engine; one of the suggested pathways was through technological developments that occur as part of the progress of science and engineering. While it is nearly impossible to argue that any one specific investment is critically necessary to maintaining the future health of the enterprise, the committee does recognize the value of a U.S. FRIB as one element of a much broader portfolio in the physical sciences.

[14]NAS, NAE, and IOM, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, Washington, D.C.: The National Academies Press, 2007.

5

Findings and Conclusions

A new era is beginning in low-energy nuclear physics research with the advent of facilities capable of providing beams of radioactive, or unstable, atomic nuclei. These exotic nuclear species can be studied themselves or used to induce nuclear reactions to access still-more-exotic nuclei. These new developments can open up new frontiers in nuclear physics research—both basic and applied.

POLICY CONTEXT

The Rare-Isotope Science Assessment Committee (RISAC) was charged by the National Research Council, the Department of Energy (DOE), and the National Science Foundation (NSF) to define a scientific agenda for a U.S.-sited facility for rare-isotope beams (see Appendix A for the charge). A U.S. Facility for Rare-Isotope Beams (FRIB) was identified as a priority in the 2002 long-range plan of the DOE/NSF Nuclear Science Advisory Committee (NSAC), in which it was further ranked as the "highest priority for new construction" and the second overall (after support of the operating facilities, the Relativistic Heavy Ion Collider [RHIC], the CEBAF Large Acceptance Spectrometer Detector at the Thomas Jefferson National Accelerator Facility, and the National Superconducting Cyclotron Laboratory, and the university research programs). A large and active segment of the nuclear physics community has worked to develop a scientific case in support of a version of a FRIB called the Rare Isotope Accelerator (RIA). Two strong efforts by groups interested in hosting RIA have developed facility plans and the required technology for a U.S. FRIB. These groups had developed impressive technical plans with significant similarities, each incorporated a 400 MeV/A superconducting radio-frequency linear accelerator driver and capabilities to produce rare isotopes by in-flight fragmentation, the traditional Isotope Separator On-Line (ISOL) technique, and gas stopping and reacceleration. The expected cost of either facility was about $1.1 billion.

After RISAC began its work, the DOE announced that it intended to pursue a FRIB at about half the cost, with funds for project-engineering definition not to begin until 2011. In response to these new guidelines for a U.S. FRIB, both groups pursuing a FRIB presented the committee with new plans for a smaller facility based on a 200 MeV/A linear accelerator (linac) and somewhat reduced experimental capabilities. Although the committee could not review these preliminary design concepts in detail, it is important to note that both plans significantly scaled back the multiuser capabilities of the facility in order retain as much of the intensity and diversity of rare isotopes as possible. Thus, the suggested designs for a FRIB would have much reduced access compared with that of the earlier RIA proposals. However, this revised approach could engender a useful series of upgrades. While arguments can be mustered about the dire consequences of delay, experience shows that it is not always a bad choice, especially when accounting for the uncertainties in any predictions about the future of science. For these reasons and because it lay outside the charge, the committee chose not to specifically evaluate the consequences of the proposed change in schedule. Healthy stewardship of the U.S. nuclear science community and continued exploitation of the key scientific opportunities will be matters that NSAC will need to consider carefully in its next long-range plan.

In response to these events and the charge, the committee proceeded to assess the science that could be accomplished with a reduced-scope FRIB as described by the proponents, taking account of the time frame consistent with a 2011 start for engineering definition. The committee was not charged to recommend a specific facility or to make recommendations about the utility of a FRIB in comparison with other possible initiatives for U.S. nuclear science. Indeed, a new long-range planning process for nuclear science will begin in 2007, and the community will have the opportunity to assert its priorities.

SCIENTIFIC CONTEXT

Nuclear structure physics as pursued at a FRIB aims to describe nuclei as a collection of neutrons and protons. Current theoretical approaches are much more powerful than the pioneering models developed in the 1940s and 1950s. The nuclear structure approach is still the most appropriate way to understand much of nuclear physics from ordinary nuclei to neutron stars. Understanding nuclear matter in this regime is of great interest to nuclear astrophysicists and to experimentalists who attempt to exploit the atomic nucleus as a laboratory for fundamental interactions. For instance, a better characterization of nuclear structure will play an essential role in correctly extracting the true nature of the neutrino's mass from neutrinoless double-beta-decay experiments now in development. This is a fundamental issue with significant implication for physics beyond the Standard Model. Beginning more than a decade ago, the U.S. nuclear structure community, along with colleagues interested in important problems in nuclear astrophysics and the fundamental interactions, proposed that a new rare-isotope accelerator be built in the United States. This facility would produce a wide variety of high-quality beams of unstable isotopes at unprecedented intensities. The proponents of a FRIB argue that the science goals driving these subjects, and nuclear structure in particular, require a new class of experiments to elucidate the structure of exotic, unstable nuclei to complement the studies of stable nuclei that had been the primary focus of the subject in the past century. A facility with this capability could also provide critical information on the very unstable nuclei that must be understood in order to help explain the origin of the nuclear abundance observed in the universe. This facility would produce abundant samples of specific isotopes, which can serve as laboratories for studying fundamental symmetries and for applications.

RESPONSE TO THE CHARGE

As stated in its charge, the committee was asked to "define a scientific agenda for a U.S. domestic rare-isotope facility taking into account current government plans."

The committee concludes that a next-generation, radioactive-beam facility of the type embodied in the U.S. FRIB concept represents a unique opportunity to explore the nature of nuclei under conditions that previously only existed in supernovae and to challenge our knowledge of nuclear structure by exploring new forms of nuclear matter. While a facility capable of intense beams of a wide variety of radioactive nuclei will clearly impact many areas of science and technology, the committee identified several key science drivers.

- *Nuclear structure.* A FRIB would offer a laboratory for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a more broadly applicable theory of nuclei will emerge. A FRIB would allow the investigation of new forms of nuclear matter such as the large neutron excesses occurring on the surfaces of nuclei near the neutron drip line, thus offering the only laboratory access to matter made essentially of pure neutrons. A FRIB might lead to breakthroughs in the ability to fabricate the neutron-rich superheavy elements that are expected to exhibit unusual stability in spite of huge electrostatic repulsion.

- *Nuclear astrophysics.* A FRIB would lead to a better understanding of nuclear astrophysics by creating exotic nuclei that, until now, have existed only in nature's most spectacular explosion, the supernova. A FRIB would offer new glimpses into the origin of the elements, which are mostly produced in processes very far from nuclear stability and which are barely within reach of present facilities. A FRIB would also probe properties of nuclear matter at extreme neutron richness similar to that found in neutron star crusts.
- *Fundamental symmetries of nature.* Experiments addressing questions of the fundamental symmetries of nature could likewise be explored at a FRIB through the creation and study of certain exotic isotopes. These nuclei could be important laboratories for basic interactions because aspects of their structure greatly magnify the size of the symmetry-breaking processes being probed. For example, a possible explanation for the observed dominance of matter over antimatter in the universe could be studied in experiments seeking to detect a permanent electric dipole moment in heavy radioactive nuclei.

A successful scientific program in these areas would require significant theoretical input from nuclear structure physicists.

Last but not least, a U.S.-based FRIB facility, capable of producing high-specific-activity samples of exotic isotopes, could contribute to research in the national interest. The applications of rare-isotope technology could influence many areas, including medical research, national security, energy production, materials science, and industrial processes. It would provide an important contribution to the education and training of future U.S. scientists in the physics of nuclei. The aspects of nuclear physics addressed by the FRIB community directly impact the basic-science knowledge base relevant for nuclear reactors and nuclear weapons.

As part of the overall strategy for nuclear science in the United States, the committee believes that the United States should plan for and develop the technologies for a national facility for rare-isotope science of the type embodied in the FRIB concept. The overall scientific priority for this facility will be evaluated in a forthcoming NSAC study developing a long-range plan for the field.

The committee was asked to address the importance that a FRIB would have "in the future of nuclear physics, considering the field broadly."

It is useful to recall the primary mission of nuclear science: "To explain the origin, evolution and structure of the baryonic matter of the universe."[1] Clearly restrained by its charge (see Appendix A), the committee did not evaluate the relative importance of a FRIB compared with other major initiatives in nuclear physics. However, the committee does comment here on the role that a FRIB would play in the future of the field.

Nuclear science of the 21st century tackles this question through three broad and complementary research frontiers: (1) the exploration of quantum chromodynamics and its implications and predictions for the origin of matter in the early universe, quark confinement, the structure of hadrons, and the nature of strong force; (2) the study of nuclei and nuclear astrophysics, which explores the structure and limits of nuclei, the origin of the elements, and the evolution of the cosmos; and (3) the formulation of the Standard Model and its possible extensions as they are manifested in the properties of neutrinos, neutrons, and other subatomic particles. These three frontiers, and the facilities that explore them, are the pillars of the field. In order to make progress on a broad front, investments are needed in all three areas. The modern nuclear physics facilities RHIC and CEBAF provide the state-of-the-art experimental tools for addressing the first of these nuclear science frontiers; FRIB, with its ability to produce groundbreaking research on nuclei far from stability, would provide similar world-class opportunities for the second. Thus, by creating and characterizing a broad range of exotic nuclei, a FRIB would contribute directly to the quest of nuclear physics to understand the multibody phenomena that underpin all nuclei. A variety of instruments and experiments under way or planned will address the third frontier.

The committee believes that studies of nuclei and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Failure to pursue such a capability will not only lead to the forfeiture of U.S. leadership but will likely erode the nation's current capability and curtail the training of future U.S. nuclear scientists. The federal research agencies (primarily DOE's Office of Science and the National Science Foundation) have a responsibility to address the major science questions that the committee has identified; in particular, DOE and NSF as a whole have the responsibility to ensure a competence in nuclear science necessary to support the national interests of the United States.

[1]DOE/NSF Nuclear Science Advisory Committee, *Guidance for Implementation of the 2002 Long Range Plan*, Washington, D.C.: U.S. Department of Energy, 2005.

The committee was asked to address the role of a U.S. FRIB "in the context of international efforts in this area."

Other countries throughout the world are aggressively pursuing rare-isotope science, often as their highest priority in nuclear science, attesting to the significance accorded internationally to this exciting area of research. The remarkable technical innovations developed for RIA appear to be directly applicable to the FRIB concept and could enable the United States to maintain its position among the leaders in this highly competitive field.

The committee concludes that a U.S. facility for rare-isotope beams along the lines presented to the committee would be complementary to existing and planned international efforts. A FRIB would offer unique technical capabilities to the American region. As a partner among equals, a U.S. rare-isotope facility constructed in the next decade could be well matched to compete with the new initiatives in Asia and Europe and would support world-leading scientific thrusts within the United States. Additionally, the committee heard testimony that global "demand" for radioactive beams exceeds projected "supply."

The committee concludes that the science addressed by a rare-isotope facility, most likely based on a heavy-ion driver using a linear accelerator, should be a high priority for the United States. The facility for rare-isotope beams envisaged for the United States would provide capabilities, unmatched elsewhere, that will directly address the key science of exotic nuclei.

Appendixes

A

Charge to the Committee

Following is the charge to the Rare-Isotope Science Assessment Committee from the National Research Council's Board on Physics and Astronomy, the Department of Energy, and the National Science Foundation:

The committee will define a scientific agenda for a U.S. domestic rare-isotope facility, taking into account current government plans. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on nuclear structure, nuclear astrophysics, fundamental symmetries, stockpile stewardship and other national security areas, and future availability of scientific and technical personnel. The need for such a facility will be addressed in the context of international efforts in this area.

In particular, the committee will address the following questions:

- What science should be addressed by a rare-isotope facility and what is its importance in the overall context of research in nuclear physics and physics in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science agenda? What scientific role could be played by a domestic rare-isotope facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

B

Meeting Agendas

FIRST MEETING
WASHINGTON, D.C.
DECEMBER 16-17, 2005

Friday, December 16, 2005

Closed Session

8:00 a.m.	Welcome and Plans for the Meeting —John Ahearne and Stuart Freedman, *Co-Chairs*
8:15	Committee Balance and Composition Discussion —Donald Shapero, Director, Board on Physics and Astronomy (BPA)
9:15	Introduction to the National Research Council (NRC) —Timothy Meyer, Senior Program Officer, BPA
9:30	General Discussion
9:45	Break

Open Session

10:00 a.m.	Perspectives from the Department of Energy (DOE)/ Nuclear Physics —Dennis Kovar, Associcate Director, DOE Office of Nuclear Physics
10:30	Perspectives from the National Science Foundation (NSF)/Physics —Joseph Dehmer, Director, NSF Division of Physics
11:00	Perspectives from the Office of Management and Budget (OMB) —Joel Parriott, Budget Examiner, OMB
11:30	General Discussion
12:00 noon	Lunch
1:00 p.m.	Perspectives from the Office of Science and Technology Policy (OSTP) —Rob Dimeo, Assistant Director, Physical Sciences and Engineering, OSTP
1:30	Nuclear Physics Context of Rare-Isotope Science —James Symons, Lawrence Berkeley National Laboratory, and Chair, DOE/NSF Nuclear Science Advisory Committee (NSAC) Long-Range Planning Report (2002)
2:15	Perspectives from Capitol Hill —Michael Holland, Chairwoman's Staff, House Science Committee
2:45	General Discussion
3:15	Break
3:30	Public Comments from User Groups
4:30	Public Comments from Major Facilities
5:30	Other Public Comments
6:00	Adjourn

Saturday, December 17, 2005

Open Session

8:30 a.m.	International Context of Rare-Isotope Science —Peter Bond, Brookhaven National Laboratory, and Chair, NSAC Rare Isotope Accelerator (RIA)/GSI Comparison Report (2004)
9:00	Discussion

Closed Session

9:45 a.m.	Initial Impressions —John Ahearne and Stuart Freedman, *Co-Chairs*
10:30	Discussion of Work Plan
12:30 p.m.	Lunch
1:30	Adjourn

SECOND MEETING
IRVINE, CALIFORNIA
FEBRUARY 11-12, 2006

Saturday, February 11, 2006

Closed Session

8:30 a.m.	Welcome and Plans for the Meeting —John Ahearne and Stuart Freedman, *Co-Chairs*
8:45	Initial Discussions
9:15	Break

Open Session

9:30	Rare-Isotope Science in the Context of Nuclear Physics —Richard Casten, Committee Member
10:00	Discussion
10:30	The Rare-Isotope Accelerator Facility —Jerry Nolen, Argonne National Laboratory (ANL)
11:00	Discussion
11:45	Lunch
12:45 p.m.	Rare-Isotope Science: Nuclear Structure (Experiment) —Bradley Sherrill, Michigan State University (MSU)
1:15	Rare-Isotope Science: Nuclear Structure (Theory) —Erich Ormand, Lawrence Livermore National Laboratory (LLNL)
1:45	Discussion
2:15	Rare-Isotope Science: Nuclear Astrophysics —Hendrik Schatz, MSU
2:45	Rare-Isotope Science: Astronomy and Astrophysics —John Cowan, University of Oklahoma (by telephone)

3:15 p.m.	Discussion
3:45	Break
4:00	Rare-Isotope Science: Stockpile Stewardship —David Crandall, DOE National Nuclear Security Administration (NNSA)
4:30	Discussion
5:00	Rare-Isotope Science: Fundamental Symmetries —Guy Savard, ANL
5:30	Discussion
6:30	Adjourn

Sunday, February 12, 2006

Open Session

8:45 a.m.	Rare-Isotope Science and Technology: Additional Applications —Larry Ahle, LLNL
9:15	Discussion
9:45	Guidance for Implementing NSAC Long-Range Plan —Robert Tribble, Texas A&M University, and Chair, Report of the NSAC Subcommittee (2005)
10:15	Discussion
10:45	Break
11:00	Perspective on RIA and Nuclear Physics —John Schiffer, ANL, and Chair, 1999 NRC Survey
11:30	General Discussion
12:00 noon	Lunch

Closed Session

1:00 p.m.	Committee Deliberations
4:30	Adjourn

THIRD MEETING
WASHINGTON, D.C.
MARCH 12-13, 2006

Sunday, March 12, 2006

Closed Session

8:30 a.m.	Welcome and Plans for the Meeting —John Ahearne and Stuart Freedman, *Co-Chairs*
8:45	Initial Discussions
9:15	Break

Open Session

9:30	New Developments in Planning for RIA —Dennis Kovar, DOE, and Joel Parriott, OMB
10:30	Two Views on "The Elements of RIA: Options for Staging or Descoping"
10:30	The View from Michigan State University —Konrad Gelbke, MSU
11:00	The View from Argonne National Laboratory —Donald Geesaman, ANL
11:30	Discussion
12:00 noon	Lunch
1:00 p.m.	The Role of Nuclear Structure in the Science Case for RIA —Francesco Iachello, Yale University

Closed Session

2:00	Discussion
6:30	Adjourn

Monday, March 13, 2006

Closed Session

8:30 a.m.	General Discussions
10:00	Break
10:30	General Discussions

11:45 a.m.	Lunch
1:00 p.m.	Adjourn

FOURTH MEETING
VANCOUVER, BRITISH COLUMBIA, CANADA
JULY 14-15, 2006

Friday, July 14, 2006

Closed Session

9:00 a.m.	General Discussion

Open Session

11:00	Perspectives from TRIUMF —Jean-Michel Poutissou, Associate Director, TRIUMF
12:00 noon	Lunch

Closed Session

1:00 p.m.	General Discussions
6:00	Adjourn

Saturday, July 15, 2006

Closed Session

9:00 a.m.	General Discussions

Open Session

12:00 noon	Lunch
1:00 p.m.	Tour of TRIUMF
2:00	Adjourn

C

Selected List of Operating and Planned Rare-Isotope Facilities Worldwide

TABLE C.1 Selected List of Rare-Isotope Beam Facilities: Existing and Near-Term Capabilities in Asia, Europe, and North America

Facility	Region	Country	Type	Driver
BFRIB	Asia	China	ISOL	100 MeV, 200 μA cyclotron
HIRFL at IMP	Asia	China	IF	HI cyclotrons and storage ring and cooler
RARF at RIKEN	Asia	Japan	IF	HI linac and K540 cyclotron and K70 AVF cyclotron
RIBF at RIKEN	Asia	Japan	IF	Cascade of K520, K980, and K2500 HI cyclotrons to 440 (LI) and 350 (very HI) MeV/A
TRIAC at KEK-JAEA	Asia	Japan	ISOL	40 MeV, 3 μA tandem
VEC-RIB	Asia	India	ISOL	K130 cyclotron to 400 keV/A
CRC	Europe	Belgium	ISOL	30 MeV H^- cyclotron to 300 μA
DRIBS at Dubna	Europe	Russia	IF and ISOL	U400 and U400M and U200 HI cyclotrons 100 MeV/A
EURISOL	Europe	European Union	ISOL	Linac providing 1 GeV protons with up to 5 MW and multiple 100 kW targets

Accelerated Rare-Isotope Beams	Status	Comments
SC linac proposed	Construction from 2003	Up to 10 MeV/A for RIB
	Operating driver	1100 MeV/A for ^{12}C and 540 MeV/A for ^{238}U driver
	Operating	Provides intense A < 60 RIBs
Phase II includes degraders, a gas catcher, e-RI collider, polarized RI beams, etc.	Construction	Goal of up to 100 kW of U on target, Phase I operational in 2007, Phase II proposed
18 GHz (CB-ECR) and SC RFQ and IH and SC linacs	Operating	Low-energy RNBs up to 1.1 MeV/A are currently available; RNBs from 5 to 8 MeV/A are planned
HI RFQ linac to 86 keV/A; IH linacs to 400 keV/A	Cyclotron exists, RFQ prototype operational, funded project	Photofission option for producing neutron-rich RIB under consideration; Phase 2 proposal for acceleration up to 2 MeV/A submitted
K110–Cyclone cyclotron	Operating	Up to 9 kW on target and RIBs accelerated from 0.2 to 12 MeV/A
RIB can be accelerated in U400 cyclotron.	Operating	Also uses photofission technique with the MT25 microtron
SC linac	4-year design study funded in 2005.	Continuous energies between keV/A and 100 MeV/A for m < 130

continues

TABLE C.1 Continued

Facility	Region	Country	Type	Driver
EXCYT at LNS	Europe	Italy	ISOL	HI SC k = 800 cyclotron up to 1.3 kW on target
FAIR at GSI	Europe	Germany	IF	Uranium to 2 GeV/A for fragmentation
GSI	Europe	Germany	IF	Uranium to 1 GeV/A
ISOLDE at CERN	Europe	European Union	ISOL	1.4 GeV synchrotron with up to 2 μA average
MAFF	Europe	Germany	ISOL	Munich Research Reactor FRM-II
SPES	Europe	Italy	ISOL	100 MeV proton beam on UC_x target
SPIRAL at GANIL	Europe	France	ISOL/ IF	HI cyclotrons producing up to 95 MeV/A
SPIRAL 2 at GANIL	Europe	France	ISOL	SC linac produces 40 MeV and 5 mA deuterons; and 1 mA HI up to 14.5 MeV/A
HRIBF at ORNL	North America	United States	ISOL	42 MeV ORIC cyclotron
ISAC-I	North America	Canada	ISOL	100 μA, 500 MeV cyclotron
ISAC-II	North America	Canada	ISOL	Accelerates ISAC-I beams
NSCL at MSU	North America	United States	IF	HI coupled SC cyclotrons 80 to 160 MeV/A for LI and 90 MeV/A for U
RIA	North America	United States	ISOL/ IF	400 kW linac providing 400 MeV/A HI and LI or 900 MeV p

NOTE: BFRIB—Beijing Facility for Rare Isotope Beams; HIRFL—Heavy Ion Research Facility; IMP—Institute of Modern Physics, Chinese Academy of Sciences; RARF—RIKEN Accelerator Research Facility; RIBF at RIKEN—Rare-Isotope Beam Factory at RIKEN; TRIAC at KEK-JAEA—Tokai Radioactive Ion Accelerator Complex at High Energy Accelerator Research Organization-Japan Atomic Energy Agency; VEC-RIB—Variable Energy Cyclotron Radioactive Ion Beam; CRC—Centre de Recherche du Cyclotron; DRIBS—Dubna Radioactive Ion Beams; EURISOL—European Isotope Separator On-Line; EXCYT—Exotic Nuclei Production with Cyclotron and Tandem; LNS—Laboratori Nazionali del Sud; FAIR—Facility for Antiproton and Ion Research; GSI—Gesellschaft für Schwerionenforschung; ISOLDE—On-Line Isotope Mass Separator; CERN—European Organization for

Accelerated Rare-Isotope Beams	Status	Comments
15 MV tandem	Operating	Negatively charged RIBs can be accelerated to ~0.2 to 8 MeV/A.
Synchrotrons	Construction to start in fall 2007.	Increase RIB intensity by up to 10,000 and energy by factor of 15 over present facility scheduled for completion in 2014
	Operating	
REX-ISOLDE linac at 3.1 MeV/A	Operating	Accelerator upgraded to 3.1 MeV/A (5 MeV/A planned) and up to 4 kW on target
REX-ISOLDE concept with 3.7 to 5.9 MeV/A	Planned	ISOL using reactor neutrons as primary driver beam
SC linac to >20 MeV/A	Proposed	10^{13}–10^{14} particles per second for mass region 80–160; A/q = 1–3
CIME Cyclotron for 1.7 to 25 MeV/A with A < 80 and 1.7 to 10 MeV/A for A~100-150	Operating	ISOL accelerated to E < 25 MeV/A with A < 80; IF produces RIB with A < 100 having E < 100 MeV/A
CIME Cyclotron for 1.7 to 25 MeV/A with A < 80 and 1.7 to 10 MeV/A for A~100-150	Construction phase	Operation planned for 2011-2012; budgeted for 130 million euros
25 MV tandem	Operating	Actinide targets used to produce neutron-rich beams
Linac to 2.0 MeV/A	Operating	Routinely operates with 35 kW primary beam power at target
SC linac brings energy to 6.5 MeV/A for A < 150	Construction	4.3 MeV/A begins operation in 2006; 6.5 MeV/A scheduled for 2009
	Operating	Gas catcher for slow beams operational, includes A1900 separator
Linac chain	Proposed	E < 20 MeV/A for reaccelerated RIBs with A < 60, 12 MeV/A for A < 240, and >20 MeV/A for in-flight RIBs

Nuclear Research; MAFF—Munich Accelerator for Fission Fragments; SPES—Study and Production of Exotic Species; SPIRAL—Système de Production d'Ions Radioactifs en Ligne; GANIL—Grand Accélérateur National d'Ions Lourds; HRIBF—Holifield Radioactive Ion Beam Facility; ORNL—Oak Ridge National Laboratory; ISAC—Isotope Separator and Accelerator; NSCL at MSU—National Superconducting Cyclotron Laboratory at Michigan State University; RIA—Rare Isotope Accelerator; ISOL—Isotope Separator On-Line; SC—superconducting; RIB—rare-isotope beam; IF—in-flight; IH—interdigital H-mode; HI—heavy ion; RFQ—radio-frequency quadrupole; AVF—azimuthally varying field; LI—light ion; RI—rare isotope; CB-ECR—charge-breeding electron cyclotron resonance; RFQ—radio-frequency quadrapole; RNB—radioactive nuclear beam; REX—Radioactive Beam Experiment; ORIC—Oak Ridge Isochronous Cyclotron.

D

Glossary

Beta-nuclear magnetic resonance: In general, nuclear magnetic resonance (NMR) enables the study of local magnetic and electronic environments in condensed matter through the measurement of the spin precession and relaxation of a probe nucleus. In beta-NMR, a beam of appropriate radioactive, beta-decaying nuclei is created; then the nuclei are highly polarized, for example, by tuned laser hyperfine interaction with the radioactive atoms, and are finally implanted at the correct depth or sites in the material under study. The temporal response of the nuclear spin to the local environment is followed through the detection of beta-decay electrons preferentially emitted antiparallel to the nuclear spin, thereby tracking the probe's spin response to its environment. This method has much in common with muon-spin resonance in which polarized muons are used as the local probe. In both cases, detection efficiencies are as much as 10 orders of magnitude greater than with conventional NMR.

Density functional theory (DFT): A quantum mechanical method used in physics and chemistry to investigate the detailed structure of many-body systems. Basically, DFT describes an interacting system of fermions via its density and not via its many-body wave function.

Electronvolt (eV): The energy acquired by an electron accelerated through a potential difference of 1 volt. Using the standard system of measurement prefixes, the following also holds: keV = 1,000 eV; MeV = 1 million eV; GeV = 1 billion eV.

Exotic nucleus: A nucleus whose proton number (Z) and neutron number (N) are different from those nuclei in the valley of stability. The term is often used synonymously with "a nucleus far from stability" or "a rare isotope." Such nuclei are unstable and hence decay to more stable configurations.

Fast breeder reactor and fast neutron reactor: The fast breeder reactor is a type of fast neutron reactor designed to produce more fissile material than it consumes. More generally, in fast neutron reactors, fast neutrons maintain the chain reaction. This kind of reactor requires no moderator; instead, it uses enriched fuel and has an efficient neutron "economy." In the fast neutron reactor, excess neutrons can be used either to produce extra fuel, as in the fast breeder reactor, or to transmute long-half-life waste to less troublesome isotopes, or to do both.

Fission: A process in which the heavy nucleus rapidly divides into two lighter species of roughly equal mass, releasing energy.

Fragmentation: A nuclear reaction process in which the primary high-energy heavy ions irradiate targets of light materials such as lithium or carbon. The breakup of the heavy ion produces short-lived nuclear fragments that have approximately the primary beam velocity. Fragmentation is the opposite of the spallation reaction.

Gas catcher ion source: An apparatus used to provide high-quality beams of rare isotopes of any element except helium. In a gas catcher ion source, high-energy rare isotopes are decelerated by solid absorbers and finally slowed to rest in pure helium gas. Rare isotopes stopped in this way remain charged and can be extracted quickly from the helium gas by a combination of electric fields and gas flow.

Inertial fusion: The achievement of controlled fusion through the tailored implosion of small deuterium-tritium capsules driven by lasers, ion beams, or pulsed power. There are several schemes for carrying out inertial fusion, including direct drive, indirect drive, and "fast ignition," depending on how the lasers (for instance) are used to deposit their energy and drive the capsule.

In-flight: A production method in which the fragmented exotic nuclei directly exit the production target at velocities similar to those of the primary beam and are isotopically separated and then directly used for experiments.

ISOL: Isotope Separator On-Line. A method for producing exotic nuclei in which the nuclei are produced (often by the collision of an energetic light ion with a high Z target) in a thick hot target. These rare species diffuse out of the target, are ionized, and extracted to form a beam for reacceleration. Limitations arise owing to the time required (relative to the lifetimes of some exotic nuclei) of the diffusion process, the near impossibility of extracting refractory elements (those elements that are not sufficiently volatile at the elevated temperatures to effuse out of the ISOL target and diffuse into the ion source), and the peculiarity of the chemistry and surface physics of each element produced. For those nuclei that can be extracted by this method, it often provides the most intense beams.

Isomer: A metastable nuclear excited state. Isomers can play significant roles in nuclear-reaction kinetics in astrophysics and stockpile stewardship applications. Isomers can also have technological significance—for example, the single photon emission computed tomography (SPECT) gamma-emitting isomer ^{99m}Tc.

Linac: Short form of "linear accelerator," which is a device used to accelerate ions or electrons. This type of accelerator is "straight" and comprises a series of resonators or cavities that provide the acceleration via high-frequency electric fields. One of its principle advantages is the ease with which the accelerated beam can be extracted from the accelerator.

Monoclonal antibody: Derived from a single kind of immune cell that in turn is a clone of a single cell. In principle able to bind specifically to any antigen (such as those produced by cancers), monoclonal antibodies can both detect and target cancer cells by radioimmunotherapy.

Mössbauer effect: The recoil-free, resonant emission and absorption of narrow-line-width gamma rays by atoms bound in cooled solids.

Perturbed angular correlation (PAC): The angular correlations in the gamma-gamma decay of radioactive probe atoms due to perturbations induced by the neighboring atoms.

Positron emission tomography (PET): A medical imaging method by which a metabolically active compound is tagged with a radionuclide decaying via positron emission. The positrons in turn annihilate with electrons mainly producing nearly back-to-back gammas that are detected in coincidence and used for the three-dimensional tomographic reconstruction of the local metabolic activity. ^{11}C, a typical PET nuclide, with a lifetime of 20.3 minutes, can be produced via ^{14}N(p,α).

Reaccelerated beam: A mode of operation for a rare-isotope facility based on bringing short-lived isotopes to rest using irradiation of targets with a primary beam, and then using a second or "post" accelerator to create beams of these stopped isotopes at the energies required for nuclear science or other applications. Reacceleration can follow either an ISOL or gas catcher ion source method.

Reaction notation (n,γ), (n,xn), (n,p), and so on: In nuclear reactions that have two bodies interacting to produce two bodies in the final state, the reaction is denoted as (x,y) with x, y being the light bodies entering and leaving the reaction: $n + {}^{88}Y \rightarrow {}^{89}Y + \gamma$, or ${}^{88}Y(n, \gamma){}^{89}Y$ is an example of a (n,γ) reaction on the nucleus ${}^{88}Y$.

Single photon emission computed tomography (SPECT): The attachment of a gamma emitter such as ${}^{99m}Tc$ to a biologically active compound aimed at specific tissues or biochemical pathways. The spatial and angular dependence of the gamma emission is then "inverted" to produce a metabolism-dependent three-dimensional image of the target.

Slow neutron-capture process (s-process): A nucleosynthesis process that occurs at lower-neutron-density, lower-temperature conditions in stars. Under these conditions the rate of neutron capture by atomic nuclei is slow relative to the rate of radioactive beta decay.

Spallation: A nuclear reaction process in which a high-energy light ion such as a proton or deuteron irradiates a thick target of heavier nuclei to produce rare isotopes. Spallation is different from fragmentation in that the heavy nucleus is at rest in the case of the former.

Specific activity: The fraction of radioactive atoms in a sample that have a specifically desired radioactive property.

Statistical reaction model: A now widely applied model proposed by Hauser and Feshbach in 1952. It is often used in cases in which neutron cross sections on excited nuclei are desired and it is sufficient to apply approximations based on the idea that the neutron plus nucleus forms an intermediate "compound" nucleus subject to simple statistical rules.

Storage rings: The storage of energetic exotic nuclei for use in experiments. The energetic nuclei are guided in a circular orbit by magnetic fields. A storage ring has the advantage that thin targets can be used, since the beam of exotic nuclei can be cooled and recirculated to pass through the same target thousands of times. It has the disadvantage of being typically limited to exotic nuclei with half-lives on the order tenths of seconds or more.

Superconducting driver accelerator: A high-power primary accelerator or linac employed for the production of rare isotopes. In a superconducting linac, the acceleration of the particles is provided by electric fields in a series of superconducting resonant cavities. In a superconducting cyclotron, the magnetic field keeping the particles in circular orbits is generated by a superconducting magnet, but the accelerating fields are created by room-temperature structures.

Surrogate method: In cases in which it is difficult to measure a desired cross section directly because the target has too short a lifetime or otherwise cannot be obtained, it is sometimes possible to infer the cross section from a surrogate reaction that exploits different initial particles but shares a common intermediate product nucleus with the desired reaction. As a point example of the surrogate method, consider the partial cross section for $n + {}^{155}Gd \rightarrow {}^{156}Gd^{**} \rightarrow {}^{156}Gd^{*} + \gamma$. One can infer the cross section from the "inverse" neutron removal reaction ${}^{3}He + {}^{157}Gd \rightarrow {}^{156}Gd^{*} + \alpha + \gamma$, under the assumption that the common intermediate excited nucleus, ${}^{156}Gd^{**}$ equilibrates (the Weisskopf-Ewing approximation). Recently, the surrogate method has been experimentally and theoretically revisited to successfully measure the energy-dependent fission cross section for ${}^{235m}U$. Furthermore, the equilibration and angular momentum constraint assumptions that underlie the surrogate method have been the subject of experimental tests.

Two-step method: A production method for exotic nuclei in which the primary beam impacts a first target, which produces secondary projectiles that produce exotic nuclei in a secondary target. The most frequent case refers to a primary deuteron beam impinging on a target nucleus to produce an intense beam of neutrons, which bombards a heavy target such as uranium to produce exotic neutron-rich nuclei. This technique has the advantage of separating the area of intense beam heating (the first target) from the exotic-nucleus production target.

E

Additional Remark on Clinical Use of Rare Isotopes

The medical community continues to investigate new isotopes for use in radiation therapy. Recently, studies of the rare isotope ^{149}Tb (terbium) were reported in the *European Journal of Nuclear Medicine and Molecular Imaging.*[1] The research, headed by G.-J. Beyer, involved a collaboration between the On-Line Isotope Mass Separator (ISOLDE) group at the European Organization for Nuclear Research (CERN) and medical researchers from a variety of institutions, including the Memorial Sloan-Kettering Cancer Center. The primary aim of the research was to examine the efficiency of ^{149}Tb-labeled rituximab in specifically killing circulating single cancer cells or small cell clusters in vivo. ^{149}Tb decays to alpha particles 17 percent of the time and has a half-life of 4.1 hours, which is conveniently longer than some other alpha-emitting radionuclides (e.g., ^{213}Bi). Lower-energy alpha particles, such as in ^{149}Tb decays, have been shown to be very efficient in killing cells, and their short range means that minimal damage is caused in the neighborhood of the target cells.

The ^{149}Tb for this study was produced by the on-line isotope separator facility ISOLDE at CERN. The study injected 26 female mice with 5×10^6 Daudi cells, which would normally cause the mice to quickly develop lethal lymphoma disease.

[1] G.-J. Beyer, M. Miederer, S. Vranješ-Đurić, J.J. Čomor, G. Künzi, O. Hartley, R. Senekowitsch-Schmidtke, D. Soloviev, F. Bechegger, and the ISOLDE Collaboration, “Targeted Alpha Therapy in Vivo: Direct Evidence for Single Cancer Cell Kill Using ^{149}Tb-rituximab,” *European Journal of Nuclear Medicine and Molecular Imaging* **31,** 547, 2004.

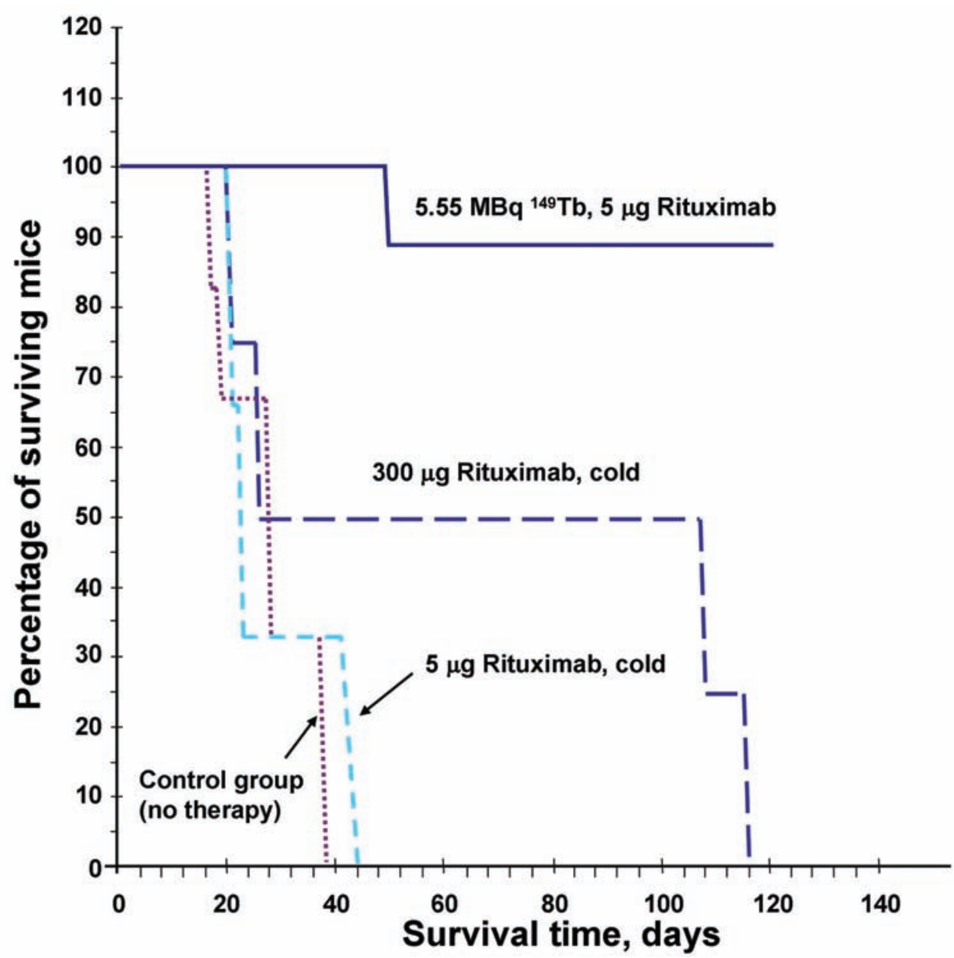

FIGURE E.1 Survival plot of mice grafted with 5×10^6 Daudi cells followed by different intravenous treatments 2 days subsequent. From *European Journal of Nuclear Medicine and Molecular Imaging* **31**(4), April 2004, G.-J. Beyer, M. Miederer, S. Vranješ-Đurić, J.J. Čomor, G. Künzi, O. Hartley, R. Senekowitsch-Schmidtke, D. Soloviev, F. Bechegger, and the ISOLDE Collaboration, "Targeted Alpha Therapy in Vivo: Direct Evidence for Single Cancer Cell Kill Using ^{149}Tb-rituximab," Figure 3, Copyright Springer-Verlag 2004 with kind permission of Springer Science and Business Media.

The mice were separated into 4 groups: 6 received no further injection (control group), 6 received 5 μg of rituximab, 4 received 300 μg of rituximab, and 10 received 5 μg of rituximab labeled with radioactive ^{149}Tb with a decay rate of 5.5×10^6 decays per second. These second injections were administered 2 days after the Daudi cell inoculation. Rituximab is a monoclonal antibody that targets CD20 antigens, which are expressed in large numbers by the Daudi cells.

The dramatic results of the study are shown in Figure E.1, which indicates the mice's survival in days in terms of the percentage surviving. All of the mice except those receiving the ^{149}Tb-labeled rituximab had perished by 120 days, and approximately half had developed macroscopic tumors. In the group treated with the ^{149}Tb-labeled rituximab, only one of the nine had died; the remainder showed no pathological changes upon further examination.

The low-energy alpha particles and longer lifetime properties of ^{149}Tb made it the best isotope available for performing this research. Rare-isotope facilities can examine many more isotopes and can be expected to discover more particular isotopes with the ideal chemical and radiological characteristics for the treatment of disease.

F

Biographical Sketches of Committee Members

COMMITTEE MEMBERS

John F. Ahearne, Sigma Xi and Duke University, *Co-Chair*

Dr. Ahearne is the director of the Ethics Program for Sigma Xi, the Scientific Research Society, and an adjunct scholar at Resources for the Future. His professional interests are reactor safety, energy issues, resource allocation, and public policy management. He has served as commissioner and chair of the U.S. Nuclear Regulatory Commission, system analyst for the White House Energy Office, Deputy Assistant Secretary of Energy, and Principal Deputy Assistant Secretary of Defense. Dr. Ahearne currently serves on the Department of Energy's Nuclear Energy Research Advisory Committee and chairs the University of California President's Council National Security Panel that provided oversight of the nuclear weapons programs of the Los Alamos and the Lawrence Livermore National Laboratories. In addition, Dr. Ahearne has been active in several National Research Council (NRC) committees examining issues in risk assessment. He is a fellow of the American Physical Society, the Society for Risk Analysis, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences, and he is a member the American Nuclear Society and the National Academy of Engineering. Dr. Ahearne received his Ph.D. in physics from Princeton University.

Stuart J. Freedman, University of California at Berkeley, *Co-Chair*

Dr. Freedman is the Luis W. Alvarez Chair of Experimental Physics at the University of California at Berkeley, with a joint appointment to the Nuclear Science Division of the Lawrence Berkeley National Laboratory. He received his Ph.D. from the University of California at Berkeley in 1972. His research experience spans nuclear and atomic physics, neutrino physics, and small-scale experiments in particle physics, all focused on fundamental questions about the Standard Model. He was co-chair of the recent American Physical Society Neutrino Study and was a member of the NRC's Committee on Elementary Particle Physics in the 21st Century (the EPP2010 committee). He is a member of the National Academy of Sciences.

Ricardo Alarcon, Arizona State University

Dr. Alarcon is a professor of physics at Arizona State University. He did his undergraduate studies at the University of Chile and received his Ph.D. in 1985 from Ohio University. He did postdoctoral work at the University of Illinois at Urbana-Champaign until 1989, when he joined Arizona State University as an assistant professor. His research covers experiments in electromagnetic nuclear physics and more recently in fundamental neutron science. He has held visiting professor appointments at the Massachusetts Institute of Technology (MIT) in 1995-1997 and 1999-2001 and served as project manager for the Bates Large Acceptance Spectrometer project at MIT-Bates from 1999 to 2002. He was a member of the Department of Energy/National Science Foundation (DOE/NSF) Nuclear Science Advisory Committee from 2001 to 2005. In 2003 he was elected a fellow of the American Physical Society.

Peter Braun-Munzinger, Gesellschaft für Schwerionenforschung (GSI)

Dr. Braun-Munzinger is division head for Kernphysik 1 (nuclear physics) at Gesellschaft für Schwerionenforschung (GSI) and professor of physics at the Technical University in Darmstadt, Germany. He earned his Ph.D. in physics from the University of Heidelberg in 1972. His research expertise is in the area of nuclear physics, with emphasis on ultrarelativistic collisions and detector development. Dr. Braun-Munzinger has been spokesperson for several nuclear physics experiments in the United States and elsewhere and is a leading participant in the high-energy-density experiments ALICE at the European Organization for Nuclear Research (CERN). He has also served on numerous program advisory committees, several panels of the DOE/NSF Nuclear Science Advisory Committee, and has held faculty positions at the State University of New York at Stony Brook. Dr. Braun-

Munzinger is chair of the Committee for Nuclear and Hadron Physics in Germany. He is a fellow of the American Physical Society and received the prize of the Polish Ministry for Science in 2003.

Adam S. Burrows, University of Arizona

Dr. Burrows is a professor of physics and astronomy at the University of Arizona. He received his A.B. in physics from Princeton University in 1975 and his Ph.D. in physics from the Massachussetts Institute of Technology in 1979. His research is focused on supernovae and on the formation of small objects such as brown dwarfs and extrasolar planets. Dr. Burrows was a member of the Panel on Theory, Computation, and Data Exploration of the NRC's 2000 astronomy and astrophysics decadal survey and recently served as the chair of NASA's roadmapping effort for the search for Earth-like planets.

Richard F. Casten, Yale University

Dr. Casten is D. Allan Bromley Professor of Physics and director of the Wright Nuclear Structure Laboratory at Yale University. He received his Ph.D. from Yale in 1967 and held positions domestically and in Europe before returning to Yale in 1995. He received the Humboldt Prize (Senior U.S. Award) in 1983, was awarded an honorary doctorate from the University of Bucharest, and is a fellow of the Americal Physical Society, the American Association for the Advancement of Science, and the Institute of Physics (United Kingdom). He was chair of the Nuclear Science Advisory Committee (NSAC) from 2003 to 2005, a member of NSAC from 1997 to 2001, and of the NSAC Long Range Plan Working Groups in 1989, 1999, and 2001. He is vice-chair of the Division of Nuclear Physics of the APS (chair-elect in 2007, chair in 2008) and associate editor of *Physical Review C.* He was a founder and chair (1989-2003) of the IsoSpin Laboratory Steering Committee, co-chair of the Rare Isotope Accelerator (RIA) Users Organization Executive Committee (2002-2003) and currently chair. Among many other committees on which Dr. Castan has served, he was chair of the International Nuclear Structure and Astrophysics Community (NUSTAR) Advisory Panel for GSI-FAIR (Facility for Antiproton and Ion Research) (2003-2004) and a member of panels to review U.K. physics and astronomy research (1999, 2005). Dr. Casten has made major contributions to the study of collective behavior in nuclei, to algebraic models (IBA, dynamical symmetries), and to the study of correlations of nuclear observables, quantal phase transitions, critical point symmetries, and the valence p-n interaction.

Yanglai Cho, Argonne National Laboratory (retired)

Dr. Cho is retired from the Argonne National Laboratory and now chairs the technical advisory committee for a project based in Darmstadt, Germany: the Facility for Antiproton and Ion Research. His expertise is in accelerator science and technology; he has played a leading role in the design and construction of proton, electron, and neutron accelerators in the United States, Europe, and Asia. Dr. Cho has chaired numerous international conferences on accelerator science and technology, including the International Linac Conference in 1998. He also had a leading role in facilitating the joint proposal between two agencies in the Japanese government that gave rise to the Japan Proton Accelerator Research Complex.

Gerald T. Garvey, Los Alamos National Laboratory

Dr. Garvey is an experimental nuclear physicist and a senior fellow at the Los Alamos National Laboratory. He is expert in neutrino physics and nucleon-nucleon interactions, as well as being experienced in issues of science policy. Dr. Garvey served for 2 years as assistant director for physical sciences in the White House Office of Science and Technology Policy. He has also served on the Brookhaven National Laboratory's Program Advisory Committee and is familiar with the scientific and technical aspects of large experimental nuclear physics facilities. He was director of the Los Alamos Meson Physics Facility from 1985 to 1990 and is a former director of the Argonne National Laboratory's Physics Division. He earned his Ph.D. from Yale University in 1962.

Wick C. Haxton, University of Washington

Dr. Haxton received his Ph.D. in physics from Stanford University in 1976, after which he worked for 7 years as a research associate, Oppenheimer Fellow, and staff member in the Theory Division of the Los Alamos National Laboratory. In 1984 he joined the University of Washington, where he directed the Department of Energy's Institute for Nuclear Theory (INT) from 1991 to 2006. He is currently professor of physics and a senior fellow of the INT. His research interests include atomic and nuclear tests of symmetry principles and conservation laws, nuclear and neutrino astrophysics, and many-body techniques. Dr. Haxton chaired the American Physical Society's Division of Nuclear Physics in 1992 and the APS Division of Astrophysics in 1996, and is a former APS general councillor. He was awarded the Hans Bethe Prize of the APS in 2004. He is a member of the National Academy of Sciences, a fellow of the American Academy of Arts and Sciences, and a past Guggenheim Fellow (2000). Currently he is an editor of *Physics Letters* and serves on the Board on Physics and Astronomy of the National Research Council.

Robert L. Jaffe, Massachusetts Institute of Technology

Dr. Jaffe is the Jane and Otto Morningstar Professor of Physics at the Massachusetts Institute of Technology (MIT), where he has been chair of the faculty and director of the Center for Theoretical Physics. His research specialty is the theoretical physics of elementary particles, especially the dynamics of quark confinement, the Standard Model, and the quantum structure of the vacuum. He has also worked on the quantum theory of tubes and the astrophysics of dense matter and on many problems in scattering theory. Dr. Jaffe received his A.B. from Princeton University and his M.S. and Ph.D. degrees from Stanford University. He has served on the program advisory committees of several national laboratories, including the Stanford Linear Accelerator Center and the Brookhaven National Laboratory. At present he chairs the Science and Technology Steering Committee of Brookhaven Science Associates. For a decade he chaired the Advisory Council of the Physics Department of Princeton University. Since 1996, Dr. Jaffe has been an adviser to and visiting scientist at the RIKEN-Brookhaven Research Center. He spent the fall term of 1997 on leave from MIT at the RIKEN-Brookhaven Center, and was a resident at the Rockefeller Foundation's Bellagio Study and Conference Center in the fall of 2004. Dr. Jaffe is a fellow of the American Physical Society and the American Association for the Advancement of Science and has been highly recognized for his teaching of undergraduates at MIT.

Noemie B. Koller, Rutgers, The State University of New Jersey, New Brunswick

Dr. Koller is professor of physics at Rutgers University. She earned her Ph.D. in 1958 from Columbia University and went to Rutgers in 1960. She is a fellow of the American Physical Society and the American Association for the Advancement of Science. At Rutgers, she served as associate dean of the faculty of arts and sciences (1992-1996) and was director of the Nuclear Physics Laboratory (1986-1989). She chaired the APS Division of Nuclear Physics in 1993, served on many APS and NSF committees, served on the NRC's 1980 nuclear physics decadal survey, and chaired the APS Committee for the International Freedom of Scientists (2002-2004). Dr. Koller's research is mostly in experimental nuclear structure physics, but she has made contributions to the fields of ion-solid interactions, surface magnetism, and condensed-matter physics studied via nuclear and Mössbauer techniques. Her research group carries out experiments and develops techniques designed to measure magnetic dipole moments of very short-lived nuclear states. Recently, she has extended these techniques for experiments with radioactive beams. She has received many honors, most recently the APS Division of Nuclear Physics Distinguished Service Award. A scholarship for the best female undergraduate physics major at Rutgers was endowed in her honor.

Stephen B. Libby, Lawrence Livermore National Laboratory

Dr. Libby is the Theory and Modeling Group Leader in V Division in the Physics and Advanced Technologies Directorate at the Lawrence Livermore National Laboratory (LLNL). His current research focuses on high-energy-density physics and its application to stockpile stewardship, inertial confinement fusion, and short-wavelength lasers. This work includes proposals for experiments at the National Ignition Facility currently under construction at LLNL. Dr. Libby received his B.A. from Harvard University in 1972 and his Ph.D. in physics from Princeton University in 1977. He performed postdoctoral work at the Yang Institute for Theoretical Physics at the State University of New York at Stony Brook and was subsequently a research assistant professor at Brown University. During this period, he worked on quantum chromodynamics and the theory of the quantum Hall effect. In 1986, he joined A Division at LLNL. Focusing on x-ray laser research, he eventually became the design group and program leader. He was also a consulting professor at Stanford University from 1992 to 1994. Dr. Libby is a fellow of the American Physical Society. In addition, he holds a certificate in international security from Stanford University.

Shoji Nagamiya, Japan Proton Accelerator Research Complex

Dr. Nagamiya is director of the J-PARC Center—the Japan Proton Accelerator Research Complex—an initiative of the Japanese federal government for building a $1.3 billion national accelerator laboratory centered on a massive, high-intensity proton accelerator. Dr. Nagamiya received his B.S. in 1967 from the University of Tokyo and his Ph.D. in 1972 from Osaka University. His research expertise is in relativistic heavy-ion physics, with experience at the Bevalac, the Relativistic Heavy Ion Collider (RHIC), and CERN; he was most recently spokesperson for the PHENIX experiment at RHIC. He served as chair of Japan's Committee on Nuclear Physics and chair of C12—the Commission on Nuclear Physics for the International Union of Pure and Applied Physics (IUPAP). Dr. Nagamiya has been a member of many international program advisory committees for laboratories in particle and nuclear physics and has also been on the editorial board of a number of major nuclear physics journals. He was professor at the University of Tokyo and also at Columbia University before assuming his present position. Dr. Nagamiya is a member of the Science Council of Japan and chair of the Physics Section of this council.

Witold Nazarewicz, University of Tennessee, Knoxville

Dr. Nazarewicz is a professor of physics in the Department of Physics and Astronomy at the University of Tennessee, Knoxville, with an adjunct appointment at the Oak Ridge National Laboratory (ORNL). He is also scientific director of the Holifield Radioactive Ion Beam Facility at ORNL. He received his Ph.D. from the Warsaw Institute of Technology in 1981. His research has centered on the theoretical nuclear many-body problem. Dr. Nazarewicz is a fellow of the American Physical Society and the Institute of Physics, U.K. He is listed by ISI as among the most highly cited in physics. Dr. Nazarewicz has authored or co-authored more than 280 research papers in refereed journals and has conducted more than 160 invited talks at major international conferences. He has served on numerous national and international advisory and review committees, including the NRC's Committee on Nuclear Physics, and on various editorial boards

Michael V. Romalis, Princeton University

Dr. Romalis is an atomic physics faculty member in the Department of Physics at Princeton University. He received his Ph.D. in physics from Princeton in 1997 and went to the University of Washington as a postdoctoral researcher, later becoming faculty there. In Washington, he became interested in a possible aberration in known physical laws, a hypothetical idea called CPT violation. His research group is most interested in using atomic physics to probe fundamental symmetries. At the present time, Dr. Romalis is conducting experiments to test symmetries of physical laws: specifically, the symmetries of time-reversal, CP, Lorentz, and CPT. While these symmetries are on firm ground within a conventional field theory, they can be violated in more general theories, including quantum gravity. Dr. Romalis is also exploring practical applications of precision atomic physics techniques, including the development of a very sensitive atomic magnetometer that can surpass low-temperature superconducting quantum interference device (SQUID) detectors in magnetic-field sensitivity. In collaboration with Princeton University's Center for Brain, Mind and Behavior, his group is developing applications for the imaging of magnetic fields produced by the brain.

Paul Schmor, TRIUMF

Dr. Schmor is head of the Accelerator Systems Division at the TRIUMF laboratory, which includes the 500 MeV driver cyclotron facility as well as the Isotope Separator and Accelerator (ISAC) facility. TRIUMF is Canada's accelerator-based laboratory for particle and nuclear physics, located on the campus of the University of British Columbia. ISAC can provide beams of rare, short-lived radioactive isotopes for use in various experiments, including nuclear and condensed-matter physics as well as medicine and industrial applications. Dr. Schmor was appointed project leader for the ISAC construction project in 1996. He was a member of the 1999 DOE/NSF NSAC Isotope Separator On-Line Task Force and at present is a member of the European ISOL (EURISOL) International Advisory Panel. He was a member of the Accelerator Systems Advisory Committee during the construction phase of the Spallation Neutron Source (SNS) as well as a member of the Target Subcommittee for the DOE's review of the SNS. Dr. Schmor is a senior member of the Canadian Section of the Institute of Electrical and Electronics Engineers.

Michael C.F. Wiescher, University of Notre Dame

Dr. Wiescher is the Freimann Professor of Nuclear Physics at the University of Notre Dame. He received his Ph.D. in nuclear physics at the Universität Münster, Institut für Kernphysik, in 1980. Dr. Wiescher is the director of the Nuclear Science Laboratory at Notre Dame and the director for the Joint Institute for Nuclear Astrophysics (JINA) at the University of Notre Dame, Michigan State University, and the University of Chicago, funded through the NSF Physics Frontier Center program. The central research interest of Dr. Wiescher is the experimental and theoretical study of nuclear reactions important to the understanding of energy production and the origin of the elements in stars and in explosive stellar environments. Currently, his research focuses on understanding nucleosynthesis in explosive hydrogen- and helium-burning processes that occur in novae, supernovae, and accreting neutron stars. In addition, he studies nucleosynthesis during the late stages of stellar development, in particular in AGB stars. Dr. Wiescher has made several presentations on the science case for RIA and has been involved with several exploratory RIA working groups. He is a fellow of the American Physical Society's Division of Astrophysics and Division of Nuclear Physics, was awarded the Hans A. Bethe Prize in 2003 by the American Physical Society, and is a member of the American Astronomical Society, the American Association for the Advancement of Science, and the Deutsche Physikalische Gesellschaft.

Stanford E. Woosley, University of California at Santa Cruz

Dr. Woosley is a professor of astronomy and astrophysics at the University of California at Santa Cruz. His research is in nuclear astrophysics, especially the origin of the elements, and in theoretical high-energy astrophysics, especially models for supernovae and gamma-ray bursts and other violent events. He was awarded the 2005 Hans A. Bethe Prize in nuclear astrophysics by the American Physical Society and the 2005 Rossi Prize in high-energy astrophysics of the American

Astronomical Society. Dr. Woosley is a member of the National Academy of Sciences and the American Academy of Arts and Sciences.

NRC STAFF

Donald C. Shapero, Board on Physics and Astronomy

Dr. Shapero is the director of the NRC's Board on Physics and Astronomy. He received a B.S. from the Massachusetts Institute of Technology in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., Dr. Shapero became a Thomas J. Watson Postdoctoral Fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the NRC in 1975. He took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. Dr. Shapero returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Physical Society, the American Astronomical Society, the American Association for the Advancement of Science, and the International Astronomical Union. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

Timothy I. Meyer, Board on Physics and Astronomy

Dr. Meyer is a senior program officer at the NRC's Board on Physics and Astronomy. He received a Notable Achievement Award from the NRC's Division on Engineering and Physical Sciences in 2003 and a Distinguished Service Award from the National Academies in 2004. Dr. Meyer joined the NRC staff in 2002 after earning his Ph.D. in experimental particle physics from Stanford University. His doctoral thesis concerned the time evolution of the B meson in the BaBar experiment at the Stanford Linear Accelerator Center. His work also focused on radiation monitoring and protection of silicon-based particle detectors. During his time at Stanford, Dr. Meyer received both the Paul Kirkpatrick and the Centennial Teaching awards for his work as an instructor of undergraduates. He is a member of the American Physical Society, the American Association for the Advancement of Science, the Materials Research Society, and Phi Beta Kappa.