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PHYSICS OF A RARE ISOTOPE ACCELERATOR*

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■ **Abstract** Major progress in nuclear research and in observations of the cosmos has made it clear that critical issues in understanding the nucleus and astrophysical processes require abundant new sources of exotic nuclei, away from the realm of the stable ones. Recent advances in accelerator and isotope-production technology make access to these rare isotopes possible. This review examines the impact of the new reach in physics provided by a rare isotope accelerator in nuclear structure, astrophysics, and searches for physics beyond the standard model. We also touch briefly on some of the benefits of these isotopes for other important societal needs.

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INTRODUCTION

Nuclear physics encompasses the quest to understand the origin, structure, and evolution of baryonic matter in the universe. The properties of nuclei influence the timescales and amount of energy produced in the cosmos, the creation of the chemical elements, and the chemical evolution of the universe. In nuclear systems, all the fundamental forces hold sway, from the strong interactions that form the basic building blocks, the hadrons, and the nucleon-nucleon forces, to the weak interactions that initiate stellar burning; from the electromagnetic interactions that limit the stability of heavy nuclei to fission, and to gravity that constrains the structure of neutron stars. As systems ranging from a few (deuterium, ^{3}He) to 10^{57} (neutron stars) particles, nuclear systems exhibit almost all of the diverse phenomena characteristic of mesoscopic systems, many of which are uniquely influenced in this case by the dominantly two-quantum fluid nature of aggregates of neutrons and protons. Nuclei provide classic examples of the critical intellectual ideas that shape our understanding of dynamical systems, including the underlying chiral symmetry of quantum chromodynamics (QCD), dynamical symmetry breaking in the deformed ground states of many nuclei, quantum chaos—first delineated in the properties of nuclear energy-level distributions—and emergent phenomena. Hence, nuclear physics has important intellectual links to other disciplines and has a strong impact on other scientific endeavors such as astrophysics, elementary particle physics, atomic and molecular physics, materials science, medicine, and many other applications of critical importance to the nation's security and economic well being.

Much has been learned so far, but much remains to be understood. In the past few years researchers have made remarkable progress in their fundamental understanding of these complex systems. This progress has been driven by new theoretical insights, increased computational power, and access to new isotopes with a large excess of neutrons or protons. Approximately 7000 nuclearsystems are believed to be bound by the strong and electromagnetic interactions and to have half-lives longer than 1 microsecond (i.e., bound to rapid-proton, neutron, alpha, and fission decays). Of this total, only approximately 300 have lifetimes in their ground states sufficiently long (>1 billion years) to be considered stable. Some information, although in many cases quite limited in scope, such as the lifetime and approximate mass, has been obtained for approximately 3000 more nuclear systems.

Figure 1 illustrates the nuclear landscape, with the stable nuclei depicted by solid black squares. Nuclei with half-lives longer than microseconds where some information is known are indicated by the tan region, and the "terra incognita" of the unknown isotopes whose lifetimes are expected to be greater than 1 microsecond are displayed in green. These tan and green areas are the domain of radioactive or rare isotopes. At the most basic level, more than 50% of the "periodic table" of nuclear isotopes remains to be discovered and characterized. Figure 1 also indicates the approximate pathways of several of the processes essential for the production of elements in the cosmos, including the rapid-proton-capture (rp) process (found in novae and X-ray bursts) and the rapid-neutron-capture (r) process (thought to occur in the expanding bubble around a type II supernova and responsible for the production of approximately half the elements heavier than iron).

Many of the known properties of nuclei are expected to change significantly in nuclei far from stability. Recent experimental results provide intriguing indications of these changes. Unfortunately, they cannot yet be predicted reliably by theory and, therefore, require experimental exploration. Their importance cannot be underestimated, as the requirements on the level of precision needed, for example, to make accurate astrophysical calculations often dramatically exceeds our current knowledge. Today, accelerator and isotope production and separation technologies have advanced to the point that we now know how to access the most important exotic nuclei (rare isotopes) and measure the critical quantities needed for developing reliable nuclear and astronuclear models. To accomplish this goal, an advanced rare isotope accelerator must be constructed.

Snapshot of Nuclear Physics and Nuclear Structure

The properties of nuclei define the core of this quest to understand the origin, structure, and evolution of baryonic matter in the universe. In its infancy, nuclear physics faced a set of remarkable challenges. The force between nucleons was unknown and found to be complex. The operator structure revealed by experiments on nucleon-nucleon scattering required short-ranged (~ 1 fm, approximately the Compton wavelength of the pion) forces with spin-dependence, tensor and spin-orbit forces that couple different angular momentum states, and, at higher levels of precision, required differences in the forces between neutron-proton and proton-proton pairs that break the approximate symmetry relating them, isospin. Even today, with a strong prejudice that the fundamental theory of strong interactions, QCD, has been found, and with lattice and continuum methods making great progress in calculating hadron structure, only the general features of the nucleon-nucleon interaction can be deduced from effective field theories on the basis of the symmetries of QCD. Links to high-density QCD emerge from the search for possible changes in the structure and interactions of nucleons as a function of density and from the search for exotic (quark or meson condensate) forms of matter at the core of neutron stars. A second challenge arises from the small number of particles with a surface-to-volume ratio of order $3/A^{1/3} \sim 0.5$ ($1\ \mathrm{fm} \times 4\pi R^2/(4\ \pi R^3/3)$), even for a nucleus of mass (A) 200. This leads to physics more related to that of metal clusters and quantum dots, than to that of bulk material.

Nuclear Structure as We Learned it at Our Parent's Knee versus the Real World

The following is a summary of the conclusions of classic nuclear structure studies as presented in a variety of standard textbooks (1):

The forces between protons and neutrons and between identical nucleons are very similar. Ultimately this can be traced to the fact that the QCD interaction between a quark and a gluon is independent of flavor and that the masses and mass differences of the light current quarks are small compared with the nucleon mass. This leads to quite a small breaking of the SU(2) isospin (proton-neutron) symmetry in nuclei.

In contrast to the first impressions of a many-body system of strong, short-ranged interactions, the single-particle motion of nucleons can be well represented by motion in a mean field. The shape of the mean field is close to a Woods-Saxon potential: $V(r) = V_0/(1 + \exp[\{r - R\}/a])$, where R is the nuclear radius ($\sim 1.2\ A^{1/3}$ fm) and a (~ 0.55 fm) is the diffuseness. Except for the weaker Coulomb interaction, this field is common for neutrons and protons, and so the neutron and proton radii are very similar. This mean field and the resulting density distributions are illustrated schematically in Figure 2. The bunching of the energy spectrum of the single-particle orbitals in the mean field (i.e., the origin of the magic numbers of particularly stable nuclei) provides a natural truncation scheme for nuclear many-body calculations, the nuclear shell model. The residual pair-wise interaction beyond the mean field is most strongly attractive for spin-zero states, which leads to the formation of Cooper pairs of identical nucleons and strong Bardeen-Cooper-Schrieffer correlations in the nuclear wave functions.

Dynamical symmetry breaking leads to strongly deformed axial quadrupole or triaxial shapes of the nuclear ground states in regions of high single-particle level density. These deformed shapes strongly modify the arrangement and symmetries of the single-particle orbitals (Nilsson model), but mean-field motion continues to be evident. The deformations of the proton and neutron fluids tend to follow one another.

The very strong short-range repulsion of the nucleon-nucleon interaction leads to significant renormalization of the mean-field wave functions due to pair correlations.

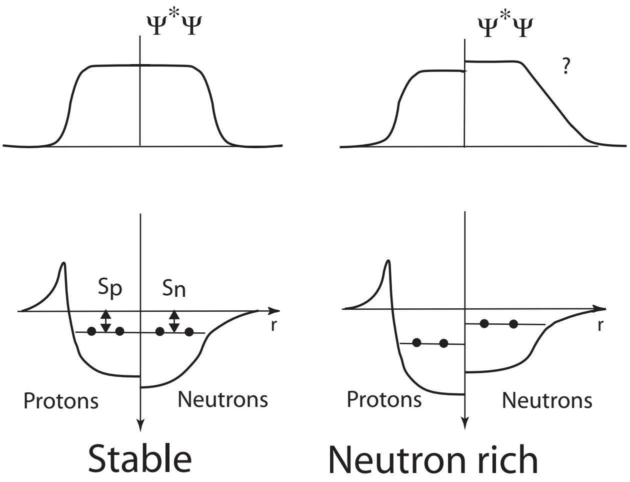

Figure 2 An illustration of the mean fields (*bottom*) and density distributions (*top*) for neutrons and protons in stable and neutron-rich nuclei. The weak binding of valence neutrons in nuclei with a large neutron excess leads to significant differences in both quantities. S_p and S_n are the proton and neutron separation energies, respectively.

Integrating these elements provides a reasonable description of the nuclei close to the valley of stability. However, when extrapolating to very neutron-rich nuclei, most, if not all, of these basic assumptions break down at some level. Adding a large number of neutrons leads to systems in which the neutrons are much more weakly bound than the protons. Without a Coulomb barrier, the neutron wave functions extend much farther out in radius, as illustrated in Figure 2, increasing both the radius and diffuseness of the neutron potential, explicitly breaking the isospin symmetry, changing the ordering and spacing of single-particle orbitals, and in some cases decoupling the proton and neutron deformations. As the weakly bound valence neutrons are, on average, much more distant, the pairing and short-range correlations can change in character, leading either to more pure mean-field behavior or to more subtle pairing effects, depending on the level density and the nearby continuum states. The fundamental point here is that nuclei far from stability are expected to be qualitatively different from their more strongly bound stable cousins. Therefore, it should come as no surprise that when we extrapolate our well-tested models of stable nuclei to new systems far from stability, by, for example, predicting either the location of the island of more stable superheavy elements or the properties of the nuclei involved in the r-process, our current models, at worst, fail decisively or, at best, are unreliable in their predictions.

However, when we are able to do the many-body physics comprehensively, our understanding can be remarkably good. One of the major advances in nuclear physics in the past decade is that, with advancing computing capabilities and new algorithm techniques, ab initio calculations can be done, e.g., quantum

Monte Carlo many-body calculations (2), by starting with two-nucleon forces accurately fit to two-body scattering data, and three-body forces (necessary from QCD effective field theory or meson-exchange theories). These calculations, as illustrated in Figure 3 (S.C. Pieper & R.B. Wiringa, private communication), do an excellent job of describing the structure of light nuclei (to date up to ^{12}C) and of explaining how the features of nuclear structure emerge. The primary unknown ingredient in this approach is the isospin dependence of the three-body force, as scattering experiments cannot be done on three-neutron or three-proton systems. This isospin dependence leads to an uncertainty in the mean-field spin-orbit interaction and thus to our uncertainty in extrapolating to neutron-rich systems. Now that many-body physics is under control, experiments on very neutron-rich light nuclei promise to resolve this uncertainty and provide a firm foundation for evaluating the many-body approximations required to move to heavier systems.

How Well Do We Need to Understand Nuclei?

In his 2000 review article (4) "Why the Universe Is Just So," Hogan argues that nuclear processes hold a unique role in the evolution of the universe. Phenomena at very high energy scales may one day be understood in terms of simple symmetry principles, and at the very soft scales of chemistry and biology, the multitude of possible pathways may lead to the "life will find a way" principle. The unique nature of nuclei means that the critical bottlenecks in nuclear processes, which govern the evolution of the universe, involve a small number of specific pathways, and hence there is great sensitivity to details of the underlying physics. For example, the abundant stellar production of carbon and oxygen, which lead to the elements necessary for organic life, depends on the existence and nonexistence of selected nuclear levels at the precision of 0.1% of the total nuclear binding energy in ^{8}Be, ^{12}C, ^{16}O, and ^{20}Ne. The production of the heavy elements in the r-process depends on the masses of some of these nuclear systems at the 100-keV level. To understand this physics places very stringent demands on our ability to calculate reliably—or measure these properties in systems that live a fraction of a second. Yet this is just what is needed to capitalize on the major advances in new generations of astronomical observatories, and the physics of rare isotopes will provide the answers at the very smallest distance scales to questions posed at the largest scales.

This overview has outlined the challenges and the rewards of studying nuclei far from stability. We expect the new measurements on unstable nuclei to isolate the new emergent phenomena and provide explanations to long-standing issues in nuclear science. The following three sections focus on nuclear structure, astrophysics, and searches for physics beyond the standard model. The technical advances that make a great leap forward possible at this time are outlined in the fifth section, and the sixth section discusses some of the more general opportunities to use this bounty of new isotopes to address societal needs.

THE PROPERTIES OF NUCLEI

Given that nuclei can be treated as two-fermion quantum systems, it should come as no surprise that their description requires the exploration of the neutron-proton degree of freedom. Until recently, this endeavor was severely hampered by the fact that the accessible nuclei had a rather limited range of proton to neutron numbers. The situation has improved gradually with the advent of the first radioactive beams and the development of more advanced facilities, which promise experimental access to both very neutron-deficient and very neutron-rich nuclei.

There are two parts to understanding the nuclear system. One is to approach nuclei in terms of their fundamental building blocks (neutrons and protons) and their interactions, which should ultimately be grounded in QCD. As shown below, a key step in this description is the access to very neutron-rich nuclei, so that previously unknown parts of the interactions can be determined. The other is to master how these complex objects can exhibit remarkable simplicities, such as rotational structures and giant resonances, where all nucleons act coherently. The insight gained from studying these regularities and their origins mirrors a broad spectrum of science. Again, progress in understanding the underlying dynamics requires access to exotic nuclei.

Figure 4 encapsulates a broad-brush look at the properties of nuclei. The left panel shows the difference between the total binding energy of nuclei and the finite-range liquid drop picture (5). The connected center and right panels display prototypical spacings of single-particle energy levels. In the central panel, the shell structure typical of spherical nuclei is readily apparent, with the extra binding of the nuclei around magic neutron numbers 2, 8, 20, 28, 50, 82, and 126. This shell structure is well described by mean-field theories, with the precise location of the magic numbers determined by the strength of the mean-field spin-orbit interaction (6). Approximations such as density-dependent Hartree-Fock, or Skyrme-Hartree-Fock, have been quite successful, as evidenced, for example, by the demonstration via elastic electron scattering (7) that the spatial distribution of the mean-field $3s_{1/2}$ orbital in ^{205}Tl is well described even in the center of the nucleus. Yet many of the basic ingredients in the description of the nuclear system are not understood. For example, the origin and properties of the nuclear spin-orbit force are still not well determined, although progress is being made, as illustrated by relativistic mean-field calculations in which the magnitude of the spin-orbit interaction appears to arise naturally from the cancellation of strong relativistic scalar and vector interactions (8). Away from the closed shells, the nuclear binding energies are much closer to liquid-drop values, but the ground states often spontaneously break the rotational symmetry of the Hamiltonian and become strongly deformed. Moreover, in many nuclei, states of dramatically different shapes coexist near the ground state. Collective features associated with these geometrical symmetries dominate the excitation spectrum; these have been successfully described using mean-field descriptions with cranking (9) or algebraic models such as the interacting boson approximation (10). Many nuclear structure studies over the past two decades have focused on the critical interplay between single-particle and collective degrees of freedom.

Despite apparent successes in describing systems close to the valley of stability, extrapolations of present knowledge into new regions in which nuclei have an excess of neutrons or protons are unreliable, as illustrated by two examples in Figure 5: the dependence on neutron number of the two-neutron separation energies in the Sn isotopes (11) and the predictions for the location of tightly bound superheavy nuclei (12). In the region in which data are available, nuclear models can be empirically tuned to reproduce the two-neutron separation energies quite well. However, wide variations occur within the various formulations when predictions are made for regions in which no data exist, e.g., for very neutron-rich nuclei. Calculations with a relativistic mean-field model predict a superheavy island of stability that may possibly be reached with combinations of stable beams and targets. However, calculations with a Skyrme-Hartree-Fock model or a microscopic-macroscopic approach (a liquid-drop description with empirical shell corrections) predict a more neutron-rich island of stability that can be reached only with beams of neutron-rich rare isotopes. Thus, progress requires access to nuclei far from stability so that key parts of the effective interaction can be determined (13).

Ab initio Calculations and Light Nuclei

Until recently, it was not at all clear that a description of nuclei as finite, many-body quantal systems with two types of fermions was fully warranted. It was possible to blame difficulties in understanding nuclear structure on our limited knowledge of both the QCD substructure of the nucleon and the nucleon-nucleon interaction. Today, two major advances provide considerable confidence. Experimental progress at Jefferson Laboratory validates hadron-based models of the nucleus to short-distance scales of 0.5 fm or less (e.g., Reference 14). At the same time, new theoretical techniques and improvements in computational capabilities have shown that many long-standing issues in nuclear structure can be resolved by much improved many-body calculations. Three calculational frameworks, Green's function Monte Carlo, no-core shell model (15), and coupled cluster (16), now give consistent results and thereby demonstrate that limitations of previous theoretical approximations were the source of many of the issues raised.

In these calculations the starting point is a nuclear Hamiltonian that includes a two-body interaction derived from nucleon-nucleon scattering data and from

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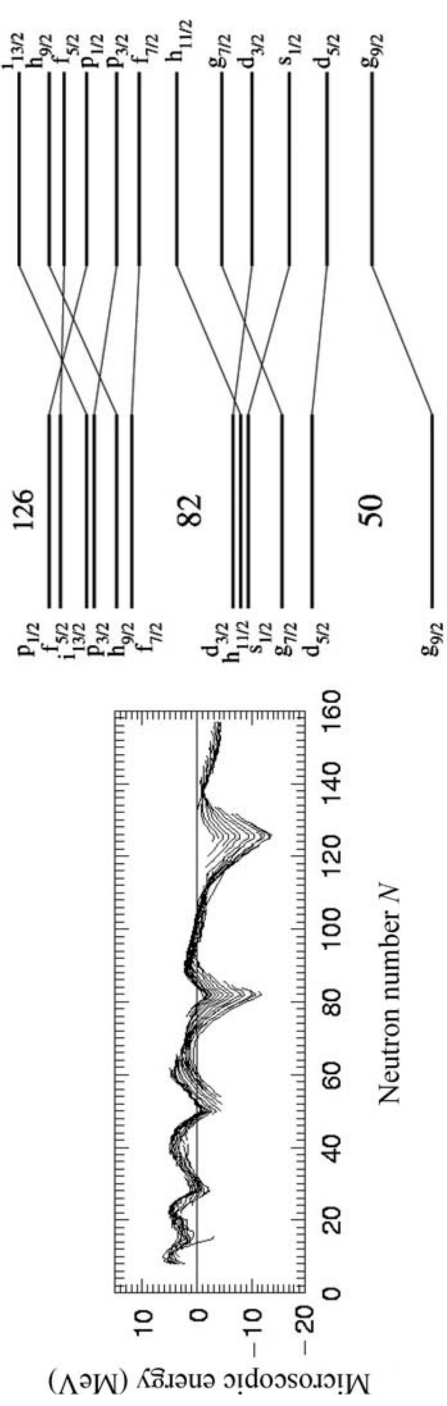
Figure 4 (*Left panel*) Nuclear shell energies relative to a finite-range liquid-drop model. (*Connected center and right panels*) Shell structure characteristic of nuclei close to the valley of stability and possible shell structure for a shallow single-particle potential anticipated for nuclei close to the neutron drip line. The connecting lines link the same single-particle orbital in the two cases.


Microscopic energy (MeV)
10
0
−10
−20
0
20
40
60
80
100
120
140
160
Neutron number N
126
82
50
$p_{1/2}$
$f_{5/2}$
$i_{13/2}$
$p_{3/2}$
$h_{9/2}$
$f_{7/2}$
$d_{3/2}$
$h_{11/2}$
$s_{1/2}$
$g_{7/2}$
$d_{5/2}$
$g_{9/2}$
$i_{13/2}$
$h_{9/2}$
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$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
$h_{11/2}$
$g_{7/2}$
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
$g_{9/2}$

the properties of the deuteron (e.g., Reference 17). As illustrated in Figure 3, two-body interactions alone cannot reproduce the binding energy of the simplest nuclei. Both effective field theory and meson-exchange approximations point to the need for a three-body interaction that can provide the additional amount of binding. There is evidence that higher-order interactions are small and can be safely neglected. By constraining the three-body interaction—most importantly the isospin dependence—by fits to the experimental spectra (18), excellent agreement between theory and experiment is obtained (see the red and green bars in Figure 3). One of the major surprises of this type of calculation is that these three-body interactions significantly affect the isospin dependence of the average nuclear mean field, and compared to calculations with two-body interactions alone, they may contribute as much as half of the mean-field spin-orbit interaction, as seen in the increased splitting of the $p_{3/2}$ and $p_{1/2}$ levels in the odd-A nuclei. The isospin-dependent three-body force has important and sometimes unexpected consequences. For example, neutrino scattering cross sections in ^{12}C (19) are affected. Also, although realistic two-nucleon interactions alone predict the wrong ground state (1^+) for ^{10}B (Figure 3), the inclusion of three-body interactions provides the stronger spin-orbit components that resolve this problem.

The success of the ab initio calculations goes far beyond the reproduction of energy levels. Key features in nuclear structure, such as the strong and apparently rather universal effects of the short-range interaction on renormalizing the single-particle strength, are reproduced (e.g., Reference 20). Transition rates such as β-decay appear to be under control with bare nucleon currents and well-understood meson-exchange currents (21). Even the long-standing issue of the Nolen-Schiffer anomaly in the Coulomb energies of mirror states in light nuclei (22) can be understood by the isospin breaking of modern nucleon-nucleon interactions. Crucial features of nuclear correlations, such as the strong alpha clustering phenomena generated by the spin-isospin properties of the interaction, emerge naturally. These are essential for processes such as the triple alpha capture (synthesis of ^{12}C) and ^{12}C$(\alpha,\gamma)^{16}$O reactions so important in stellar evolution. These clustering phenomena are given much less emphasis in mean-field approximations to nuclear structure. However, they may well be a key feature left out in the physics of heavier nuclei.

The three-nucleon potentials available today remain empirical, and, in particular, new experimental data and theoretical progress are needed to shed light on the dependence of these potentials on the proton-neutron asymmetry and on the density of the medium. In this context, the properties of nuclei such as ^{6,8}He or ^{11}Li, which a rare isotope accelerator will provide in large quantities, are of great importance. In these loosely bound systems, just before the neutron drip line is reached, the valence neutrons occupy orbits with large spatial extensions. Because of their large radii, such systems are referred to as halo nuclei and, for example, ^{11}Li can be viewed roughly as a three-body system made up of a densely packed ^{9}Li core and two additional neutrons spreading throughout a volume as large as that occupied by ^{208}Pb. Calculations show that the charge radius of ^{6}He is sensitive to the choice of three-body forces and that the recent atom trap measurement of this quantity (23) is reproduced by using modern forces. With much-improved beams of these halo nuclei it will be possible to probe their properties further by, for example, carrying out measurements investigating the degree of correlation of the neutrons in the halo, the radial distribution of the halo, and whether the halo nucleons can be induced to oscillate against the core (so-called pigmy resonance). It will also be important to extend the study of halo systems to heavier nuclei.

The results obtained so far with ab initio approaches are impressive and will continue to illuminate our understanding of nuclei. However, the current generation of calculations with realistic nuclear forces can be expected to be carried out only for the lightest systems, i.e., for nuclei with mass $A < 12$–16, even in an era in which the available computer power doubles every 18 to 24 months. They are also currently limited in weakly bound nuclei by slower convergence of the numerical techniques, a situation that should be remedied in the near future. New numerical approaches, such as auxiliary field Monte Carlo (24) may extend this approach to heavier systems, perhaps up to a mass of 40. Nevertheless, new experiments on rare neutron-rich nuclei are required to fully pin down the microscopic input so that these ab initio calculations can become the standard against which to evaluate the success of other many-body approximations that can be realistically implemented for heavier nuclei.

Shell Structure and New Magic Nuclei

For decades the cornerstone of nuclear structure has been the concept of single-particle motion in a well-defined potential leading to shell structure and magic numbers. Only rather recently have we learned that the magic numbers are not immutable (25). This is illustrated in Figure 6. A number of measured properties such as the mass, the energy of the first excited state, and the $B(E2;\, 0^+ \rightarrow 2^+)$ transition probability indicate that the magic numbers 8, 20, and 28 no longer apply to neutron-rich nuclei such as $^{12}\mathrm{Be}_8$, $^{32}\mathrm{Mg}_{20}$, or $^{44}\mathrm{S}_{28}$. The $N = 28$ shell closure appears to retain its character in the very neutron-rich $^{42}\mathrm{Si}_{28}$ nucleus (26), but additional stability occurs for near drip-line oxygen nuclei with neutron numbers 14 and 16, as well as for $N = 32$ neutron-rich Ca, Ti, and Cr isotopes (27). Shell model descriptions with effective interactions derived from nuclei close to the valley of stability seem inadequate far from stability.

New experiments on single-nucleon transfer reactions map out the changes in single-particle orbitals with particle number. Neutron knock-out measurements on ^{12}Be indicate that its ground state has a very large $1s_{1/2}$ (28) and $0d_{5/2}$ (29) occupancy, compared with the dominant 0p-shell occupancy expected in a simple shell model. In heavier nuclei, recent measurements (30), illustrated in Figure 7, demonstrate the unexpected and drastic change with neutron excess of the relative energy between (*a*) the $h_{11/2}$ and $g_{7/2}$ proton orbits and (*b*) the $h_{9/2}$ and $i_{13/2}$ neutron orbits. In this case, the evolution of nuclear shells with neutron number can be understood on the basis of the effects of the neutron-proton tensor

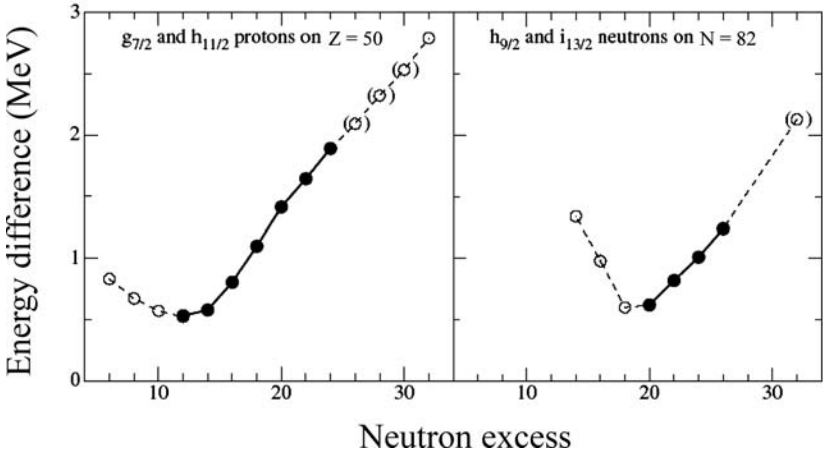

Figure 7 Comparison of energy differences between pairs of single-particle states for single nucleons outside the Z = 50 and N = 82 shells as a function of the neutron excess of the core. The open circles within the parentheses indicate less certain or indirect assignments. The pronounced minimum in the two curves is near the neutron excess corresponding to maximum stability. See Reference 30 for details.

force as nucleons are added to the core (31). However, critical future measurements with rare isotope beams should extend these single-nucleon transfer reactions toward more neutron-rich nuclei to clarify whether the changes in the orbital spacings are encapsulated by these residual interaction effects or whether they represent a lack of understanding of the density dependence and isospin dependence of the spin-orbit interaction in systems with increasingly weak binding.

Beams from a rare isotope accelerator provide a unique opportunity to improve our knowledge and understanding of shell structure. For example, three (possibly) doubly magic nickel (Z = 28) isotopes, i.e., $^{48}Ni_{20}$, $^{56}Ni_{28}$, and $^{78}Ni_{50}$, are available, as well as the tin (Z = 50) isotopes ^{100}Sn and ^{132}Sn. The region around ^{132}Sn is especially pivotal: The anticipated high-production yields translate into the possibility of gathering the required knowledge on single-particle states and on the occupation of these states by nucleons from one- and two-nucleon transfer reactions and nucleon knock-out reactions that directly probe the single-particle wave functions.

Shell Structure and the Heaviest Nuclei

The heaviest nuclei occupy a special place in our understanding of nuclear systems, as they owe their very existence to the subtle interplay between the repulsive Coulomb force and the added binding coming from shell effects. As illustrated in Figure 5, both the magnitude and location of stabilizing shells in this superheavy region are a matter of considerable theoretical uncertainty, as are properties such as the associated lifetimes and decay modes. In addition, the possibility has been raised that these nuclei would form new topologies, such as bubble shapes, owing to the relative strength of the Coulomb force in high-Z nuclei (32).

Intense beams of a rare isotope accelerator will make it possible to reach the more neutron-rich nuclei close to the center of the predicted island(s) of stability and to characterize the decay of neutron-rich isotopes of elements with $Z = 100$–112, which will play a decisive role in the identification of new superheavy elements as part of their α-decay chains. (Fusion reactions with stable projectile and target combinations unavoidably lead to systems with too few neutrons.) The neutron-rich $Z = 100$–112 nuclei are predicted to have sufficiently long half-lives to allow studies of their chemical properties. The latter are affected by the relativistic motion of the valence electrons in the strong nuclear electric field. Finally, the stability of heavy nuclei is directly related to the potential barrier to spontaneous fission. Recent experiments in No isotopes indicate these shell-stabilized nuclei are surprisingly stable against fission up to at least spin 20 (33). For the vast majority of neutron-rich heavy nuclei, the fission barrier is unknown, yet its height and shape have a direct impact on their very existence. A rare isotope accelerator provides the opportunity to map the full fission-barrier surface for the first time.

The Limits of Neutron-Rich Nuclei

Although we do not know at present where the periodic table of nuclei terminates in the limit of high Z, the situation is not much better for neutron-rich nuclei, the unexplored territory in Figure 1. The neutron drip line has thus far been delineated for only the eight lightest elements. The nucleus ^{24}O ($Z = 8$ and $N = 16$) is the heaviest oxygen isotope that is stable against nucleon emission. This result is quite surprising, as one might have expected the nuclear landscape to extend up to at least ^{28}O, in view of the doubly magic character of this nucleus ($Z = 8$ and $N = 20$). Perhaps even more astounding is the experimental discovery that the addition of a single proton (to form fluorine) binds at least six more neutrons. Indeed, ^{31}F ($Z = 9$ and $N = 22$) is particle bound (34), and this nucleus may not be located at the drip line; searches for the heavier fluorine isotopes ($A = 33, 35$) are being pursued. A rare isotope accelerator will establish the limits of nuclear existence for elements up to at least manganese ($Z = 25$), and depending on the exact location of the neutron drip line, perhaps again in the $Z = 40$ and $Z = 60$ regions (Examples of the reach of future accelerators are shown later in Figures 13 and 14.) For heavier nuclei, such a facility will establish nuclear existence along isotopic chains 10 to 20 neutrons beyond the heaviest isotopes identified thus far and will allow the determination of masses and lifetimes—basic quantities essential for our understanding of astrophysical processes, especially the r-process. This new knowledge will allow safer theoretical extrapolations beyond the limits directly accessible to experiment.

Weak Binding and Neutron-Rich Nuclei: New Forms of Nucleonic Matter

Figure 2 illustrates that weakly bound neutron-rich nuclei are characterized by a large, diffuse surface region. This can be accompanied by close coupling to the continuum. As an example, Figure 8 compares calculated density distributions of $^{100}\mathrm{Sn}_{50}$ and $^{100}\mathrm{Zn}_{70}$ (35). The distributions are strikingly different, with neutrons extending much farther out and forming a "skin" in the neutron-rich system. Unfortunately, the reliability of these calculated density distributions cannot yet be ascertained for nuclei far from the line of beta stability because neutron radii are notoriously difficult to determine and measurements with neutron-rich beams await facilities such as a rare isotope accelerator. The calculations are sensitive to the dependence of the effective neutron-proton forces on neutron excess, which is at present poorly known. It is also possible that the neglect of alpha-particle clustering alluded to above leads to an overestimate of the predicted skin effects, except in the most weakly bound cases. The diffused neutron density of $^{100}\mathrm{Zn}$ also gives rise to a shallow mean-field potential affecting the spin-orbit force and to the resulting bunching of levels into major shells. Some calculations suggest that near the neutron drip line, existing shell gaps may be quenched and new magic numbers may possibly emerge, as illustrated in the right panel of Figure 4. Researchers have even suggested that, in such weakly bound neutron-rich systems, the pairing interaction (discussed below) together with the presence of skin excitations may invalidate altogether the picture of a nucleon moving in a single-particle orbit.

Correlations and Residual Interactions

Within the framework of the nuclear shell model, deeply bound nucleons are described as being in fully occupied states, whereas nucleons closer to the Fermi sea have occupancies that gradually decrease with excitation energy because of configuration mixing. This approximation ignores correlations from short-range nucleon-nucleon interactions and from longer-range couplings involving, for example, shape changes (36) or giant-resonance excitations (37). These correlations reduce the nucleon occupancies of the deeply bound states and shift strength to higher excitation energies. Occupancies of valence nucleons, measured primarily via (e,e'p) and one-nucleon transfer reactions on stable nuclei, were found to be quenched by factors 0.6–0.7 relative to shell model predictions. More recently, one-nucleon knock-out reactions with intermediate-energy exotic beams extended such studies to nuclei close to the drip line and revealed an interesting dependency on nuclear structure. The ratio of the experimental and shell model spectroscopic factors was 0.90 ± 0.04 for the weakly bound neutron in the neutron-rich nucleus $^{15}\mathrm{C}$ (38) and 0.24 ± 0.05 for the strongly bound neutron in proton-rich $^{32}\mathrm{Ar}$ (39), suggesting a significant link between correlation effects and the nucleon separation energy. Further studies are required to investigate the physical origin of this dependence of the strength of in-medium correlations on the asymmetry of nuclear matter, and beams from a rare isotope accelerator will play a decisive role in probing the issue.

Residual interactions in the altered mean field of very neutron-rich nuclei likely differ from those near stability. For example, the effect of the nucleonic environment is likely much weaker for neutrons in the skin than for neutrons in the center of a neutron-rich nucleus, requiring improved modeling of the density dependence of the effective forces. Also, neutron-rich nuclei are predicted to be very superfluid: The close-lying particle continuum provides a large reservoir for neutron Cooper pairs, whose scattering from bound to continuum states should drastically increase pair correlations (40). However, the pairing force can no longer be treated as a residual interaction, as is the case for nuclei near the valley of stability. Rather, its effect on the nuclear binding of the outer nucleons becomes comparable in magnitude to that generated by the shell effects.

Proton-Rich Nuclei

For proton-rich systems, the Coulomb interaction limits the number of protons that can be bound. As a result, the drip line lies closer to the valley of stability and its exact location is essentially established experimentally up to bismuth with present accelerators and experimental techniques (41). Nevertheless, here too beams from a rare isotope accelerator offer many opportunities to explore important physics questions such as the nature of proton radioactivity, the structure of nuclei beyond the proton drip line, the effects of the proton-neutron interaction, the role of isospin-breaking interactions in mirror nuclei, and shell structure. Of special interest here are the nuclei with the same number of protons and neutrons for which tin ($Z = 50$) forms the approximate upper boundary of the region in which such nuclei lie inside the proton drip line. Because protons and neutrons in these $N = Z$ nuclei can occupy the same orbitals, special symmetries may play a significant role. In particular, a unique new type of proton-neutron pairing interaction, i.e., a new type of superconducting phase, can be present. In addition to the usual Cooper pairs of like nucleons with a net angular momentum of zero, protons and neutrons may form pairs coupled not only to spin zero, but also to spin one, i.e., they may form deuteron-like ($^3S_1$) pairs and, indeed, the free neutron-proton interaction is more attractive than that between identical nucleons. There is no comparable system known in other areas of physics with two types of similar fermions interacting. How such a pairing field manifests itself in the properties of $N = Z$ nuclei is not at all clear theoretically nor experimentally at the present time. Transfer reactions with $N = Z$ beams from a rare isotope accelerator are required to establish clear signatures. However, if such a pairing field with protons and neutrons coupled to spin one does not exist, the reasons for its absence will also challenge our understanding and may have a wide impact.

New Collective Modes

One of the remarkable properties of nuclei is that their spectra often exhibit regularities that can be described in terms of many-body symmetries, which dramatically simplify the interpretation of certain classes of states by introducing simple degrees of freedom, such as deformation. Studies of nuclei close to the valley of stability have uncovered a rich variety of phenomena associated with the interplay between single-particle and collective degrees of freedom and successful descriptions have been provided in terms of collective variables. In this context shell effects play a decisive role, as the occupation of specific orbitals can drive the overall nuclear shape away from sphericity. Hence, changes in shell structure will affect collectivity, and deformation can appear in unexpected regions. The so-called "island of inversion" (42) phenomenon discovered in neutron-rich exotic nuclei near $N = 20$ (^{30}Ne, ^{31}Na, $^{32-34}$Mg) is an example of such an unanticipated structural change. The inversion, i.e., the presence of deformed rather than spherical ground-state configurations, results from promotions of neutrons across the $N = 20$ shell closure and has been attributed to their strong mutual interactions, as well as their interactions with valence protons, and to shifts in single-particle energies.

An intriguing feature of very proton-neutron asymmetric nuclei is the prediction that rather different deformations apply for protons and neutrons (43). Hence, unexpected types of collective excitations, such as oscillations of the two deformed systems with respect to one another, may give rise to collective states of low excitation energy and also to new types of band structures at high angular momentum. Moreover, at the drip lines, in the region occupied by nuclei with halos or skins, a more fundamental question arises. The concept of a nuclear shape implies a well-defined surface. Such a geometric picture may break down in the limit of a diffuse surface resulting from weak binding. For example, the shape of a neutron halo may be determined by the spatial distribution of the valence nucleons, independently of the shape of the core, and this situation may give rise to new types of collectivity.

The probing of the key concepts of nuclear structure alluded to above, such as independent particle motion, the occurrence of magic numbers, the role played by correlations, and formulations of how the interactions evolve with the neutron-to-proton asymmetry, requires access to specific nuclei whose structure allows the amplification and isolation of those components of the effective interaction and those features of nucleonic correlations that depend most sensitively on the neutron-to-proton ratio. This is precisely the role of a rare isotope accelerator. A comprehensive experimental approach to these issues implies that they be studied not only at the very extremes of accessibility, but also well inside the drip lines. It also requires that a number of experimental techniques be available. For example, direct single-nucleon, pair-transfer, and removal reactions with both beams reaccelerated to energies above the Coulomb barrier and fast beams will emphasize single-particle properties and many-body correlations. Coulomb excitation with reaccelerated exotic beams, single-step Coulomb excitation with both fast and low-energy beams, and β-decay of stopped nuclei and a number of other techniques with fast, reaccelerated, and stopped beams will provide unprecedented avenues to extend our knowledge of nucleonic correlations, collective modes, new phases of nuclear superconductivity, phase transitional behavior in nuclei, and the way in which structure evolves with nucleon number.

Bulk Properties

Giant resonances are another manifestation of nuclear collectivity seen at high excitation energies. These basic excitation modes are understood as coherent vibrational states involving a large number of nucleons inside a nucleus, and they primarily probe bulk properties of nuclear matter. For instance, the giant monopole resonance has delivered the most precise information on the compressibility of nuclear matter at normal density and low temperature, whereas the properties of the giant dipole resonance are determined mainly by the nuclear symmetry energy (44). A large proton-neutron asymmetry will have a significant impact on these collective excitations. The spectral shapes of the resonances should be much more fragmented than in stable nuclei, as the particle-hole energies involved for protons and neutrons will differ considerably from each other. In nuclei with a large proton or neutron excess, a clear separation into isoscalar (protons and neutrons vibrating in phase) and isovector (protons and neutrons vibrating out of phase) modes will no longer apply. This effect is again related to the presence of skins or halos. The nucleons forming these regions are much less bound than the ones remaining in the core. A new type of vibration may evolve, i.e., a vibration of skin nucleons against core nucleons. Clear experimental evidence for such soft collective resonances has not yet been obtained, although low-lying dipole strength exhausting a considerable fraction of the total strength has been found in halo nuclei (45). This dipole strength, which appears just above the neutron separation threshold, is most likely associated with single-particle transitions enhanced in strength by the strong spatial overlap of the asymptotic part of the valence-neutron wave function with neutron continuum states, but this interpretation still needs validation.

As nuclear matter can be compressed to densities roughly twice the saturation density during nucleus-nucleus collisions at energies of the order of 300–400 MeV/nucleon (MeV/u), valuable information can be obtained on the relation between pressure, density, and temperature, i.e., on the equation of state (EoS) of nuclear matter. This is done primarily by studying observables constructed from the momenta of the particles originating from the collisions associated with the highest pressures and densities (46). They have led, for example, to a value of the nuclear incompressibility that agrees with that inferred for normal nuclear density from giant monopole resonance investigations (47). Thus far, experimental studies have focused on the isoscalar dependence of the EoS of nuclear matter. A rare isotope accelerator offers the opportunity to explore the isovector dependence, i.e., the dependence on the difference between neutron and proton densities.

Outlook

As shown above, the opportunity exists to answer long-standing questions in nuclear physics such as those related to (*a*) changes in the effective interactions as a function of neutron excess, (*b*) the origins of shell structure and its evolution with binding energy and proton-to-neutron ratio, and (*c*) the nature of excitation modes in weakly bound systems. The overarching goal of this scientific endeavor is to guide the development of a unified theory of the nucleus in which both the familiar properties and excitation modes of nuclei at and near stability, and those of the exotic species far from stability, can be described in a single framework. This is possible only with sufficient access to rare isotopes and is needed, specifically, to determine isospin-dependent parts of the nuclear interaction and, more generally, to gain better insight into the physics of the nuclear many-body system.

NUCLEAR PHYSICS OF THE UNIVERSE

The study of rare isotopes is an essential part of the effort to answer the questions of how the elements were created, how elemental abundances have evolved over time, and how stars evolve and explode. Stellar evolution and nucleosynthesis, in particular explosive nucleosynthesis scenarios such as novae, supernovae, and X- or γ-ray bursters, are governed by the largely unknown properties of rare isotopes. Hence, progress in astrophysical modeling is tied to our knowledge of these short-lived nuclei and their properties. Recent progress in accelerator and experimental technologies makes it feasible to construct a facility that can provide nearly all of the needed information by producing most of the isotopes important for nucleosynthesis and by allowing measurement of the properties of unstable nuclei that will be needed for the development of improved nuclear models capable of making reliable predictions of those properties not accessible to experimental study.

The chemical history of the universe starts with the hydrogen, helium, and a small amount of lithium created in the big bang and continues with the ongoing synthesis of the other elements inside stars or in explosive stellar environments (48, 49). Unraveling this history is a challenge. Little is known about the astrophysical sites, and most of the underlying nuclear and atomic physics remains to be explored.

Heavy elements play a significant role in galactic evolution, star formation, and planet formation and serve as a diagnostic in identifying the past history of galaxies and stars. In 2003, the United States National Academy of Sciences performed a study to determine and highlight the most important open questions connecting the physics of the very large distance scales to that of the very small (50). Many of the identified "Eleven Questions" relate to research in nuclear science, and one in particular recognizes the importance of chemical evolution, namely, How were the heavy elements from iron to uranium made?

The time is ripe to address this question. Rapid progress in the delineation of galactic chemical evolution is made possible by a wealth of new data on the chemical makeup of various astrophysical sites, as well as new data from meteorites and ocean sediments—and a promise of further data of unprecedented quality from next-generation, high-resolution space- and Earth-based observatories. Astronomical missions such as the Hubble Space Telescope, CHANDRA, Spitzer, and the Sloan Digital Sky Survey provide increasingly detailed information on element synthesis, stellar explosions, and neutron stars over a wide range of wavelengths. Improvements in computer power, computational techniques, and advances in accelerators and nuclear science will provide the technical and factual underpinning needed for modeling galactic chemical evolution and stellar evolution.

Subsequent to the National Academy study, scientific funding agencies in the United States formed an interagency task force to consider the large-scale scientific facilities needed to answer the "Eleven Questions." The resulting report, *A Strategic Plan for Federal Research at the Intersection between Physics and Astronomy* (51), highlighted a number of facilities. The report states, "Looking forward, the proposed Rare Isotope Accelerator (RIA) will be able to specify, control, and vary precisely the number of protons and neutrons in nuclei in order to study not only the properties of individual nuclei, but also the evolution of these properties across the nuclear chart. The goal is to achieve a comprehensive, unified theory of nuclear structure across the entire landscape of ordinary and exotic nuclei, leading to a detailed understanding of the processes that led to production of heavy elements."

Astronomical Data and Open Questions

There is a wealth of new data on elemental and, in some cases, isotopic abundances. In part, these data are based on terrestrial measurements, but more often the new data come from Earth- and space-based observatories. The breadth of data is remarkable; nearly all require information on rare isotopes to interpret their meaning.

Interesting new information comes from the relative isotopic abundances of C, Si, N, Ca, Mg, Ti, Ne, Xe, Kr, Ba, Nd, Sr, Sm, Dy, Mo, and Zr in presolar grains found in meteorites (52). These isotopic ratios help identify the origin of the various grains and determine the abundance patterns in the environments in which the meteorites were formed. Complementary data are now extracted from ocean sediments distinguished by unusual abundance patterns, presumably formed by large meteoritic impacts (53, 54). This constrains nucleosynthesis in a number of environments, from red giant stars to supernovae. Qualitative agreement with models has been obtained, but uncertainties in nuclear reaction rates limit the conclusions that can be drawn.

Large-aperture telescopes provide the opportunity to obtain detailed elemental distributions from the absorption spectra of single stars. Of particular interest are studies of extremely metal-deficient (hypermetal poor) stars that have an iron-to-hydrogen ratio of less than 1/100,000 that of our Sun (this is written by astronomers in logarithmic notation as $[\mathrm{Fe/H}] = -5.0$ dex) (55). Such low metal abundances indicate that these stars may be more than 10-billion years old. Remarkably, the metal abundance patterns of these stars show very little variation, indicating a common process of early element formation (56). Among these stars (see Figure 9), are r-process-enhanced stars (57), s-process-enhanced stars (58), and stars with high concentrations of CNO (59). The details of the required nuclear physics input to interpret these data are discussed below.

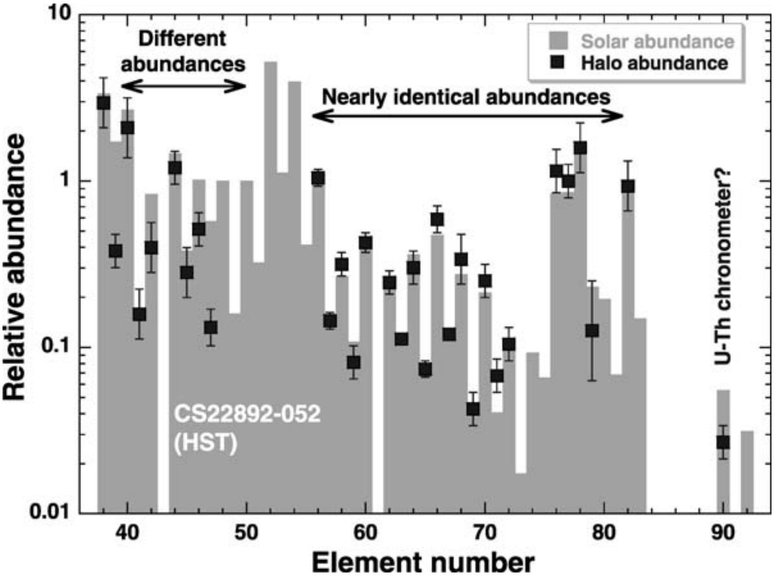

Figure 9 Abundance pattern measured for a very metal-deficient halo star CS22892-052 (*black data points*) compared with solar system rapid-neutron-capture (r) process abundances (*gray bars*). The data for CS22892–052 indicate that the r-process is active in the early universe, but that there may be two different r-processes because the patterns do not agree in heavy and light nuclei. Radioactive uranium (U) and thorium (Th) are sometimes used as chronometers for the production process. (Figure and data taken from Reference 57 and J. Cowen, private communication.)

Current (INTEGRAL, CHANDRA) and next-generation (Constellation X) X-ray and γ-ray observatories provide a wealth of detailed elemental data and the ability to identify specific nuclei. For example, observation of ^{26}Al, a radioactive nuclide with a half-life of approximately 1 million years, in the Galaxy clearly demonstrates active nucleosynthesis. The observation indicates that approximately two solar masses of ^{26}Al are produced every million years in the Galaxy (corresponding to 1.5×10^{42} atoms/s). Surprisingly, the source of this nuclide is still unknown. There are three likely candidates: type II supernovae, novae, and Wolf-Rayet stars. It appears that supernovae cannot be the sole source of ^{26}Al because the recently measured ^{60}Fe/^{26}Al ratio by the Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) is in disagreement with supernovae models (60). The ^{59}Fe(n,γ) reaction is a critical and sensitive step in nucleosynthesis calculations. Measurement of the pertinent cross sections is feasible at a future facility, but not at existing facilities. Better observations and better nucleosynthesis calculations are needed to further address this problem.

Another example of a galactic radionuclide is ^{44}Ti, observed, for example, in the Cas A supernova remnant and in SN1987a. The observed abundances of such nuclides can provide sensitive probes for the conditions under which they were produced (61) (provided the underlying nuclear physics is known). Initial observations indicate that compared with supernova models ^{44}Ti is overproduced by a factor of two to three (62). This raises questions about the progenitor mass and other parts of the models. To illustrate the importance of nuclear measurements, a new measurement of the ^{40}Ca(α,γ) was performed at Argonne National Laboratory and Hebrew University (63). Researchers found that the cross section for this reaction was a factor of two higher than previous extrapolations. With the revised rate, supernova models are in much better agreement with observations.

The General Problem of Galactic Chemical Evolution

Understanding the detailed abundances of specific nuclides tells us a great deal about the history of our Galaxy, i.e., number of novae, supernovae, age, possible mergers, and by inference, about the chemical history of the universe (and Galaxy) (64). Various authors have attempted to model galactic chemical evolution, with recent work focusing on the elemental abundances for elements up to nickel (65–68). These models can be used to infer the age of the Milky Way and disk, determine the number of supernovae (or other events) that lead to element creation, and study other features of galactic evolution, provided the input data and assumptions are accurate. It is interesting to see cases in which there is large disagreement between calculated and measured abundances and to attempt to understand the origin of these discrepancies. It is also possible that the Milky Way, and in particular our solar system, may not have typical abundance distributions. Recent work comparing the Milky Way to M31 has found interesting differences in chemical composition that may tell about the histories of the two galaxies (69). The chemical composition of individual stars can also be used to identify original Milky Way stars from those captured from other galaxies (70).

Chemical evolution will be a focus of future work in astronomy. The most recent Astronomy Decadal survey (71) in the United States identified two high-priority space-based observatories. Constellation X will study compact object accretion and supernovae remnant abundances and be “[t]he premier instrument to. . .contribute to nuclear physics by measuring the radii of neutron stars, and trace the formation of the chemical elements.” The Webb Space Telescope will address a number of fundamental questions such as, What is the history of star formation and element production in galaxies? What is the shape of the universe? How do galaxies evolve? How do stars and planetary systems form and interact? How did the universe build up its present elemental/chemical composition? and What is dark matter (72)?

Nuclear data are necessary, but not sufficient, ingredients in understanding the origin of the elements. In addition, a concerted effort between computational, nuclear, atomic, and astrophysicists, as well as observational astronomers will be needed. Significant progress toward this end is being made. Recently, the Joint Institute for Nuclear Astrophysics was formed to foster such cross-discipline collaborations (73).

THE ORIGIN OF ELEMENTS HEAVIER THAN IRON The elements from iron to uranium are thought to be synthesized mainly by neutron-capture processes. Solar system abundances indicate that there are two such processes, a slow s-process taking place in the outer regions of red giant stars (74) and the r-process taking place in a very neutron-rich environment and on a short time scale (75). It is still unknown where the r-process occurs, and there is some evidence for two distinct r-processes and maybe even a third neutron-capture process (n-process) (76). A likely location for the r-process(es) are neutrino-driven winds in supernovae explosions. The confirmation of this requires advances in our ability to calculate three-dimensional hydrodynamics and radiation transport, in astronomical observation (to obtain statistics on element abundances in various stars and other environments), and in nuclear physics. Advances in any of these areas alone is insufficient.

The r-process represents a challenge because it requires an extremely high density of free neutrons that current astrophysical models do not reproduce and because its reaction sequence of neutron capture, β-decay, and fission includes exotic nuclei far beyond the reach of current accelerator facilities. From solar system elemental abundances, we can infer that the path of the r-process must be approximately that shown in Figure 1, far beyond the reach of current facilities but within reach of a future rare isotope accelerator. Without knowledge of the half-lives and binding energies of the nuclei involved, any model prediction of r-process abundances (and hence of the origin of the heavy-elements) remains questionable and semiquantitative at best.

Finding the location of the r-process is one of the prime challenges of astrophysics. Possible candidates include supernovae or merging neutron stars. Recently, the surface abundances of a few extremely metal-poor stars in the halo of our Galaxy have provided the first hints of the products of individual r-process events in the early Galaxy. In the coming decade, large-scale astronomical surveys such as SEGUE (Sloan Extension for Galactic Understanding and Exploration, the recently approved extension to the Sloan Digital Sky Survey) (77), followed by extensive campaigns of high-resolution spectroscopy with 8–10-m class telescopes, are expected to provide data on hundreds of these extremely rare stars.

Qian (78) has pointed out that neutrino post-processing of nuclei produced in the r-process could explain differences between calculated and observed abundances. Unfortunately, similar effects can arise from a possible quenching of nuclear shells far from stability (79). Until such model uncertainties from the underlying nuclear physics can be removed, hints as to the location of the r-process encoded in the r-process abundance pattern are difficult to decode.

The relative s- and r-process contributions to the observed elemental abundances can be understood only if each of these processes can be accurately modeled. This requires a greatly improved understanding of the underlying nuclear physics. Future rare isotope facilities can provide access to the vast majority of the neutron-rich nuclei involved in the r-process and allow measurements of the needed decay lifetimes, masses, and other properties. In particular, an advanced rare isotope

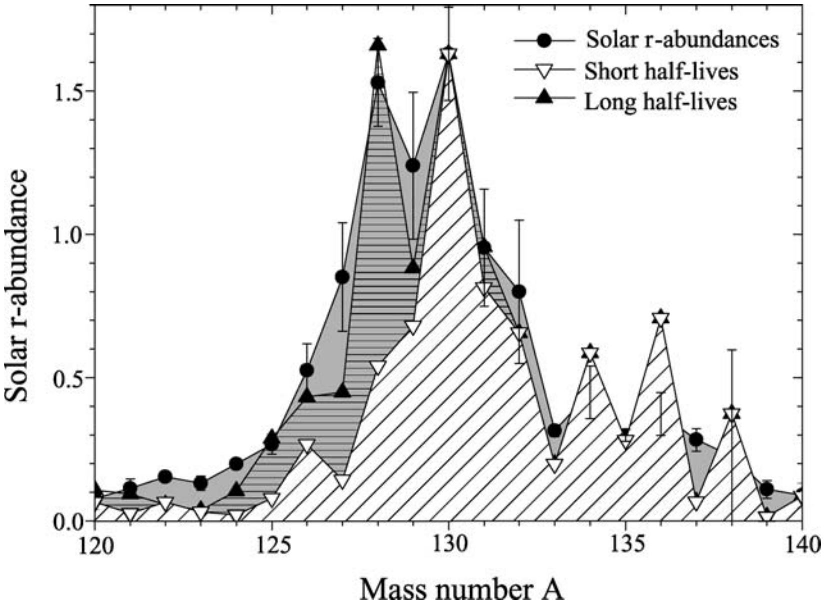

Figure 10 Comparison of rapid-neutron-capture (r) process abundance patterns relative to solar system abundances, based on calculations of the standard "waiting point" assumption using standard short half-lives and calculations based on new data for ^{130}Cd that indicate longer half-lives should be used. The figure shows the significant impact that changes in nuclear data can have on the calculated abundance patterns.

facility is needed to access r-process nuclei near the shell closure at neutron number 126. As the last 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.

To illustrate the importance of nuclear data, we show the impact of a recent β-decay study of ^{130}Cd (80) in which the details of the decay pointed to changes needed in models of the structure of nuclei in this region. As a result of using refined mass models based on the new data, the predicted r-process abundances were significantly altered (see Figure 10). The result is that the measured solar system abundance patterns around the $A = 130$ peak are reproduced much better. Clearly, searches for specific details, like a neutrino fingerprint or other hints of the r-process site, can be futile because of the existing uncertainties in the needed nuclear data.

The Role of Rare Isotopes in Astrophysical Environments

METHODS TO DETERMINE THE IMPORTANT NUCLEAR PHYSICS PROPERTIES Parallel to the progress in astronomy, there has been significant progress in nuclear science relevant to astrophysics. Improved radioactive ion beam capabilities have allowed direct measurements of some important reaction rates, e.g., that for ^{21}Na(p,γ) ^{22}Mg at TRIUMF/ISAC-I (81). Such experiments typically require intense, reaccelerated beams of rare isotopes of more than 10^9 ions per second.

Alternative indirect techniques provide additional information on astrophysical reaction rates. Although it appears that these techniques can produce reliable results, more work is underway to fully characterize when they can be safely applied. Representative examples of such indirect techniques include the following:

1. the Trojan Horse Method; see, e.g., the work on d(^{11}B,α ^{8}Be)n to determine the ^{11}B(p,α)^{8}Be cross section (82);
2. charge-exchange reactions with medium-energy probes to determine electron capture rates;
3. transfer reactions, e.g., (d,p), that can be used to infer capture rates, e.g., as done at Argonne National Laboratory with a ^{56}Ni beam (83);
4. determination of asymptotic normalization coefficients by near-Coulomb barrier transfer and elastic scattering, developed at Texas A&M University (see, e.g., Reference 84);
5. use of Coulomb breakup for the determination of s-factors, e.g., ^{8}B(γ,p)^{7}Be studies at RIKEN (85), GSI (86), and NSCL (87);
6. nucleon knock-out that can provide spectroscopic factors for beams as weak as 0.1 ions/s (88); and
7. decay studies that can be performed with a few atoms per week (89).

The required secondary beam intensities range from 10^7 atoms per second for the reactions at the top of the list to a few atoms per week for the decay studies. A key point is that a number of tools are available and that advances in this area now make it possible to obtain important information with as few as 10 atoms.

We now consider some of the important astrophysical phenomena and illustrate the relevant nuclear physics quantities that must be determined.

NOVAE The elemental abundances from novae probe the conditions during the explosion—and our understanding of white dwarf binary systems. This understanding is necessary for putting type Ia supernovae models on a firm footing. Sensitivities to reaction rates were studied in novae models by Iliadis et al. (90). Important open questions related to novae nucleosynthesis are the extent of nova contributions to galactic γ-ray activity, why the mass ejection from novae seems to be so large, and to what extent the white dwarf material is mixed into the explosive ejecta.

Recent measurements of reactions involving radioactive nuclei include the important reactions ^{13}N(p,γ)^{14}O at LLN (91), ^{17}F(p,γ)^{18}Ne at ORNL (92), and ^{21}Na(p,γ)^{22}Mg at ISAC using 2×10^{9} ^{21}Na ions/s. One current open question is whether or not ONeMg novae could be a source of the ^{26}Al γ-rays detected by

INTEGRAL. A number of additional important reaction rates involving radioactive nuclei must be measured before this question can be settled. Many of these studies require intensities that may not be available until advanced rare isotope accelerator facilities are built.

TYPE I SUPERNOVAE The model for type I supernovae is a white dwarf star in a close binary system that accretes enough mass from a companion star to explode as a supernova. Carbon ignites in the central region and launches a thermonuclear flame that burns through the white dwarf and completely disrupts it. Such type Ia supernovae are observed to have characteristic light curves that allow an empirical calibration of their intrinsic luminosities, and they have provided evidence that the expansion of the universe is accelerating. Discovering why these supernovae are a homogeneous class and what spread occurs in their luminosity and nucleosynthesis are high-priority objectives of supernova research. Electron capture rates on unstable nuclei, which must await a future facility for comprehensive measurements, both directly and in charge-exchange reactions strongly influence the resulting nucleosynthesis and may affect the explosion energetics. Quantitative analysis of the observed composition of nova ejecta, including gamma radiation from the radioactive decay of the synthesized material, when combined with a thorough understanding of the underlying nuclear physics from new facilities, will enable us to determine the trigger of the explosion leading to type Ia supernova and the role that novae play in synthesizing the light elements.

S-PROCESS Modeling the details of the s-process requires the precise measurement of (n,γ) cross sections. Using isotope harvesting from rare isotope facilities, important neutron-capture cross-section measurements of long-lived unstable nuclei in the s-process can be performed. Such data are needed to accurately determine the contribution of the s-process to the observed abundances of heavy elements. Generally, rare isotope yields greater than 10^9 s^{-1} are required, but because the isotopes of interest are near stability, the next-generation facilities should supply many of the needed nuclides.

TYPE II SUPERNOVAE As mentioned above, r-process calculations require knowledge of masses, half-lives, and beta-delayed neutron-emission rates of very neutron-rich nuclei. Important new insight has come from measurements of very old stars by Hubble, Keck, and Subaru. These stars, with $[Fe/H] < -3$ dex, show a relatively uniform r-process abundance pattern that matches the solar system abundance. The detection of radioactive nuclides of uranium and thorium in these very old stars allows comparison to solar abundances and inferences on the date of nucleosynthesis. Hence, these uranium and thorium abundances provide another test of the age of the universe; thorium:europium and thorium:uranium ratios yield an age of 13.8 ± 4.0 Gy (93). At present, only a few such stars have been found, but new surveys conducted over the next 10 years may find thousands of such ancient stars (see also Reference 94).

Nuclear physics determines the structure of the collapsing core, especially the iron core mass, which is sensitive to weak decay rates in the pre-explosive star, and the strength of the prompt shock that emerges from the bounce. Much experimental work is needed on the electron capture rates (which can be measured in charge-exchange reactions) and to infer neutrino-induced cross sections. More theoretical work is needed to determine how variations of the weak interaction rates affect the explosion mechanism. The related nucleosynthesis involves high temperatures and densities—and short-lived nuclides very far from stability. Often the properties of these short-lived nuclei are critical to the final abundance distributions and/or to the energy generated. Often, the abundances of a few nuclei can offer a sensitive diagnostic. For example, ^{44}Ti is produced in supernovae and its γ-decays can be detected directly in the remnant. Given reliable nuclear physics, nucleosynthesis abundance determinations in supernova ejecta and the solar system will serve as a powerful diagnostic of the explosion mechanisms and, in the case of core-collapse supernovae, determine the boundary that separates ejected matter from matter falling back onto the remnant neutron star or black hole.

X-RAY BURSTS Type I X-ray bursts are thermonuclear explosions on the surface of a neutron star accreting matter from a companion star in a binary system. The fuel, hydrogen and helium, accretes onto the neutron star surface for periods ranging from hours to days and then ignites in a thermonuclear runaway, releasing typically 10^{40} ergs of energy and lasting 10 to 100 s. Recent observations by the Beppo SAX, RXTE, and CHANDRA satellites have provided a wealth of information on light curves, burst oscillations, and a new class of extremely energetic and long-duration bursts termed superbursts. Interpretation of this observational information requires a detailed understanding of the underlying nuclear physics. The bursts are driven by a breakout of the CNO cycle into a series of rapid proton captures known as the rp-process (95), which fuses hydrogen and helium into heavier elements. Recent progress in modeling these bursts now allows for one-dimensional simulations with the full nuclear physics of the rp-process (96). The predictions of these models depend on accurate astrophysical nuclear reaction rates. With accurate nuclear data on nuclear masses, (p,γ) and (α,p) reaction rates, the new observations could be the beginning of a precision era in the study of X-ray burst systems. New techniques to study rp-process nuclei include neutron-stripping reactions (97) and the use of Penning traps for precise mass measurements of short-lived nuclei (98). A large body of nuclear data is still needed to reach the precision era in these studies, but the rates at a rare isotope accelerator are available to fill in nearly all of the details needed.

NEUTRON STARS AND THE EQUATION OF STATE OF NEUTRON MATTER A key piece of nuclear physics information needed for astrophysics is the neutron matter EoS. The neutron matter EoS is critical to models of neutron stars and supernovae (99). There are constraints on the EoS of symmetric matter (equal numbers of protons and neutrons), but there are few constraints on neutron matter. Radioactive beams provide an opportunity to explore the neutron matter EoS. At 200–1000 MeV/u, collisions compress nuclear matter to up to three times normal density. In collisions of heavy ions, the sideward flow, balance energy, and elliptic flow can be measured, and researchers have proposed several new observables that facilitate the necessary extrapolations to the EoS of very neutron-rich nuclear matter. In addition, data on the size of neutron skins in neutron-rich nuclei will provide constraints on the volume asymmetry term (100, 101).

Observations of superbursts and the cooling of the neutron star crust during periods when the mass transfer is interrupted could provide constraints on the possible existence and nature of exotic phases of matter in the neutron star core. These studies are presently limited by the lack of understanding of the physics of very neutron-deficient and very neutron-rich nuclei.

PHYSICS BEYOND THE STANDARD MODEL

An ultimate challenge for science is to determine the fabric of the universe, the building blocks of nature, and their interactions. The scale of this task, the Planck scale (10^{19} GeV), requires probes far beyond the current and next generation of accelerators, in which the Large Hadron Collider and the Linear Collider will directly probe physics at the scale of 10^4 GeV. Hints for physics beyond this limit come from the observed nature of the universe and from precision, low-energy tests of fundamental quantities that are sensitive to corrections at a much higher energy scale. Nuclear science, and rare isotopes, makes a small but important contribution to the quest. Nuclei and nuclear transitions can have special symmetries and/or enhanced sensitivity to new physics.

Indeed, nuclear experiments pioneered much of our understanding of the weak interaction, including the first direct detection of neutrinos, parity violation, the establishment of the vector-axial vector structure of the weak current, neutrino helicity, direct limits on neutrino masses, and the establishment of neutrino mixing. The broad variety of nuclear systems often allows one to use a specific nuclear system to isolate or amplify the important physics. For example, electron capture measurements on ^{152}Eu gave a unique determination of the helicity of the neutrino from the polarization of the nuclear γ-ray (102). Even as direct searches for physics beyond the standard model test physics at higher and higher mass scales, new access to abundant radioactive isotopes can still provide sensitive tests of possible new physics.

Electric Dipole Moments

One of the most fundamental questions in modern science is the dominance of matter over antimatter in the known universe. An explanation could come from some type of violation of time-reversal (T) symmetry or, equivalently, by the CPT theorem, charge conjugation times parity symmetry (CP) (103). Although the standard model contains a mechanism for CP violation (the single CP-violating

TABLE 1 Spins I, half-lives $T_{1/2}$, and calculated electric dipole moments (108) for a given dimensionless time-reversal violating coupling strength η

Parameter	^{223}Rn	^{223}Ra	^{225}Ra	^{221}Fr	^{225}Fr	^{225}Ac	^{229}Pa	^{129}Xe	^{199}Hg
I	7/2	3/2	1/2	5/2	3/2	3/2	5/2	1/2	1/2
$T_{1/2}$	23.2m	11.4d	14.9d	4.9m	22m	10.0d	1.5d		
10^{25} d_A (η e-cm)	2000	2700	2100	240	2800	—	—	0.5	5.6

η has only a weak dependence on nuclear structure.

phase in the quark weak-mixing matrix), the magnitude of this violation cannot account for the observed matter asymmetry: Possible explanations include CP being violated in the strong interactions of light quarks or yet undetected forces that are not contained in the standard model. Indeed, one of the unnatural features of QCD is the apparent absence of the CP-violating theta term in the interaction. A very sensitive test for such interactions is the search for a static electric dipole moment (EDM), which is forbidden by T symmetry. Experiments that have searched for an EDM of electrons, neutrons, and nuclei currently provide the best limits on these possible new interactions (104). Extensions of these measurements are planned for the future. Improved sensitivity in each of these classes of searches is required to separate possible contributions from electron EDMs, quark EDMs, and CP violation in the interactions between quarks.

In the past decade researchers have realized that nuclear structure can strongly amplify the sensitivity of nuclear EDM measurements to the underlying physics (105). Regions of pear-shaped octupole deformation and enhanced octupole vibrations in nuclei lead to closely spaced parity doublets and considerably larger Schiff moments, the difference between the mean-square radius of the nuclear dipole moment distribution and the nuclear charge distribution, that is the experimental quantity of interest. Table 1 lists a calculation of the EDM for a number of nuclear cases, including ^{199}Hg, for which the current best limits exist (106). The general features of these relative enhancements appear quite robust, although detailed calculations can vary by factors of a few depending on the nuclear structure approximations (107). What is needed for progress are abundant sources of these radioactive isotopes for the experiments and continuing improved understanding of the structure of these unstable nuclei to buttress the theoretical analysis. When measurements can be performed at the current levels of systematic uncertainty in these systems, they represent an extremely effective way to search for new physics at the multi-TeV scale.

Atomic Parity Violation

Another sensitive search for physics beyond the standard model is the precise measurement of how the weak mixing between the photon and Z bosons, usually parameterized as the Weinberg angle θ_W, depends on the distance scale over which the force is active. Atomic parity violation is a textbook example of these measurements, but present information is limited by both the experimental systematic errors and uncertainties in the atomic structure. New measurements with radioactive atoms promise to help both areas. The electron-nucleus interaction scales classically as Z^3, and even faster with relativistic enhancements of the electron density (109). For francium, in which the atomic structure is simple and can be calculated with precision, the effects are 18 times larger than in the present measurements (110) in cesium. Moreover, by performing experiments on a broad range of neutron numbers in the francium isotopes, the theoretical uncertainty can be significantly constrained (111). Hence, experiments on these unstable isotopes offer the most direct path to improve measurements of atomic parity violation.

Measurements of the nuclear anapole moments (which scale as $A^{2/3}$) provide a unique possibility to test parity-violating neutral-current hadronic interactions. The weak interactions among quarks produce parity-violating components in the effective interactions among nucleons and mesons. Theory tells us which terms are important in the nuclear interactions at low momentum, but their coupling strengths seem to be quite different from the predictions of quark-based models. Determining them experimentally teaches us about the interplay between weak and strong interactions in hadronic systems, and they may provide new insights into long-standing puzzles surrounding strangeness-changing hadronic weak decays.

Other Directions

Searching for new physics is truly a quest for the unknown and takes many forms. Historically, many other nuclear phenomena have been important as theoretical expectations move in and out of fashion. Areas of current activity include searches for scalar, axial-vector, and tensor weak interactions (112), precise measurements of V_{ud} to study the unitarity of the weak quark mixing matrix (113), and nuclear double β-decay to search for a Majorana mass term. Although it is unclear where the most significant advances are needed in the coming years, it can be said with great confidence that the abundant production of unstable isotopes will play an important role in this future research.

Many of the measurements discussed in this section, including attempts to determine the neutrino mass through double β-decay, rely on accurate calculations of nuclear matrix elements in complex nuclei. The improvements in nuclear theory, guided by results from experiments at advanced rare isotope facilities, will be a significant advantage to these calculations, and these facilities will also provide a variety of new observables to help test and calibrate the models.

THE IDEAL RARE ISOTOPE ACCELERATOR

In 1998 and 1999 the Nuclear Science Advisory Committee's (NSAC) Isotope Separation Online (ISOL) Task Force studied and evaluated the options to build the next-generation rare isotope accelerator facility in the United States (114). They recognized that the study of rare isotopes is a worldwide field and that a new facility should have capabilities that allow it to compete with facilities that would likely be built elsewhere, and have capabilities that would be unique in the world. Researchers recognized that the scientific program described in this review requires intense sources of stopped beams, reaccelerated beams up to approximately 10 MeV/u, and in-flight beams of a few tens to a few hundred MeV/u. The concept that emerged was the Rare Isotope Accelerator (RIA). The considerations leading to the choice of the RIA concept are as follows:

1. The accelerator must be capable of delivering all beams up to uranium at energies of ∼400 MeV per nucleon to efficiently employ in-flight fission, as well as projectile fragmentation as a primary production mechanism.
2. A superconducting linac has the capability of accelerating simultaneously multiple charge states (115), which drastically reduces the normal beam loss by factors of 2–5 at each ion charge state–stripping step, an especially important aspect for heavy beams such as uranium or expensive isotopes such as ^{48}Ca.
3. Standard ISOL techniques, although very efficient for selected isotopes, have difficulty producing reaccelerated rare isotope beams of the many elements that do not diffuse rapidly through thick targets. By stopping rare isotopes produced and separated in flight in pure helium gas and extracting them rapidly and efficiently, access can be provided to all elements as reaccelerated beams essentially independent of their chemical properties.

Figure 11 shows a schematic diagram of the RIA facility concept. A highly flexible superconducting linear driver accelerator is used to produce rare isotopes. The RIA driver is capable of accelerating intense beams of all the stable isotopes from hydrogen to uranium, with a beam power of 400 kW and a minimum beam energy of 400 MeV per nucleon for uranium ions. (For lighter nuclei, the maximum beam energy is typically higher, depending on ion species. For protons and ^{3}He, the beam energy can be as high as 1 GeV and 0.78 GeV/nucleon.) The beam power of 400 kW is within reach of current ion source technology and presents an achievable extrapolation of high-power target concepts for isotope production.

The driver beams will be used to produce a broad assortment of short-lived rare isotopes, either via in-flight production and separation (projectile fragmentation or fission) or via the classic ISOL technique of thick-target irradiation leading to target fragmentation, fission, and spallation essentially at rest. The RIA concept encompasses the full arsenal of rare-isotope-production and experimentation techniques and, therefore, allows the problem-specific optimization of the best technical approach in a single facility. Enhanced facility utilization is accomplished by the installation of a beam switchyard that allows simultaneous beam delivery to separate production targets, i.e., to at least two independent experiments. Isotopes produced in flight can be used directly for experiments at high energy (≈20–400 MeV/nucleon), or they can be brought to rest, e.g., in a detector or in a gas

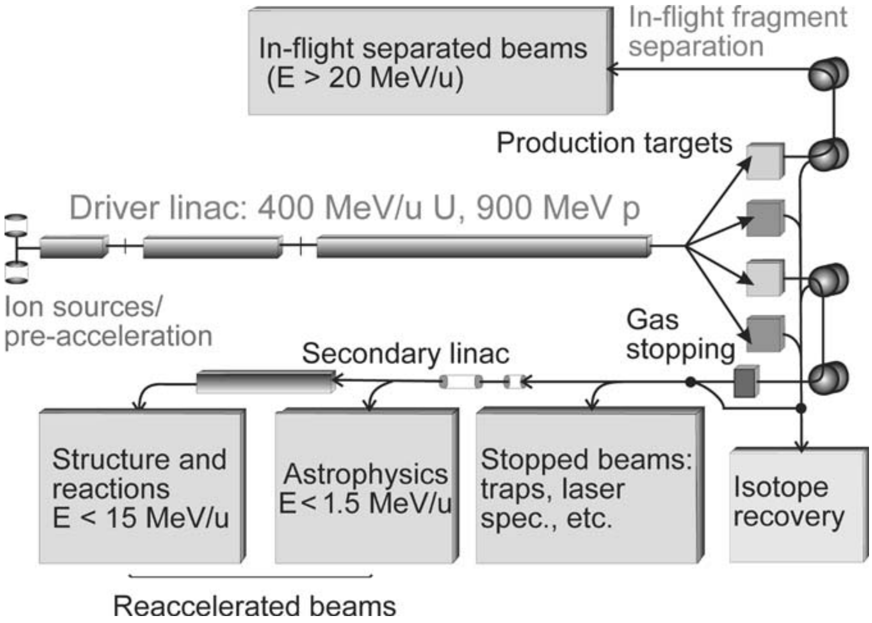

Figure 11 Block diagram of the major elements of the Rare Isotope Accelerator facility. The driver linac is capable of producing 400-kW beams of any stable isotope, with energies ranging from 400 MeV/nucleon for uranium (U) to 900 MeV/nucleon for hydrogen (p).

catcher, from which they can be extracted and used for experimentation at rest or for reacceleration. In-flight separation is independent of chemistry and occurs within microseconds, i.e., it is much faster than β-decay. For those isotopes in which ISOL techniques work well (approximately 40%), the higher stopped and reaccelerated beam yields of ISOL techniques can be efficiently employed. Figure 12 illustrates the optimum production technique for each isotope for reaccelerated beams (116).

Four independent experimental arenas allow experiments with fast beams of rare isotopes produced and separated in flight, precision experiments with trapped isotopes, low-energy experiments with reaccelerated beams of rare isotopes primarily for the direct measurement of astrophysically important reaction rates near or below the Coulomb barrier, and direct reactions or fusion reactions above the Coulomb barrier. Each of these arenas is tailored to address important aspects of the physics program discussed in the preceding sections, and all arenas are needed to fully exploit the scientific opportunities that can be accessed by RIA. In addition, RIA could be equipped with an isotope-harvesting infrastructure that would allow important applied programs to proceed parasitically. Some funding for this infrastructure and the related research would likely come from programs outside of nuclear physics.

Both fast and reaccelerated beams are needed because they offer distinct advantages that can make a critical difference for accomplishing a particular science objective. Fast beams of rare isotopes produced and separated in flight offer the direct economic production of medium-energy (E/A $\approx$ 20–400 MeV) beams of rare isotopes, without reacceleration. Because of the chemistry-independent separation, these beams require minimal development times (typically of the order of a day). In many cases, the experiments with fast beams can be performed with thick targets that result in large (up to factors of 10,000) luminosity gains. Fast beams can be tracked and tagged on a particle-by-particle basis, allowing for significant reductions in background and, in many instances, significant gains in efficiency via the use of cocktail beams, which contain a mix of interesting isotopes.

Reaccelerated beams of rare isotopes offer alternative advantages that can be critical for many classes of experiments. These reaccelerated beams have excellent beam quality—as good as that of stable beams. High-intensity, low-energy beams are needed for the direct determination of astrophysically important reaction rates because excitation functions must be measured at points at which the cross sections vary exponentially with beam energy. These high-precision beams are also the best tools for the investigation of fission barriers and fusion reactions (again because of the strong energy dependence of fusion cross sections), including those that produce superheavy elements, for high-spin spectroscopy of nuclei not too close to the drip lines, and for low-energy transfer reactions for single-particle and pairing measurements.

The scientific reach of RIA for separated fast beams directly available for experiments in flight or at rest (e.g., lifetime, magnetic moment, β-decay measurements, etc.) is illustrated in Figure 13. Figure 14 shows the intensities for separated 1+ ions available for experiments at rest (e.g., ion and atom traps) or for reacceleration. With state of the art experimental techniques, RIA is a major step forward in addressing the crucial nuclear structure, nuclear astrophysics, and fundamental interactions issues, as well as in producing a bounty of radioactive isotopes, whose applications are described in the next section.

NSAC has strongly endorsed the RIA concept. It became the nuclear science community's highest priority for major new construction (117) and is tied for third place in the 20-Year Science Facilities Plan of the Department of Energy's Office of Science (118). In an NSAC review of priorities in 2005, RIA was again the field's highest priority for major new construction (119). RIA would be the only rare isotope facility in the world that would embrace the entire arsenal of rare-isotope-production and experimentation techniques. It is the most powerful facility delivering rare isotope beams, with the highest intensity currently designed or under construction, having at least factors of 10 to 100 higher yields of secondary ions, and in many cases for reaccelerated beams, several orders of magnitude higher yields.

A NSAC subcommittee recently prepared a detailed comparison of RIA's capabilities to those of the most powerful alternative planned worldwide (the planned FAIR facility at GSI, Germany) (120). The report concluded that "RIA will provide yields of any element at intensities that are unmatched by any facility, present or currently planned. . .While both facilities will produce rare isotopes by fast-beam fragmentation and there is collaboration between the U.S. and European communities on R&D issues, we find that this overlap in capabilities is less than it would appear. It is clear that the RIA rare-isotope research capability is more extensive than GSI. The question of whether an upgrade of GSI would duplicate the rare isotope capability at RIA is answered firmly in the negative."

APPLICATIONS OF RARE ISOTOPES IN OTHER DISCIPLINES

Radioisotopes also play a key role in many scientific disciplines, serving as tracers in chemical and imaging studies. RIA will provide, in research quantities, hundreds of new isotopes—essentially any isotope of practical interest. This is a breakthrough. RIA will also produce large quantities of near-stability isotopes and large fluxes of neutrons and muons, which offer additional opportunities for advances in applied technologies, including national security, medical technology, and nuclear energy. Often such work can proceed parasitically with minimal impact on the main scientific program. To illustrate, below are a few examples.

National Security

RIA plays a clear and immediate role in the Stockpile Stewardship Program for the National Nuclear Security Administration (NNSA) and in the Nuclear Forensics/Attribution Program of the Department of Homeland Security (DHS). It provides data needed for an improved modeling of the behavior of the nation's aging nuclear weapons stockpile without a resumption of nuclear testing and data for improved forensic analyses of bomb debris that could help determine the source and design of an exploded nuclear device.

A key problem is the determination of the ultrahigh neutron fluxes encountered, e.g., in inertial confinement fusion or in nuclear explosions. For this purpose, known quantities of various isotopes are placed into or near the exploding device. The isotopic abundances of samples collected after the explosion are then compared with model predictions whose cross sections are important input for the creation, destruction, and transmutation by neutrons and X rays. Because the vast majority of the isotopes involved have lifetimes of days or less, it has so far been impossible to measure the needed cross sections, and uncertain theoretical estimates are used in place of data. The resulting uncertainties are often the largest contributors to the overall uncertainty of the model calculations.

RIA will dramatically increase the number of isotopes relevant to the Stockpile Stewardship Program for which measurements can be performed. The required research would not be classified and could help train for the next generation of nuclear physicists and radiochemists needed by NNSA and DHS. The needed equipment and infrastructure (hot cells for isotope harvesting, colocated neutron source) would also be useful for studies of nucleosynthesis in stellar environments.

Biomedicine

Advances in the use of radioisotopes as radiolabels in metabolism or imaging techniques such as positron emission tomography (PET) continue to improve diagnosis and treatment of cancer, heart disease, stroke, and other diseases. The availability of new isotopes in quantities suitable for basic research creates exciting new possibilities for biomedical research, e.g., radio-immunotherapy, radiopharmaceutical development for diagnostic imaging, tracers for metabolic studies, ligands for neuroscience research, and the study of signal transduction pathways.

Approximately 20% of single tumors preclude conventional γ-ray treatments owing to their location near critical structures, such as the spine. Targeted drugs labeled with radioactive isotopes offer promising alternatives. Isotopes emitting short-range ionizing radiation, such as alpha particles, low-energy beta particles, or Auger electrons, are ideally suited for localized destruction at the few-cell level—or, in the case of Auger electron emitters, even at the molecular level. Of particular interest are isotopes with half-lives shorter than a few days. RIA would produce many interesting isotopes in research quantities and allow case-specific selection of the most appropriate half-lives, particle energies, and chemistry. A recent example is ^{149}Tb, a 4.12-h alpha emitter produced by irradiating a Ta target with high-energy protons and demonstrated in vivo to be effective in single cancer cell kills (121). Another isotope of great interest in related applications is ^{211}At.

PET imaging is a key diagnostic tool that has become the method of choice for cancer diagnosis. γ-ray imaging and new radioisotopes promise to be of significant utility to medicine. For example, the development of PET sources such as ^{86}Y, ^{89}Zr, and ^{124}I would allow monitoring of the distribution of ^{90}Y used in radio-immunotherapy.

Materials Research

The development of new materials and the study of their structural properties are important research areas and a major instrument for economic growth. For example, isotopes allow advanced material characterization by using rare-isotope-implantation techniques to probe the magnetic and electronic environments of these materials. Ion implantation depths from few to hundreds of nanometers will allow depth-resolved β-NMR (beta-detected nuclear magnetic resonance) and nuclear spin relaxation investigations of surface layers. One could, for example, investigate temperature and magnetic-field dependencies of the magnetic penetration depth in superconductors, an important material property. Other interesting applications are studies of local field distributions in thin-film magnetic multilayers via β-NMR line-shape analyses and nuclear spin relaxation techniques. The development of nanoscale magnetic devices are important for advanced computing technologies.

RIA will also be an intense source of muons and allow materials research via the established technique of muon spin rotation, relaxation, and resonance (collectively termed μSR).

Toxicology

RIA will also provide new possibilities for developing innovative methods for tracing the metabolic consequences of ingesting certain foods and drugs. Many enzymes and genetic materials (DNA, RNA) use metals as key components in their structure and function. Isotopic substitutions can be used to find where the metal is in the structure and how it functions. Such understanding is important for the design of new drugs and for studying drug interactions with target proteins. RIA will provide an unprecedented number of metal isotopes (Cu, Mg, Zn, and other metals) useful for elucidating the role of metals in healthy and diseased organisms.

Rare isotopes enhance studies on short-distance ion fluxes through the soil matrix and short-term transfers within living food webs associated with forest soils, streams, and wetlands. Short-lived isotope labels for viruses and other microbial contaminants of water supplies and food products may be used to identify contamination sources and pathways. Isotope tracers of pollutants provide an opportunity to measure rates of reactions that are difficult, if not impossible, to obtain by other means. The knowledge of metal and nutrient uptake rates is, for example, critical to understanding rates of phytoplankton growth. Short-lived isotopes provide significant insight into the pathways of nutrient assimilation while minimizing the hazards potentially associated with longer-lived isotopes. They may also be used for mechanistic determinations of the effects of low-level radiation and for testing the linear model of radiation damage.

Nuclear Energy and Waste Transmutation

Nuclear energy is a viable option for large-scale, carbon-free energy production. Because the burning of plutonium and longer-lived fission products proceeds via shorter-lived intermediary nuclides, better nuclear data for these short-lived isotopes will improve the modeling of Generation-IV nuclear reactors or accelerator-driven transmutation of waste systems.

RIA will make it possible to produce pure samples of short-lived isotopes and perform measurements of specific production and destruction rates via neutron cross-section measurements at a colocated neutron-generator facility. In addition, the spallation neutrons generated in the RIA target area may be tailored to simulate various fast reactor energy spectra and thereby allow measurements of integrated burn rates for simulated reactor fuel composites.

SYNOPSIS AND OUTLOOK

To a very good approximation, nuclei can be described as finite droplets of a two-component (neutron and proton) Fermi liquid, whose detailed properties depend on the delicate interplay of the strong, Coulomb, and weak interactions. Their basic constituents, protons and neutrons, are not truly fundamental particles, and subnucleonic degrees of freedom must play an important role in determining the interactions between nucleons. Beyond this, QCD seems to play only a subordinate role in nuclei, with manifestations either at very short distances or very high densities and temperatures. Advances in computation techniques have allowed rather accurate descriptions of the properties of very light ($A \leq 12$) nuclei with state of the art microscopic treatments. Presently, these treatments rapidly become unfeasible for much heavier nuclei, making it necessary to introduce additional approximations to the many-body problem. Thus, the nuclear problem has strong intellectual overlap with other theories of mesoscopic quantum systems. Descriptions of nuclei have to date enjoyed substantial success in accounting for their quantum properties at low energies, but real challenges remain.

Among the thousands of nuclides that are stable on time scales relevant for the strong interaction ($\gg 10^{-20}$ s), only the few hundred close to the line of beta stability are sufficiently stable against other decays to be found on Earth. Thousands more exist and play an important role in the cosmos, where their often fleeting existence and their unknown properties define, for example, the paths of nucleosynthesis and the energy production and composition of ejecta in explosive astrophysical environments such as novae, supernovae, neutron star mergers, etc.

To a large extent, experimental investigations of the properties of nuclei have been limited to experiments that could be performed with stable or very long-lived nuclei, resulting in a rather limited purview of the range of quantum droplets that exist in nature, with significantly constrained ability to vary the relative admixtures of the proton and neutron contents. Yet nuclei with unusual proton-to-neutron admixtures are likely to have rather different properties. For example, very neutron-rich nuclei may be more appropriately described as open quantum systems, for which coupling to the continuum is important, leading to qualitatively different behavior such as nonuniform mixing of the two Fermi liquids or new types of quantum oscillations.

An advanced rare isotope accelerator such as RIA will make it possible to gain access to thousands of new nuclides that have so far been inaccessible to experimental investigation. The ensuing ability of varying the proton-to-neutron admixture of nuclei over an unprecedented range will make it possible to determine and fine tune the ingredients needed by many-body theory. Nuclear models with unprecedented accuracy and predictive power can be developed by guiding theory with targeted experiments that isolate or selectively enhance the sensitivity to selected ingredients of the various many-body treatments. This will provide much better constraints for modeling the properties of nuclei and for developing refined theories that have the predictive power needed, for example, for astrophysical simulations of stellar evolution and nucleosynthesis.

For the past half century nuclear physics experimentation (and concomitantly nuclear theory) has explored the nuclear landscape close to the world we know. An advanced rare isotope accelerator will take the next big leap, exploring the nuclear landscape that governs the often spectacular events in the cosmos and allowing improved extrapolations of the properties of neutron stars. The ensuing research is likely to find unexpected utility on Earth, beyond the already predictable benefits to national security, biomedicine, and applied research, e.g., in materials science, toxicology, pharmacology, and the environment.

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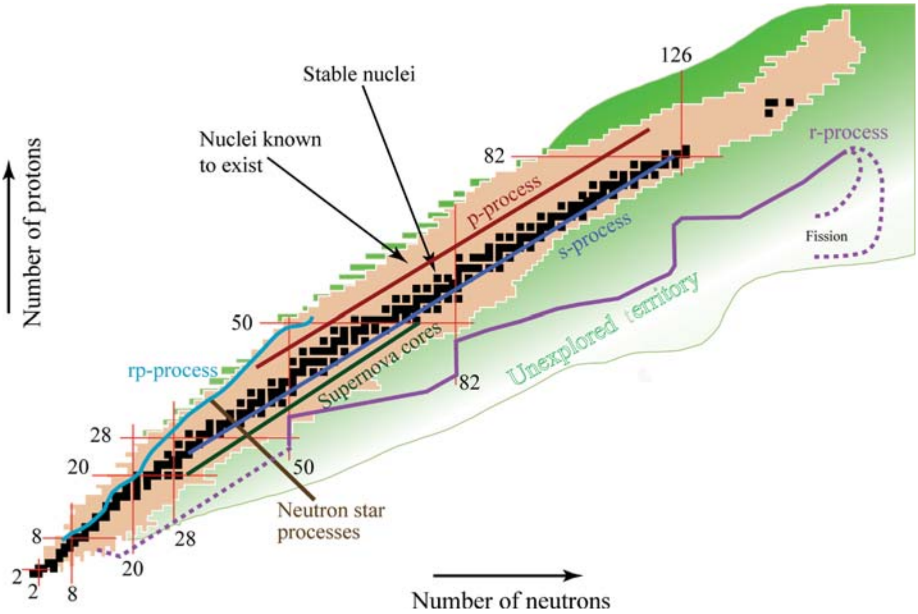

Figure 1 The landscape of nuclei. The black squares represent stable isotopes, and the tan region represents isotopes where some information is known. The colored lines indicate approximate pathways for several important nuclear reaction sequences (rp-process, rapid-proton-capture process; r-process, rapid-neutron-capture process) leading to the production of the chemical elements in the universe. The dotted purple line labeled "fission" indicates schematically that the fission process cycles heavy nuclei back to lower mass regions.

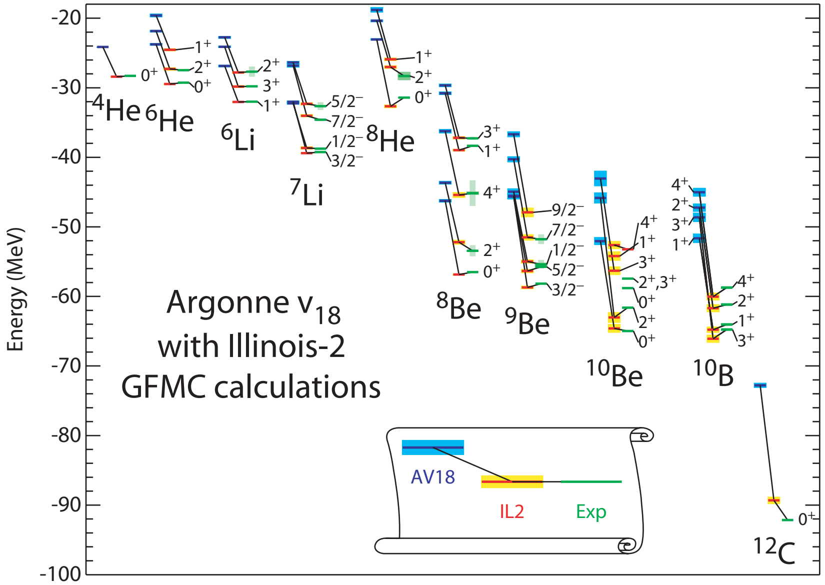

Figure 3 Ab initio calculations of a number of energy levels in light nuclei are compared with experiments (indicated as *green bands*). The blue lines are Green's function Monte Carlo (GFMC) calculations with only two-nucleon interactions; the red lines include two- and three-nucleon interactions. The blue and yellow bands indicate the statistical uncertainty of the simulations.

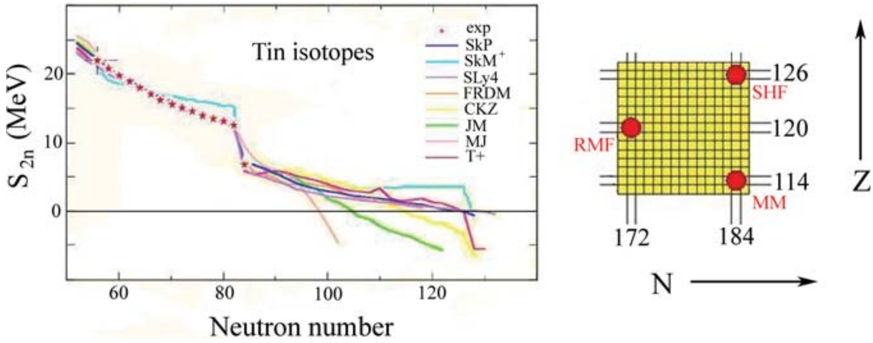

Figure 5 (*Left panel*) Neutron-number dependence of two neutron separation energies for the tin (Z = 50) isotopes compared with a number of theoretical models (SkP-FDRM) and phenomenological mass formulae (CKZ – T+). (*Right panel*) Minima in the energy surfaces for superheavy nuclei calculated with Skyme-Hartree-Fock (SHF), relativistic mean-field (RMF), and microscopic-macroscopic (MM) models.

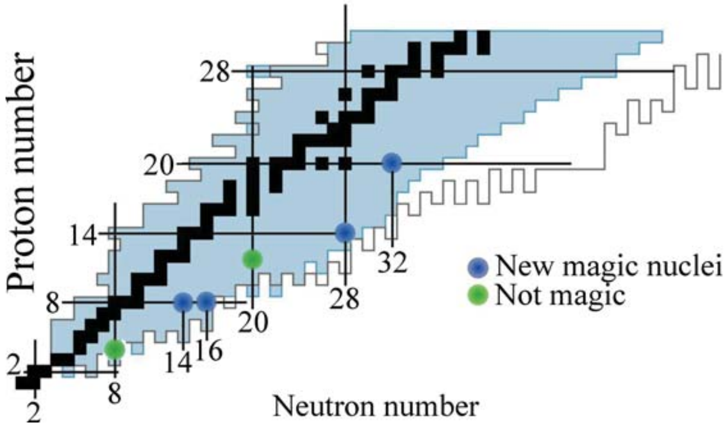

Figure 6 Partial nuclear landscape for nuclei between hydrogen (Z = 1) and zinc (Z = 30) illustrates that magic numbers are not as immutable as researchers once thought. Some anticipated magic nuclei are, in fact, not magic (*green dots*) and, conversely, recent experiments have also indicated the presence of new magic nuclei (*blue dots*).

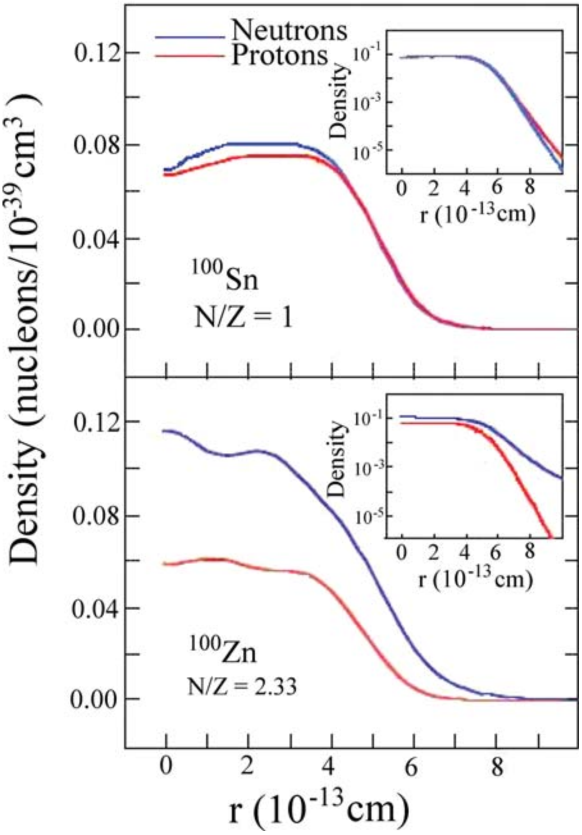

Figure 8 Calculated densities of protons and neutrons in two extreme nuclei with 100 nucleons. In the neutron-deficient ^{100}Sn (Z = N = 50) the two distributions essentially overlap (*top panel*), whereas the neutrons extend much further in the neutron-rich ^{100}Zr (*bottom panel*). See Reference 35 for details.

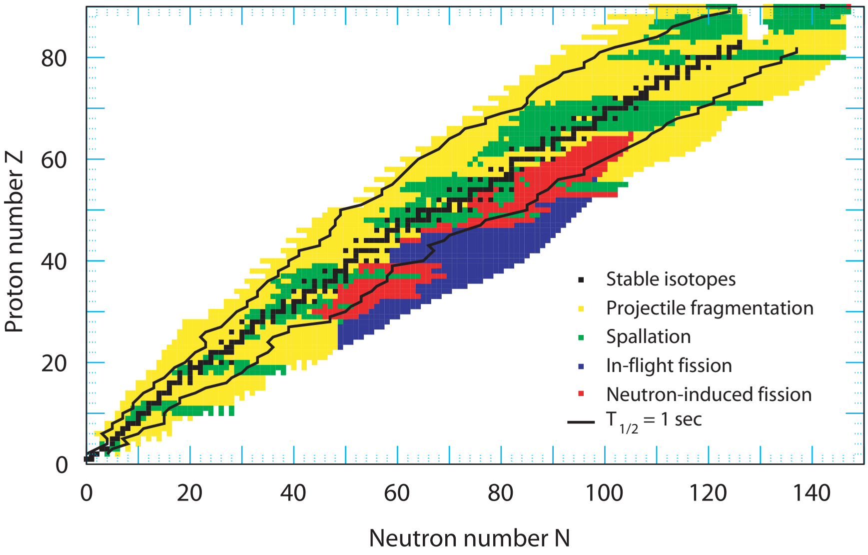

Figure 12 Production mechanism that maximizes the intensity of reaccelerated rare isotopes. Isotopes produced and separated in flight were required to have lifetimes larger than 10 ms; those produced at rest (isotope separation online) were required to have lifetimes larger than 1 s.

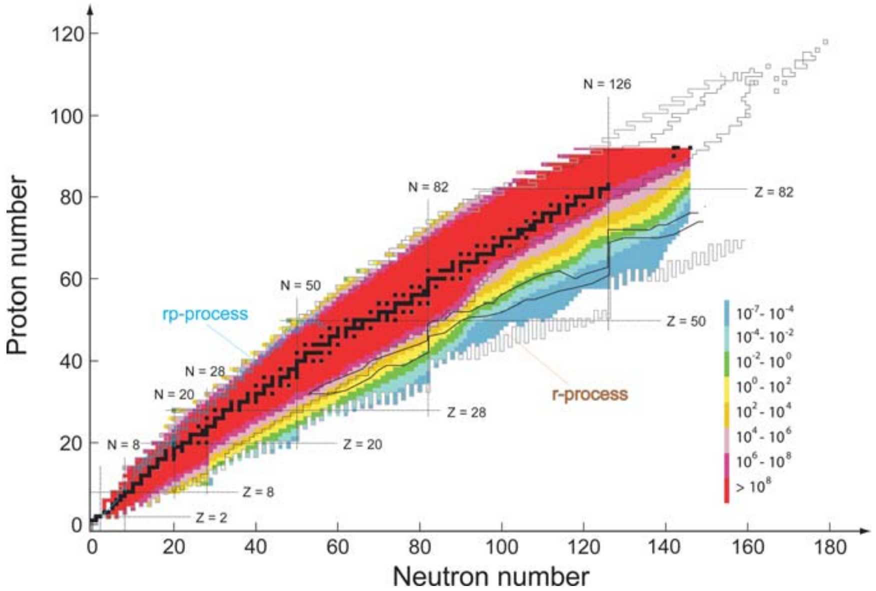

Figure 13 Projected intensities of fast beams of rare isotopes separated in flight. The curves show possible paths of the rapid-neutron-capture (r) process (*black*) and rapid-proton-capture (rp) process (*blue*) in explosive stellar environments. The prediction of rare-isotope-production yields very far from the line of beta stability has significant (factors of 10–100) uncertainties because the cross sections are unknown and have to be extrapolated via empirical models.

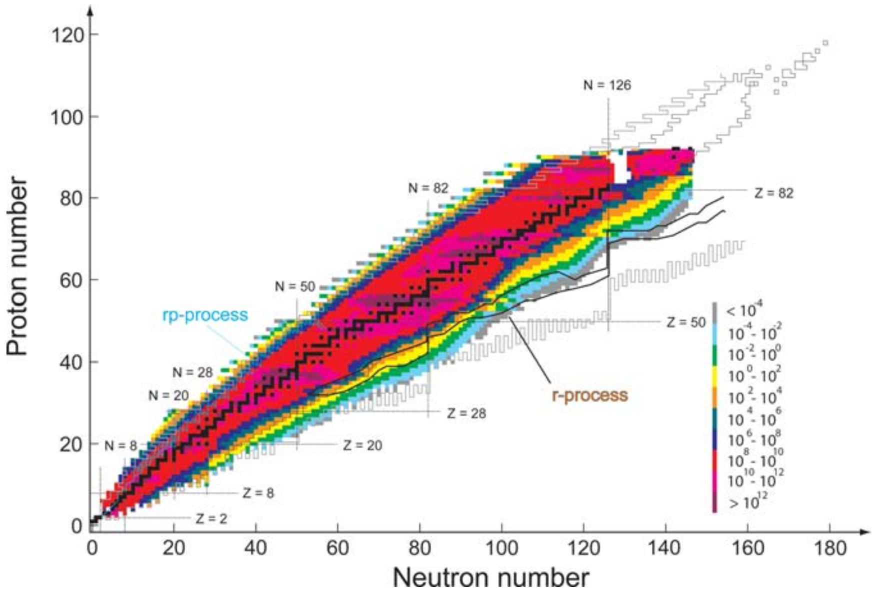

Figure 14 Projected intensities of separated 1+ ions available for stopped beams or for reacceleration from the Rare Isotope Accelerator. The lines show possible paths of the rapid-neutron-capture (r) processes (*black*) and rapid-proton-capture (rp) process (*blue*) in explosive stellar environments. The prediction of rare-isotope-production yields very far from the line of beta stability has significant (factors of 10–100) uncertainties because the cross sections are unknown and have to be extrapolated via empirical models. The efficiency for reacceleration ranges from 50% for light beams to 5% for the heaviest beams.