PHYSICS WITH RADIOACTIVE NUCLEAR BEAMS

Recently developed facilities allow a wide range of new investigations of the reactions and properties of short-lived nuclei. These studies may help to solve puzzles of nuclear structure and the Big Bang.

Richard N. Boyd and Isao Tanihata

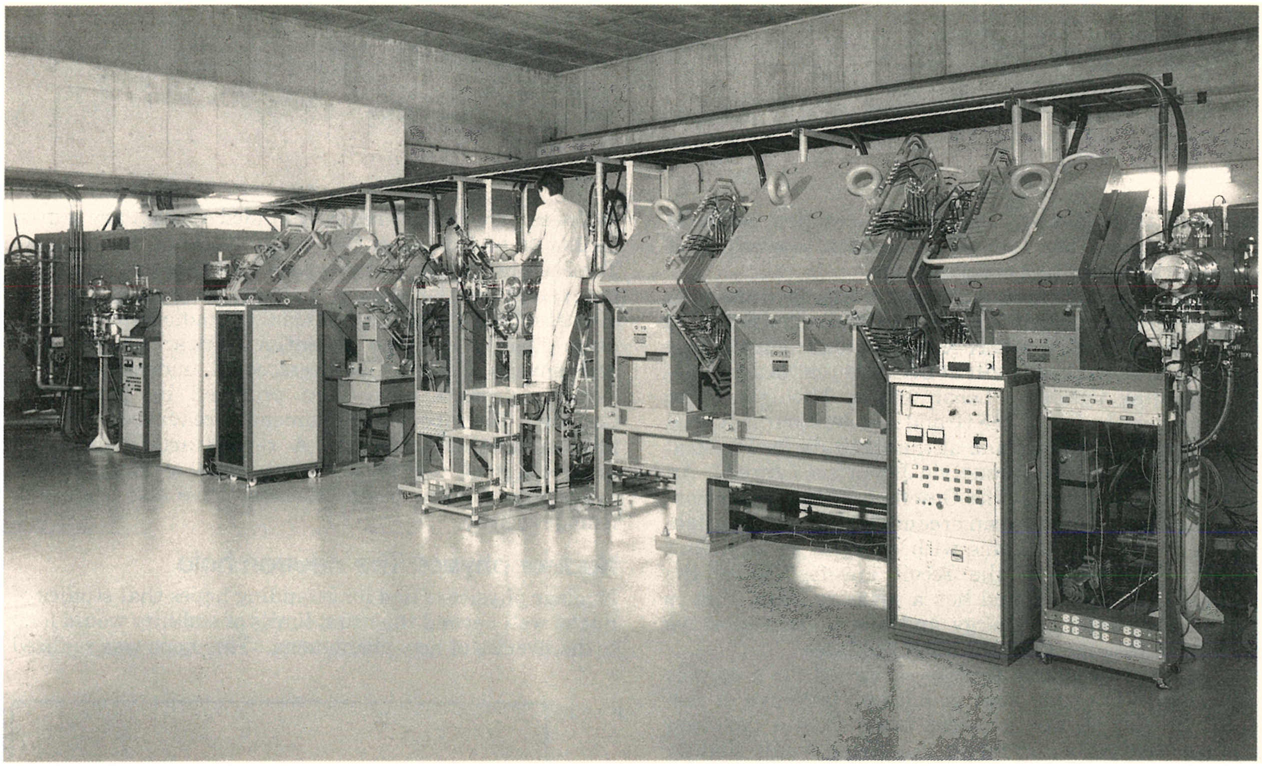
Richard N. Boyd is a professor in the departments of physics and astronomy at The Ohio State University. **Isao Tanihata** is head of the linac laboratory and a principal scientist at RIKEN, the Institute of Physical and Chemical Research, in Japan.

The purpose of nuclear physics is to measure properties of specific nuclides and infer from them global properties common to all nuclides. One goal, for example, is to understand nuclear sizes and matter distributions in terms of basic nuclear forces. Another is to understand the variation throughout the periodic table of the dominant quantum states, which are known as the "nuclear shell model" states and are characterized, much as are atomic states, by a principal quantum number and by orbital and total angular momentum quantum numbers. In turn other nuclear phenomena, such as the collective excitations known as giant resonances, can be understood in terms of the shell-model configurations and basic nuclear parameters.

Until recently nuclear physicists have obtained this kind of information by initiating nuclear reactions using beams of photons, leptons, hadrons, light ions and heavy nuclei. These reactions, however, have consisted almost entirely of interactions involving stable, or long-lived, nuclei, of which about 300 are known to exist on Earth. While theory predicts the existence of more than 6000 nuclides with halflives longer than 1 microsecond, only about one-third of them have been synthesized and studied thus far.

Being able to study only reactions of stable nuclei is a fundamental restriction, not only because it limits us to the consideration of only a small number of nuclides but also because it may limit the phenomena that we can study. Because for many nuclear phenomena we have detailed experimental information only on the relatively small number of stable nuclei, theoretical attempts to understand nuclei far from stability have extrapolated from fundamental properties of stable nuclei. The extrapolation becomes increasingly unreliable as one proceeds to more exotic combinations of neutron number N and atomic number Z. Even basic parameters such as the nuclear radius have been determined for only a very few unstable nuclei.

Facilities have been built to circumvent these prob-



Projectile-fragment separator, part of the recoil ion radioactive nuclear beam facility at RIKEN in Japan. The primary beam from an accelerator produces a high-energy, heavy-ion beam, which bombards a primary target. There fragmentation reactions produce many species of nuclei; magnets (shown above) select and then focus the desired nuclides to form a secondary beam.

lems and to allow us to probe some of the properties of short-lived nuclei, such as their masses and decay signatures. These facilities isolate the short-lived nuclei produced by nuclear reactions in radioactive nuclear beams and then accelerate them to energies high enough that they can initiate nuclear reactions. Studies of the reactions induced by these exotic species will extend our understanding of nuclei to those beyond the limit of stability—a major step forward.

Radioactive nuclear beam studies of reactions of short-lived nuclides have already yielded results with important ramifications in both nuclear physics and astrophysics. Nuclear physicists expect unstable nuclides to exhibit unusual structures or features that may test our understanding of known nuclear phenomena at extreme conditions, and perhaps even to reveal previously unknown nuclear phenomena. Astrophysicists, for their part, have known for several decades that processes in both Big Bang nucleosynthesis and stellar nucleosynthesis involve short-lived nuclides. Indeed, the original motivation for developing radioactive nuclear beams was astrophysical.[2]

Radioactive nuclear beam facilities

More than a decade ago the Isotope Separator On-Line,[1] known as ISOLDE, was built at CERN. At ISOLDE high-energy nuclei in an incident beam from an accelerator interact with heavy target nuclei, such as uranium, to produce an array of nuclides, many of them short-lived. These unstable nuclei are extracted and sent to a secondary source, where they are ionized and accelerated sufficiently to allow the formation of secondary beams composed of single nuclides. These beams are then directed to detectors, where one observes the decays of the nuclei. Facilities like ISOLDE were designed to observe the properties of the nuclei in the secondary beams, but not the products of subsequent reactions initiated by the short-lived nuclei. However, by reinjecting the secondary beams into an accelerator, one can produce intense, high-energy radioactive nuclear beams that can be used in reaction experiments. We denote facilities that use secondary beams in this fashion as "secondary source" radioactive nuclear beam facilities.

Over the past decade researchers have improved the production of intense beams of secondary ions[2] enough to study reactions involving the nuclei that make up the beams. Physicists at Lawrence Berkeley Laboratory who accelerated high-energy heavy ions in the early 1970s discovered that an incident nucleus, upon interacting with a target nucleus, would often fragment into smaller nuclei, and some of the fragments would be ejected at essentially the same velocity as the incident nucleus. This phenomenon, called projectile fragmentation, has been used to synthesize many new nuclides. The persistence of the velocities of the fragments allows one to to produce secondary beams of unstable nuclei. Because the fragments have different magnetic rigidities (a measure of the ability of a magnetic field to deflect a moving charged particle), applied magnetic fields can orient the fragments into beams containing a single nuclear species. This method of producing secondary radioactive nuclear beams is the principal means of producing beams in "recoil ion" facilities.

In both the recoil ion and secondary source facilities, one focuses the radioactive nuclear beam onto a secondary reaction target, where the reaction of interest occurs.

Detectors then identify the desired reaction products (often in competition with other reaction products) and measure their resulting cross sections.

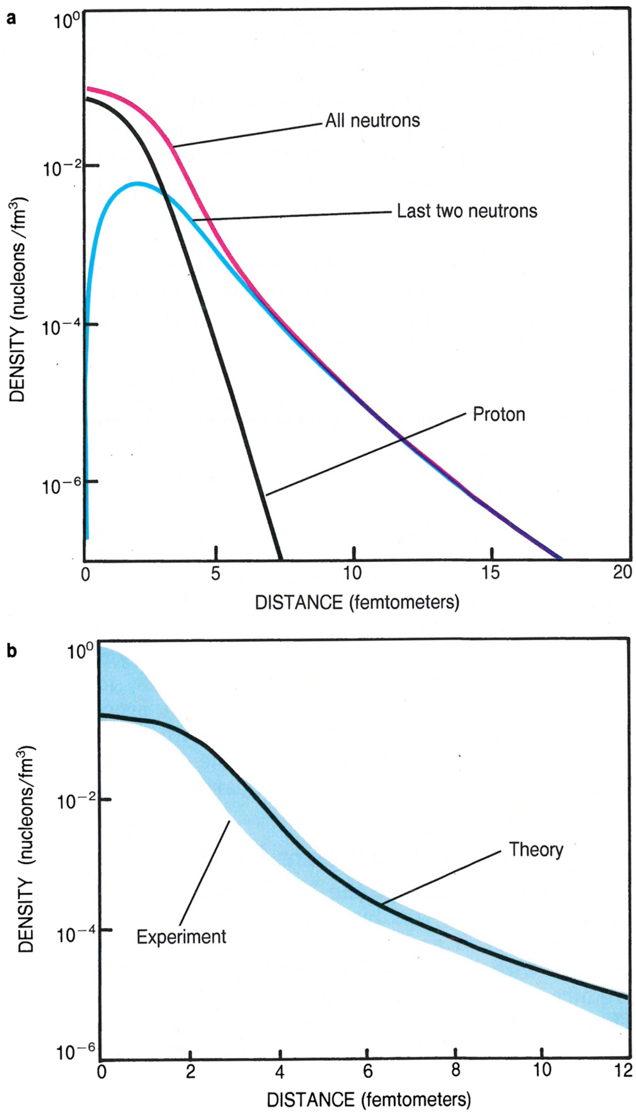
Recoil ion radioactive nuclear beam facilities can produce secondary beams of particles with energies of 10 A MeV to 100 A MeV (where A is the atomic mass). This type of facility has been built at LBL and the National Superconducting Cyclotron Laboratory at Michigan State University in the US, at the Grand Accelerateur National d'Ion Lourdes in France and at the Institute for Physical and Chemical Research (RIKEN) in Japan (see figure 1). An advanced installation at the Gesellschaft für Schwerionenforschung in Germany can produce high-intensity, high-resolution secondary beams with energies as high as 1 A GeV. A variant of the recoil ion facility at the University of Notre Dame has a primary beam that is considerably lower in energy and has a more selective production reaction than the other facilities.

A secondary source facility—designed for a specific experiment—has been built at Louvain-la-Neuve in Belgium. In that facility, a proton beam from a cyclotron impinges on a carbon-13 target, modifying it only slightly to produce nitrogen-13, the radioactive nuclide of interest. The ^{13}N nuclei are extracted from the target, transported to the secondary source, ionized and accelerated in a second cyclotron to produce a ^{13}N beam at the required energy. That beam is then directed onto the reaction target, and the reaction products are detected. Later in this article we discuss the results from that experiment and their impact on astrophysics.

The secondary source facilities appear to hold the greatest promise for producing high-intensity, high-resolution beams of short-lived nuclei. While at some facilities, such as the one at Louvain-la-Neuve, one only slightly modifies the target nucleus (^{13}C) to obtain the radioactive nuclide of interest (^{13}N), newer designs will incorporate a heavy target, such as uranium. With a heavy target, if the incoming beam is of sufficiently high energy, the target will undergo spallation, or "splatter" into pieces, producing a wide selection of nuclei that can be selected into single-nuclide beams. Indeed, planners may use the basic design of ISOLDE, which uses a heavy target nucleus, as the injector for a secondary accelerator in several future facilities. The US has recently funded a secondary source facility to be located at Oak Ridge National Laboratory. The basic properties of this type of facility were detailed in the report of the Isospin Laboratory Project,[3] which discusses both a potential national US radioactive nuclear beam facility and the potential nuclear physics and astrophysics studies that users could undertake there. (Similar projects have been proposed in Japan and Canada.) The report is recommended reading for anyone interested in this subject. A review article[4] and the proceedings of two large international conferences on radioactive nuclear beam research[5] have also been published recently.

Nuclear physics: The neutron halo

Nuclear physicists had longstanding hopes that studies of nuclei well beyond the usual limits of stability would lead to discoveries of new phenomena. This hope was realized



Nuclear density distributions of neutron-rich nuclei can be determined from radioactive nuclear beam experiments. **a:** Calculated proton and neutron density distributions[7] of ^{11}Li reveal a long tail in the density of the last two neutrons: the neutron halo. **b:** The nucleon density distribution[9] as determined from measurements of interaction cross sections of ^{11}Be beams at 33 and 790 A MeV. **Figure 2**

in the mid-1980s in the first series of experiments[6] with high-energy beams of the short-lived nucleus lithium-11, a highly neutron-rich nuclide ($Z=3$, $N=8$).

The interaction cross section is the total probability that a projectile nucleus will interact with a target nucleus and change the projectile's nuclear identity. At high energies it is directly related to the size of the interacting nuclei. The interaction cross section σ_1 can be expressed by

$$\sigma_1 = \pi[R_\mathrm{I}(\mathrm{P}) + R_\mathrm{I}(\mathrm{T})]^2 \qquad (1)$$

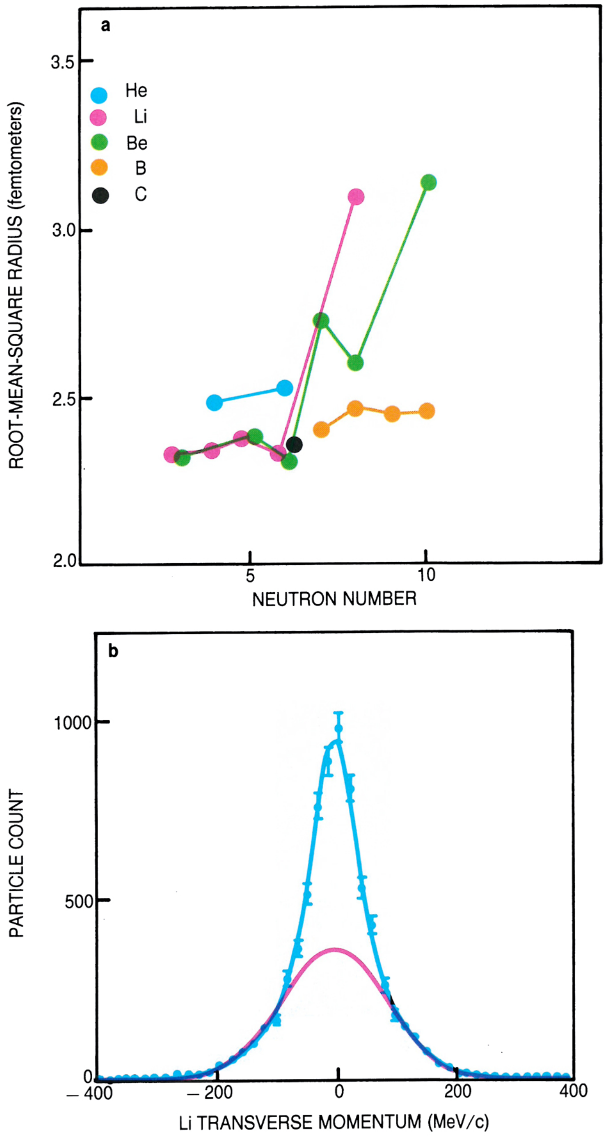
where $R_\mathrm{I}(\mathrm{P})$ and $R_\mathrm{I}(\mathrm{T})$ are the interaction radii of the projectile and target, respectively. Using equation 1 one can determine interaction radii from a series of measurements of the interaction cross sections between a nuclide and other nuclides of varying size. In practice it is necessary to employ detailed scattering theory to relate the interaction cross section to the nuclear density distribution, but the simpler approach can determine nuclear sizes, and hence density distributions, to within a few percent.

Recent measurements of interaction cross sections with a radioactive nuclear beam of ^{11}Li impinging on several different target nuclides (protons, deuterium, beryllium and carbon) at a variety of energies have revealed a new feature of nuclear matter: the neutron halo, an extended low-density tail of the neutron density distribution. Figure 2a shows the recently determined[7] density distribution of the ^{11}Li nucleus: One can clearly see in the density distribution a tail formed by two neutrons in the outermost orbital (where the orbital is defined according to the nuclear shell model). Measurements of projectile fragmentation cross sections and momentum distributions have confirmed the results of these cross section measurements, as discussed below.

Through several decades of studying the charge and matter distributions of stable nuclei, nuclear physicists have found three characteristics of nuclear density common to all nuclei: the proportionality of the nuclear radius R to the one-third power of the atomic number A ($R=r_0A^{1/3}$, where $r_0 \simeq 1.2\times10^{-15}$ m); surface thickness of about 1 femtometer (the distance over which the nuclear density drops from about 70% to 30% of its maximum value); and an almost complete spatial overlap of the proton and neutron distributions. Even for the neutron-rich nucleus calcium-48 ($Z=20$, $N=28$) the rms radii of the proton and neutron distributions differ only by 0.1 fm. However, the ^{11}Li nucleus, with its neutron halo, violates all three rules: The rms radius of ^{11}Li is 3.16 fm, as large as that of sulfur-32; the surface thickness, or diffuseness, is extremely large compared with that of the protons alone, which is more typical of a normal nuclear density distribution (see figure 2); and the halo itself consists almost entirely of neutrons.

We now understand that the formation of the neutron halo in ^{11}Li results mainly from the weak binding of the two outermost neutrons. The energy by which these two neutrons are bound to the rest of the nucleus is only about 300 keV, much weaker than the binding energies of either neutrons or protons in stable nuclei, which are typically 6–8 MeV per nucleon. Examination of a simple model for the nuclear potential, the square-well potential, reveals the origin of the halo and some of its basic features. For $r>R$ (where R is the radius of the potential and is essentially equal to the radius of the nucleus, and r is the distance from the center of the nucleus), the radial wavefunction for a particle outside this potential well is given by

$$\Psi(r) = \left(\frac{2\pi}{\kappa}\right)^{-1/2}\left(\frac{\exp(-\kappa r)}{r}\right)\left(\frac{\exp(-\kappa R)}{(1+\kappa R)^{1/2}}\right) \qquad (2)$$



Features of the neutron halo include a large radius and small momentum distribution. **a:** Effective root-mean-square radii of light nuclei determined from interaction cross sections. The neutron-rich nuclei near the neutron drip line—the limit of stability for neutron emission—exhibit anomalously large radii. **b:** Transverse momentum distribution of ^{9}Li fragments from the projectile fragmentation of a 790-A MeV beam of ^{11}Li. The large spatial distribution, the sharp momentum distribution and the small binding energy for the last two neutrons confirm the formation of a neutron halo. (Adapted from ref. 6.) **Figure 3**

In equation 2 κ determines the extension of the wavefunction; it is related to the binding energy E_B as

$$(\hbar\kappa)^2 = 2\mu E_B \quad (3)$$

where μ is the reduced mass of the system. The exponential dependence on r in equation 2 results in the spatial extent of the density distribution being greater for smaller binding energies. We now understand the independence of the surface thickness from atomic number to be the result of the small variation of the nuclear binding energy (6–8 MeV) in stable nuclei. For unstable nuclei, which have a wide range of binding energies, the radius of the neutron density appears to depend on the binding energy of the nucleons: Very small binding energies result in a neutron halo.

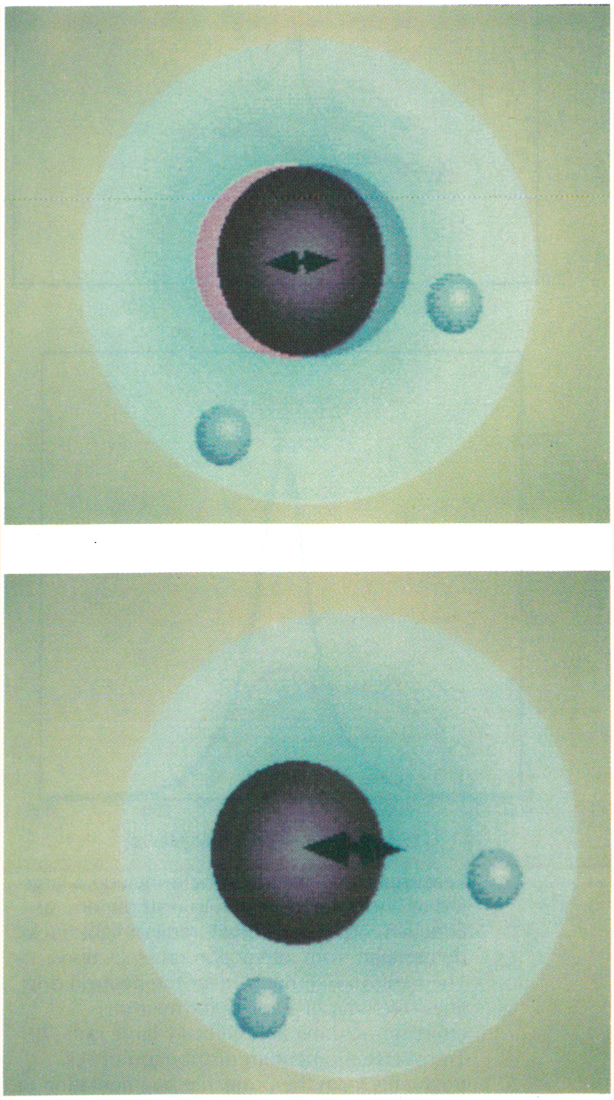
The Fourier transform of equation 2 gives the momentum distribution $f(p)$ of the particle in the same potential:

$$f(p) = \frac{c}{p^2 + \kappa^2} \quad (4)$$

In contrast to the density distribution, the momentum distribution is narrower for smaller binding energies.

Experimenters have observed all the basic features of the halo—the small binding energy of the neutrons therein, the large size and the narrow width of the momentum distribution for the outermost neutrons—in ^{11}Li. (See figure 3.) Nuclear radii of stable or nearly stable isotopes (see figure 3a) are of similar size. But ^{11}Li and other nuclei near the limit of stability for neutron emission, called the neutron drip line, have very large radii. As shown in figure 3b, for ^{9}Li fragments resulting from breakup of ^{11}Li in a nuclear reaction, the momentum distribution has a component with extremely small width: approximately 21 MeV/c. That is much narrower than the width of the momentum distribution resulting from the breakup of stable nuclei in the same mass range; for the $^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{C}$ reaction, for example, the width is approximately 126 MeV/c. One observes this narrow component only for the ^{9}Li fragment and not for other fragments of Li isotopes ($A = 6$, 7 or 8), nor is it seen among the possible fragments of He isotopes ($A = 3$, 4, 6 and 8).

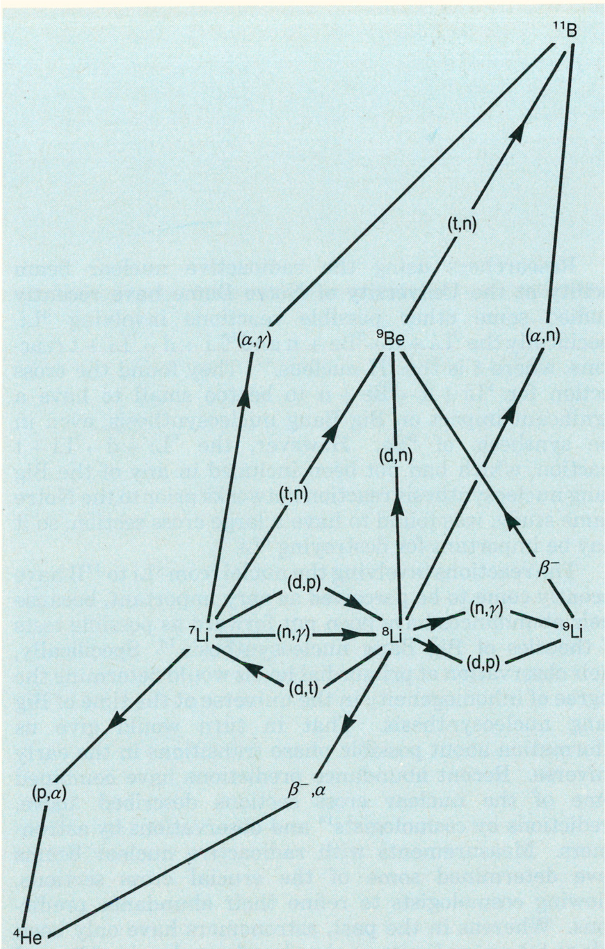
The ^{9}Li momentum distribution corresponds to that of the outermost two neutrons of ^{11}Li, which have a large spatial density distribution and hence, according to the uncertainty principle, a small momentum spread. Thus one can characterize ^{11}Li as a configuration of two loosely bound neutrons in orbits around the more tightly bound ^{9}Li core. The rms radius of the outermost neutrons is 4.5 fm, comparable to the radii of nuclei with much larger atomic number, such as zinc-70 (4 fm) or gold-197 (5.23 fm). In ^{11}Be the single outermost neutron forms a halo around the ^{10}Be core, giving it similar characteristics.[8] (See figure 2b.)



Nuclear excitations called giant E1 excitations (top), in which the neutron and proton distributions oscillate against each other, are well known throughout the periodic table. In nuclei with a neutron halo, one also expects a collective excitation electric dipole, known as the soft or low-energy E1 excitation (bottom), caused by the oscillations of the halo against the core. In the diagrams the darker the color, the greater the density of the proton (red) and neutron (blue) distributions; the two distributions overlap at the ^{9}Li core (purple). The two smaller circles represent the two outermost neutrons, which make up the halo (light blue). **Figure 4**

Excitation and structure of the halo nucleus

The discovery of the neutron halo has also brought to light new kinds of excitation modes in nuclei. Among the known collective nuclear excitations, the giant E1 excitation, which results from the oscillation of the proton and neutron distributions against each other, is the most pronounced nuclear excitation in the periodic table. In a nucleus with a neutron halo, one expects a similar additional oscillation—that of the core against the halo. This recently discovered excitation is known as the soft E1 mode (see figure 4). Because of the gradual decrease of the halo density at large distances, the restoring force is weak, and the oscillation frequency is extremely low. In fact, several model calculations predict[9] the energy for this excitation to be about 1 MeV, much lower than the typical E1 giant resonance energy of around 20 MeV. That the electromagnetic dissociation of ^{11}Li is strongly enhanced when it impinges on a high-Z target suggests the existence of such a low-frequency excitation.[6] The double-charge-exchange pion-induced reaction $^{11}\mathrm{B} + \pi^- \rightarrow \pi^+ + {}^{11}\mathrm{Li}$ suggests the existence of an excited state in ^{11}Li at about 1.2 MeV that may be connected to the ground state by an E1 transition,[10] so the soft E1 resonance may have been identified. In addition to the soft E1 mode, collective



Partial reaction network for Big Bang nucleosynthesis of nuclides from ^{7}Li to ^{11}B. Reactions that either produce or destroy ^{8}Li are crucial, because ^{8}Li appears to be central to the formation of heavier nuclides in the inhomogeneous density models of the early universe. **Figure 5**

modes of higher multipoles are predicted for nuclei with halos.

The ^{11}Li nucleus also provides us with a rare opportunity to study the weakly bound three-body system. Although the interactions among the three bodies—the two outer neutrons and the ^{9}Li core—are inherently attractive, neither the n–n nor the n–^{9}Li system forms a bound state. The n–n–^{9}Li system, however, does form a bound state, ^{11}Li, but only by 300 keV. Arkady Migdal suggested the possible existence of a dineutron, a two-neutron nucleus, as part of a weakly bound system in the field of a core nucleus.[11] Another theorist, Vitaly Efimov, predicted that an extended nuclear potential of the type expected for a nucleus with a neutron halo would produce a large number of bound states near the binding limit.[12] Thus experimenters in several laboratories are attempting to observe these effects by scrutinizing the correlation of the fragments n–n, n–^{9}Li and n–n–^{9}Li resulting from, for example, the Coulomb breakup of ^{11}Li.

Because it contains only neutrons, the halo provides us with a new laboratory for studying nuclear matter. Thus we anticipate that studies of neutron-rich nuclei with radioactive nuclear beams may provide the first opportunity to study essentially pure neutron matter in the laboratory.

Radioactive nuclear beams open other new possibilities in the study of nuclear structure and reactions far from the stability line. As noted above, investigations of nuclear structure have thus far been developed only along or close to the valley of stability, because until recently we were restricted to using stable nuclear beams and targets. Radioactive nuclear beams permit reaction studies not only of unstable nuclei but, in some cases, of nuclei in excited states. Thus one can now, for example, excite extremely complex nuclear configurations using simple nuclear reactions that can be described in terms of current reaction theories.

Radioactive nuclear beams also allow one to examine the extremes of known nuclear phenomena. For example, at bombarding energies near or below the Coulomb barrier, nuclear physicists have studied fusion reactions for synthesizing the transuranic elements and the superheavy elements—those with Z near 114—that are predicted to be more stable than other, nearby nuclear species. Low energies are suitable for synthesizing these exotic nuclei because reactions at these energies leave the resulting fused system at low excitation energy. Such a system is more likely to form the ground state of a superheavy nucleus. However, all attempts so far have failed to produce a superheavy ground state, perhaps because of the small production cross section. Recently, theorists have predicted that the fusion cross sections below the Coulomb barrier for reactions with neutron-rich nuclear beams may be enhanced as a result of the reduction of the barrier by the extended neutron distribution and the low-lying dynamical E1 oscillation. If this is the case, theory predicts an increased likelihood of producing superheavy elements.[13]

Big Bang nucleosynthesis

Several important processes of both Big Bang and stellar nucleosynthesis are known to involve short-lived nuclides. Some of those nuclei are near the proton or neutron limits of nuclear stability, beyond which such stable nuclei cannot be formed. In other words, they decay by proton or neutron emission, whereas more stable nuclei decay by β emission. Nuclei well inside the nucleon decay limits are usually sufficiently long-lived for conventional laboratory reaction studies. The reactions relevant to Big Bang nucleosynthesis occur predominantly on either stable nuclides or neutron-rich nuclides that are fairly close to stability. Stellar burning processes that involve radioactive nuclei can occur in high-temperature, proton-rich environments, resulting in "rapid proton burning." Alternatively, they can occur in high-neutron-density environments, leading to the succession of rapid neutron radiative captures that is known as the "r process."

Nuclear cross sections are critical to our understanding of the processes that occur in astrophysical environments: They determine the rate of these processes, such as the synthesis of a nuclide c from the interaction of nuclides a and b:

$$d[c]/dt = [a][b]\langle\sigma v\rangle_{a+b\to c} \qquad (5)$$

In equation 5, [c] is the density of nucleus c, and $\langle\sigma v\rangle$ denotes the convolution of the cross section with a Boltzmann energy distribution of the interacting particles. Calculations of abundances resulting either from Big

Bang nucleosynthesis or from stellar burning processes involve networks of nuclei coupled by all plausible nuclear reactions (see, for example, figures 5 and 6), each of them associated with a rate like that in equation 5. Abundance calculations therefore involve solving many coupled differential equations.

Because the standard model of Big Bang nucleosynthesis involves virtually no very-short-lived nuclei, the nuclear physics of the Big Bang has been well described for several decades. However, investigators of Big Bang nucleosynthesis have focused recently on nonstandard models, one class of which involves regions of high and low nucleon density. These inhomogeneities might have been produced by the quark–hadron phase transition, or perhaps some other transition, thought to have occurred 10^{-5} seconds after the Big Bang. Because neutrons can pass through matter much more readily than protons, the high-density regions in such a universe would have rapidly become depleted of their neutrons and so would have become proton rich; the low-density regions would have become neutron rich. Thus nuclear reactions in the different regions would have favored nuclides at or somewhat beyond either the proton- or neutron-rich side of stability. Reaction network calculations for neutron-rich regions indicate that these "inhomogeneous density" models[14] account for the synthesis of all the nuclides of the periodic table in the first few minutes of the universe, albeit at abundances far below those observed in the solar system.

Figure 5 depicts a network for synthesis of some of the light nuclides. It shows that several reactions involving ^{8}Li, a nucleus with a halflife of 0.840 sec, could be important. Network calculations indicate that ^{8}Li is indeed pivotal to nucleosynthesis in inhomogeneous density models: All nuclides heavier than 11 atomic mass units are funneled through boron-11 on their nucleosynthesis paths, and ^{11}B is formed predominantly via the $^8\mathrm{Li} + {}^4\mathrm{He} \to {}^{11}\mathrm{B} + \mathrm{n}$ reaction throughout much of the parameter space of the inhomogeneous density models. Thus understanding the $^8\mathrm{Li} + {}^4\mathrm{He} \to {}^{11}\mathrm{B} + \mathrm{n}$ reaction is crucial to making accurate predictions with this model. In addition, any other reactions that either make or destroy ^{8}Li affect the predictions of these models, because the propensity of nucleosynthesis to produce ^{11}B depends on the abundance of ^{8}Li established by the delicate balance between its creation and destruction mechanisms.

Several existing radioactive nuclear beam facilities produce ^{8}Li beams, and the installation at RIKEN has been used to study the $^8\mathrm{Li} + {}^4\mathrm{He} \to {}^{11}\mathrm{B} + \mathrm{n}$ reaction.[15] Prior to that study nuclear physicists had inferred the cross section for that reaction from a study[16] of the time-reversed reaction $^{11}\mathrm{B} + \mathrm{n} \to {}^8\mathrm{Li} + {}^4\mathrm{He}$. However, several ^{11}B states may contribute to the $^8\mathrm{Li} + {}^4\mathrm{H} \to {}^{11}\mathrm{B} + \mathrm{n}$ reaction, and one cannot determine their contributions using the time-reversed reaction method. The cross section determined by the RIKEN $^8\mathrm{Li} + {}^4\mathrm{He} \to {}^{11}\mathrm{B} + \mathrm{n}$ study was found to exceed the result based on the time-reversed reaction by about a factor of 5. This finding could have an important effect on predictions of ^{11}B and heavier-nuclide abundances by inhomogeneous density models.

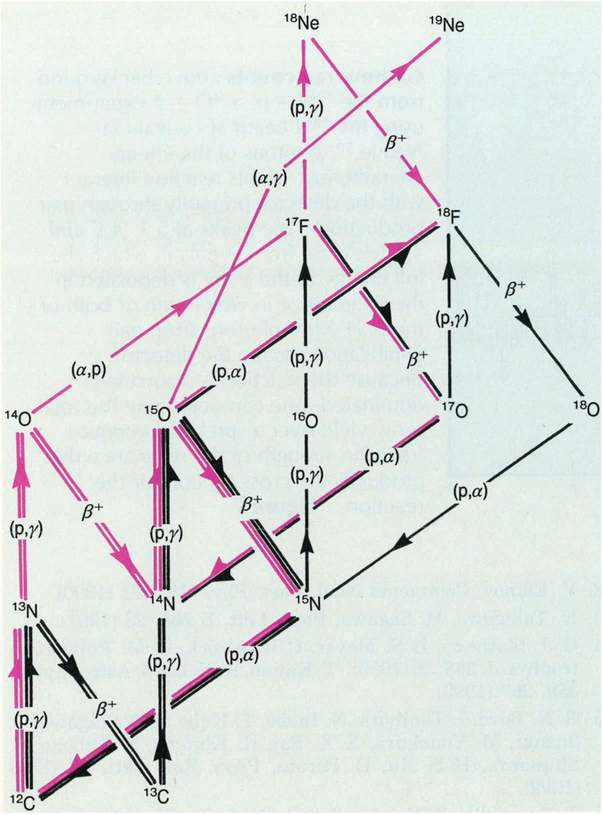
Researchers using the radioactive nuclear beam facility at the University of Notre Dame have recently studied some other possible reactions involving ^{8}Li, specifically the $^8\mathrm{Li} + \mathrm{d} \to {}^9\mathrm{Be} + \mathrm{n}$ and $^8\mathrm{Li} + \mathrm{d} \to {}^7\mathrm{Li} + \mathrm{t}$ reactions, where t is the ^{3}H nucleus.[17] They found the cross section for $^8\mathrm{Li} + \mathrm{d} \to {}^9\mathrm{Be} + \mathrm{n}$ to be too small to have a significant impact on Big Bang nucleosynthesis, even in the synthesis of ^{9}Be. However, the $^8\mathrm{Li} + \mathrm{d} \to {}^7\mathrm{Li} + \mathrm{t}$ reaction, which had not been included in any of the Big Bang nucleosynthesis reaction networks prior to the Notre Dame study, was found to have a large cross section, so it may be important for destroying ^{8}Li.

The reactions involving the nuclei from ^{7}Li to ^{11}B have recently come to be perceived as very important, because their abundances have been put forward as possible tests of theories of Big Bang nucleosynthesis.[14] Specifically, their observation at primordial levels would determine the degree of inhomogeneity in the universe at the time of Big Bang nucleosynthesis. That in turn would give us information about possible phase transitions in the early universe. Recent abundance predictions have combined some of the nuclear cross sections described above, predictions by cosmologists[14] and observations by astronomers. Measurements with radioactive nuclear beams have determined some of the crucial cross sections, allowing cosmologists to refine their abundance predictions. Whereas in the past, astronomers have only been able to set upper limits on the abundance levels of Be and B in old stars, recent improvements in detection sensitivity have allowed them to actually observe the two elements at a level an order of magnitude below their previous limits. The observed stars are low in elements heavier than He, so they are presumed to be made of material that has undergone little stellar processing since the Big Bang. Thus this stellar material should reflect the abundances that existed early in the history of the universe. Measurements of B abundances must be made by the Hubble Space Telescope, as photons with energies characteristic of strong atomic transitions of B do not penetrate the Earth's atmosphere. Current abundance determinations[18] are close to those predicted for some of the parameter space of the inhomogeneous models. Observation of primordial levels of Be and B would thus determine what our universe looked like 10^{-5} seconds after the Big Bang.

Other reactions of importance in Big Bang nucleosynthesis that involve short-lived nuclides will certainly be studied in the near future. Some reactions already known to be significant involve nuclides with masses between 14 and 28 atomic mass units. The synergism between theory and experiment should help reveal other critical reactions.

Rapid proton burning

A number of extreme astrophysical environments have the capacity to undergo rapid proton burning, also known as the rp process.[19] One such envirnonment is the region surrounding a collapsed star—a white dwarf or neutron star—in a binary system, where the collapsed star accretes matter from its companion. Such environments would



Rapid-proton-burning reaction network for processes that occur in some stellar environments. Normal and hot hydrogen-burning cycles (black and red lines, respectively) among the elements C, N, O, F and Ne are shown. Double lines indicate the primary cycles that catalyze the conversion of four protons to a ^{4}He nucleus; single lines indicate branch cycles. The proton radiative captures, nucleon transfer reactions and positron emissions that couple the various nuclides are indicated in nuclear physics shorthand: For example, (p,γ) between ^{12}C and ^{13}N indicates the $^{12}C + p \to {}^{13}N + \gamma$ reaction. The rates at which these cycles proceed—and hence the rates at which they can generate energy and synthesize new nuclides—depend on the rates at which the reactions proceed or at which the β decays occur. Branch points are thus especially important. **Figure 6**

have temperatures of several hundred million K, where the times between successive proton radiative capture reactions (such as $^{12}C + p \to {}^{13}N + \gamma$) would become much shorter than those characteristic of β decays. The β decays ordinarily intercede after roughly every other proton radiative capture, thus maintaining the rough equivalence between neutron and proton number characteristic of stable nuclei. A proton-burning scenario is sketched in figure 6, which shows both the usual CNO cycle, by which C catalyzes the conversion of four protons (with two β decays) into a ^{4}He nucleus, or α particle, and the hot CNO, or HCNO, cycle. The β decay from ^{13}N to ^{13}C always occurs before the next proton capture at the normal stellar temperatures of the CNO cycle, but in a high-temperature environment it may not have time to occur, so ^{14}O can be made via the $^{13}N + p \to {}^{14}O + \gamma$ reaction. This reaction has therefore been an archetypal one in radioactive nuclear beam research.

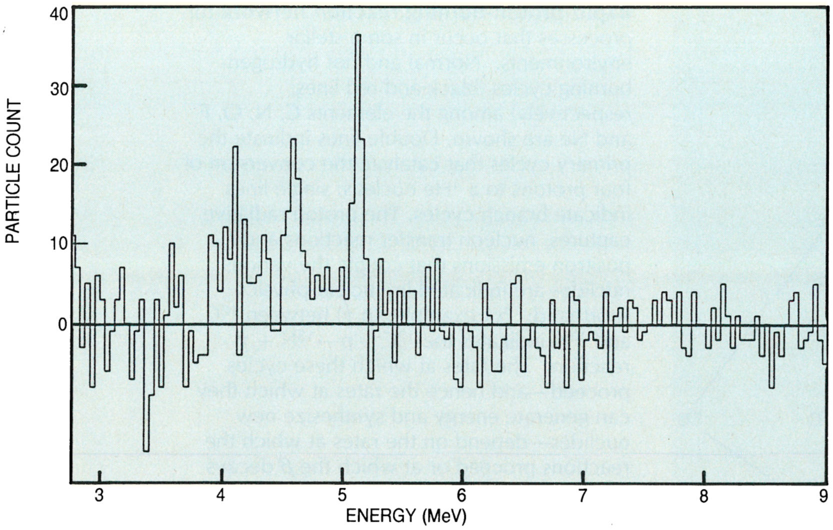
Remarkably, the rate of the $^{13}N + p \to {}^{14}O + \gamma$ reaction has been measured three times in the past two years. To obtain the first measurement,[20] experimenters studied the reaction using the ^{13}N-beam facility at Louvain-la-Neuve; figure 7 shows their data. The two other measurements[21] were based on a recently developed technique known as Coulomb breakup,[22] which involves measuring the cross section through the inverse reaction. This approach requires an ^{14}O beam, available only at a radioactive nuclear beam facility. A heavy nucleus, for example lead, Coulomb-excites the ^{14}O nuclei to states that decay by proton emission. Then, through coincidence detection, the apparatus measures the cross section for production of the proton and the ^{13}N residual nucleus. Although the laboratory energies of the proton and residual nucleus are large, the low energy of each relative to the other is about that encountered in astrophysical environments. This approach holds great promise for the measurement of a number of reactions that cannot otherwise be studied, such as those involving neutron capture on a short-lived nucleus. Of special note is that the three studies of the $^{13}N + p \to {}^{14}O + \gamma$ cross section actually agree.

Reactions involving somewhat heavier nuclides than those shown in figure 6 require somewhat higher temperatures simply to overcome the Coulomb barriers. Furthermore, rapid hydrogen burning of the more massive nuclides can be extremely complex to describe, because one must know the cross sections of reactions (mostly of proton radiative captures) that couple all the relevant nuclides. Recent studies of the most proton-rich nuclides that are stable to nucleon decay have allowed nuclear physicists to determine the limiting masses for the nuclides that must be considered in the rp process. Specifically, researchers used the radioactive nuclear beam facility at Michigan State University to find that very-proton-rich nuclides such as gallium-63, germanium-62 and -63, arsenic-65, bromine-69 and strontium-75 are stable to nucleon emission—that is, they β decay.[23] None of these nuclides had been observed previously.

Rapid neutron capture

The stellar r process is thought to occur by successive radiative captures of many neutrons on preexisting "seed nuclei" near the core of a supernova.[24] This process generates nuclides with more than ten more neutrons than the most neutron-rich stable nuclei have, thus driving the nuclides to the neutron drip line. For nuclei between nuclear shell closures these neutron captures occur rapidly. However, at the shell closures a neutron must β decay to a proton before a subsequent neutron capture can occur. Thus the rate at which the r process can proceed is mediated by the halflives of these "waiting point" nuclei. Some of the first experiments with beams of short-lived nuclei involved nuclides important to the r process. Studies of these nuclides with recoil mass spectrometers[1] allowed nuclear physicists to determine[25] halflives and information about nuclear levels of neutron-rich nuclides such as ^{80}Zn, which has 12 neutrons more than the most massive stable Zn isotope but, with 50 neutrons, has a closed shell.

It may also be important to study reactions on some of the neutron-rich nuclides important to the r process.



Gamma-ray counts above background from the $^{13}N + p \rightarrow {}^{14}O + \gamma$ experiment using the ^{13}N beam at Louvain-la-Neuve.[20] Photons of the energy characteristic of this reaction interact with the detector primarily through pair production: The peaks at 5.1, 4.6 and 4.1 MeV are from events in which the full energy of the γ ray is deposited in the detector or in which one or both of the 0.51-MeV photons from pair annihilation escape the detector. Because the reaction is resonance dominated, one can determine the total γ-ray yield over a spread of energies from the strength of the resonance that produces the cross section for the reaction. **Figure 7**

Because measurement of neutron radiative capture cross sections would require radioactive nuclear beams incident on neutron targets, they are not likely to be done in the near future. However, the Coulomb breakup technique could provide important information in many cases. Production of a beam of the residual nuclide in the reaction of interest, followed by coincidence detection of the neutron and the heavy reaction-product nucleus resulting from Coulomb breakup of the beam nuclei, could provide the desired cross sections provided excited states of the initial- and final-state nuclides do not complicate the picture.

References

1. H. L. Ravn, Phys. Rep. **54**, 201 (1979).
2. R. N. Boyd, C. Rolfs, eds., "Proc. Burr Oak Workshop on Radioactive Beams and Small Cross Sections," Ohio State U., Columbus, Ohio (1981).
3. R. F. Casten, J. M. D'Auria, C. N. Davids, J. D. Garrett, J. M. Nitschke, B. M. Sherrill, D. J. Vieira, M. Wiescher, E. F. Zganjar, "The Isospin Laboratory: Research Opportunities with Radioactive Nuclear Beams," LALP 91-51, Los Alamos Natl. Lab., Los Alamos, N. M. (1991).
4. I. Tanihata, in *Treatise on Heavy-Ion Science*, vol. 8, D. A. Bromley, ed., Plenum, New York (1989), p. 443.
5. W. D. Myers, J. M. Nitschke, E. B. Norman, eds., *Proc. First Int. Conf. on Radioactive Nuclear Beams*, World Scientific, Teaneck, N. J. (1990). T. Delbar, ed., *Proc. Second Int. Conf. on Radioactive Nuclear Beams*, Adam Hilger, Bristol, UK (1991).
6. I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D. E. Greiner, N. Takahashi, Y. Nojiri, Phys. Lett. B **160**, 380 (1985). I. Tanihata, Nucl. Phys. A **522**, 275c (1991), and references therein.
7. G. F. Bertsch, B. A. Brown, H. Sagawa, Phys. Rev. C **39**, 1154 (1989).
8. M. Fukuda, T. Ichihara, N. Inabe, T. Kubo, H. Kumagai, T. Nakagawa, Y. Yano, I. Tanihata, M. Adachi, K. Asahi, M. Kouguchi, M. Ishihara, H. Sagawa, S. Shimoura, Phys. Lett. B **268**, 339 (1991).
9. Y. Suzuki, Y. Tosaka, Nucl. Phys. A **517**, 599 (1990). G. F. Bertsch, J. Foxwell, Phys. Rev. C **41**, 1300 (1990). G. F. Bertsch, H. Esbensen, Ann. Phys. **209**, 327 (1991).
10. T. Kobayashi, in *Structure and Reactions of Unstable Nuclei*, World Scientific, River Edge, N. J. (1992).
11. A. B. Migdal, Sov. J. Nucl. Phys. **16**, 238 (1973).
12. V. Efimov, Comments Nucl. Part. Phys. **19**, 271 (1990).
13. N. Takigawa, H. Sagawa, Phys. Lett. B **265**, 23 (1991).
14. G. J. Mathews, B. S. Meyer, C. R. Alcock, G. M. Fuller, Astrophys. J. **358**, 36 (1990). T. Kajino, R. N. Boyd, Astrophys. J. **359**, 267 (1990).
15. R. N. Boyd, I. Tanihata, N. Inabe, T. Kubo, T. Nakagawa, T. Suzuki, M. Yonokura, X. X. Bai, K. Kimura, S. Kubono, S. Shimoura, H. S. Xu, D. Hirata, Phys. Rev. Lett. **68**, 1283 (1992).
16. T. Paradellis, S. Kossionides, G. Doukellis, X. Aslanoglou, P. Assimakopoulos, A. Pakou, C. Rolfs, K. Langenke, Z. Phys. A **337**, 211 (1990).
17. M. M. Farrell, R. N. Boyd, X. Gu, J. D. Kalen, J. J. Kolata, R. Lamkin, R. Smith, R. Tighe, K. Ashktorab, F. D. Becchetti, J. Brown, D. Roberts, T.-F. Wang, in *Proc. Second Int. Conf. on Radioactive Nuclear Beams*, T. Delbar, ed., Adam Hilger, Bristol, UK (1991), p. 287.
18. S. G. Ryan, M. S. Bessell, R. S. Sutherland, J. E. Norris, Astrophys. J. **348**, L57 (1990). G. Gilmore, B. Edvardsson, P. E. Nissen, Astrophys. J. **378**, 17 (1991).
19. R. K. Wallace, S. E. Woosley, Astrophys. J. Suppl. Series **45**, 389 (1981). M. Wiescher, J. Gorres, F.-K. Thielemann, H. Ritter, Astron. Astrophys. **160**, 56 (1986).
20. P. Decrock, T. Delbar, P. Duhamel, W. Galster, M. Huyse, P. Leleux, I. Licot, E. Lienard, P. Liponik, M. Loiselet, C. Michotte, G. Ryckewaert, P. Van Dupper, J. Vanhorenbeeck, J. Vervier, Phys. Rev. Lett. **67**, 808 (1991).
21. T. Motobayashi, T. Takei, S. Kox, C. Perrin, F. Merchez, D. Rebreyend, K. Ieki, H. Murakami, Y. Ando, N. Iwasa, M. Kurokawa, S. Shirato, J. Ruan, T. Ichihara, T. Kubo, N. Inabe, A. Goto, S. Kubono, S. Shimoura, M. Ishihara, Phys. Lett. B **264**, 259 (1991). J. Kiener, A. Lefebvre, P. Aguer, C. O. Bacri, R. Bimbot, G. Bogaert, B. Borderie, F. Clapier, A. Coc, D. Disdier, S. Fortier, C. Grunberg, L. Kraus, I. Linck, G. Pasquier, M. F. Rivet, F. St. Laurent, C. Stephan, L. Tassan-Got, J. P. Thibaud, in *Proc. Second Int. Conf. on Radioactive Nuclear Beams*, T. Delbar, ed., Adam Hilger, Bristol, UK (1991), p. 311.
22. R. Shuam, G. Baur, P. Banerjee, Phys. Rev. C **44**, 915 (1991).
23. M. F. Mohar, D. Bazin, W. Benenson, D. J. Morrissey, N. A. Orr, B. M. Sherrill, D. Swan, J. W. Winger, Phys. Rev. Lett. **66**, 1571 (1991).
24. J. J. Cowan, F.-K. Thielemann, J. W. Truran, Phys. Rep. **208**, 268 (1991).
25. D. Guillemaud-Mueller, C. Detraz, M. Langevin, F. Naulin, M. de Saint-Simon, C. Thibault, F. Touchard, M. Epherre, Nucl. Phys. A **436**, 37 (1984). J. A. Winger, J. C. Hill, F. K. Wohn, R. Moreh, R. L. Gill, R. F. Casten, D. D. Warner, Phys. Rev. C **36**, 758 (1987). ■