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Exotic Nuclei and Their Decay

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Eighty-one elements, from hydrogen to bismuth, occur naturally in stable form on Earth, and two more—thorium and uranium—appear with sufficiently long radioactive lifetimes that they are considered primordial. When viewed with a chemical perspective these elements provide a complete picture, which is enhanced but not dramatically changed by the 25 ephemeral elements that have by now been produced artificially or observed as natural decay products.

Summary. Recent advances in nuclear accelerators and experimental techniques have led to an increased ability to synthesize new isotopes. As isotopes are produced with more and more extreme combinations of neutrons and protons in their nuclei, new phenomena are observed, and the versatility of the nucleus is increased as a laboratory for studying fundamental forces. Among the newly discovered decay modes are (i) proton radioactivity, (ii) triton, two-proton, two-neutron, and three-neutron decays that are β-delayed, as well as (iii) ^{14}C emission in radioactive decay. Precise tests of the properties of the weak force have also been achieved.

However, if we consider instead the physics of an atomic nucleus, the repertoire of the stable elements is distinctly limited. Being comprised of neutrons and protons, nuclei exhibit quite different properties if the numbers of the component nucleons are changed. While each element, and its chemistry, is characterized by the particular number of protons in its nuclei, the various isotopes of that element are distinguished by their number of neutrons. Though chemically identical, such isotopes differ markedly in their nuclear physics.

Most stable elements have more than one constituent isotope. We find that, all told, nature has given us 263 stable isotopes, with a handful of long-lived radioactive ones and their daughters (*1*). Although this may appear to be a richly varied sample, in fact it is not.

A glance at Fig. 1 reveals that the stable isotopes lie in a narrow, gently curving band, with very little variation in proton-to-neutron ratios throughout. Since, in the most general sense, the physics of a nucleus depends on the interactive forces between its components, it would be difficult for the physicist to reach any real understanding without the ability to observe the variation of nuclear properties as a function of important changes in the proton or neutron numbers, one independently of the other. Such flexibility must be the basis of any systematic study, yet it would be impossible to attain if we were restricted to the naturally occurring isotopes.

There is, of course, no need for such a restriction. Today, many methods are available for the artificial production of new isotopes and, although these methods themselves are rarely specific, experimental techniques have been developed to isolate any selected product, establish its isotopic identity, and measure many of its properties. All this is possible even if only a few nuclei have been produced and even if their half-life is as short as milliseconds. The result of such experimental virtuosity is a full 2200 entries in the current nuclear chart (*1*), each representing an isotope for which at least one property has been measured. This large group of synthesized isotopes is also indicated in Fig. 1.

As impressive as the tenfold increase in available isotopes is, and as much as it increases our flexibility in probing the nucleus, nevertheless we still have synthesized only a modest fraction of the more than 7000 isotopes that could exist for an observable period of time (*2*). The smallness of our available sample is not, in itself, a bad thing. What does remain as a frustrating technical limitation is that we are still constrained to isotopes in the neighborhood of the stable ones, particularly if we are seeking detailed information. Only among the light elements, and only on the neutron-deficient side of stability, have we consistently produced nuclei at the "drip line" limits—those limits determined for each element by the lightest and heaviest isotope that can exist long enough to be observed (Fig. 1). In fact, on the neutron-excess side of stability we are not even close to the limit.

Unique Properties of Exotic Nuclei

Why is the drip line an important goal? It is, of course, the most extreme condition we can impose on an unexcited nucleus. As such, it provides a demanding test of nuclear theory. But there are more exciting reasons. The further nuclei are from the stable isotopes, the more energy they have for decay, and the more exotic are their decay processes. Novel processes are inherently interesting, but some of those already studied have proved their usefulness by yielding nuclear-structure information that could not have been obtained by conventional means with nuclei nearer stability. The search for nuclei near the drip lines attacks a frontier where new phenomena are to be observed and new insights gained (*3*).

Figure 2 illustrates the energy changes

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that occur with remoteness from stability (*4, 5*); it is a plot of the masses for a series of nuclei, all with the same total number of nucleons, 151. Only one corresponds to a stable isotope, $^{151}_{63}Eu_{88}$ (whose nuclei contain 63 protons and 88 neutrons); its mass is the lowest of the series. Nuclei with other combinations of 151 neutrons and protons have masses that increase rapidly with distance from the "valley of stability."

Each point plotted in Fig. 2 represents the lowest energy state, the ground state, of a nucleus. No nucleus in its ground state can release any energy except by transforming to a nucleus that comprises a different combination or a lower total number of neutrons and protons. By far the most common mechanism for this transformation is β-decay, a process in which a neutrino and a positive or negative electron are emitted from the nucleus or, equivalently, an atomic electron is captured into the nucleus and a neutrino emitted. The net result is to change a nuclear proton into a neutron (β^+-decay), or vice versa (β^--decay), without changing the total number of nucleons. Beta-decay provides the path by which nuclei decay to successive neighbors until ultimately they reach the valley of stability.

Beta-decay was one of the first forms of radioactivity to be observed nearly a century ago, yet it is only in recent years that the force responsible for the process, called the weak force, has been fully characterized (*6*). Indeed, the vector bosons W^+ and Z^0, which transmit the force (as photons transmit the electromagnetic force), have just been discovered (*7*). As a pervasive phenomenon in nuclei, β-decay has already provided a source of systematic information on this basic natural force—one example of which we shall return to later. However, in contrast to the near-stable nuclei lying close to the valley of stability, which, historically, have been the basis for most studies, nuclei farther from stability can release in excess of 10 MeV through a single β-decay. Such a large energy release opens up possibilities for investigating the properties of the weak force; it also opens up exotic decay paths.

The inset in Fig. 2 displays a few decay paths available to the neutron-deficient nucleus $^{151}_{71}Lu_{80}$. The first is the normal β-decay, already discussed, that leads to $^{151}_{70}Yb_{81}$. One transition shown actually goes directly to the daughter nucleus's ground state, a simple route that only rarely occurs alone, even in the low-energy β-decays of nuclei near stability. What happens more frequently is that, in addition to the direct ground-state transition, there are β-decay transitions to excited states of the daughter nucleus; these states subsequently decay to the ground state by the emission of electromagnetic radiation—γ rays.

As the distance from stability increases, the energy difference between adjacent nuclei increases, and the second decay route in Fig. 2 becomes available for those nuclei. It too begins with β-decay, but here the excited states of the daughter nucleus can emit a nucleon. Thus, the β-decay is accompanied by proton emission, in the case illustrated, or by neutron emission for nuclei on the opposite slope of the mass valley. This decay path, which is called β-delayed proton (or neutron) decay, not only involves the weak force but also another fundamental force, the strong force. It is the strong force that binds nucleons together into a nucleus, so the strong force is also accountable for the emission of a nucleon when the binding energy is insufficient for its retention. As its name indicates, the strong force is considerably stronger—by about five orders of magnitude—than the weak force, so the time scale for nucleon emission is much shorter than that for β-decay. While the lifetime before the initial β-decay may be seconds or longer, the interval between β-decay and the emission of a nucleon is usually less than 10^{-14} second. Thus, in practice, all components of such decay appear nearly simultaneously, though delayed by the β-decay.

Although β-delayed α-particle decay has a venerable history, β-delayed neutron decay was not observed until 1939; its proton equivalent, not until 1963 (*8*). In the past two decades, however, with our increasing ability to produce exotic nuclei, the number of isotopes known to decay by β-delayed proton emission has grown to over 60. In fact, β-delayed particle emission is one of the important classes of nuclear radioactivity.

The third decay route shown in the inset to Fig. 2 is one that only appears at the very fringes of the nuclear geography in Fig. 1. In fact, it is this process of direct nucleon emission that sets the limit on possible isotope synthesis. If a nucleus's radioactive transformation must proceed first through β-decay, then its lifetime will be long enough to permit the existence of the nucleus to be detected and its properties measured. On the other hand, if significant energy can be released from a nucleus by its emitting a nucleon, it will do so in preference to β-decay and with such rapidity that the prior existence of the nucleus itself becomes moot. This leakage of nucleons, either neutrons or protons, establishes the location of the drip lines.

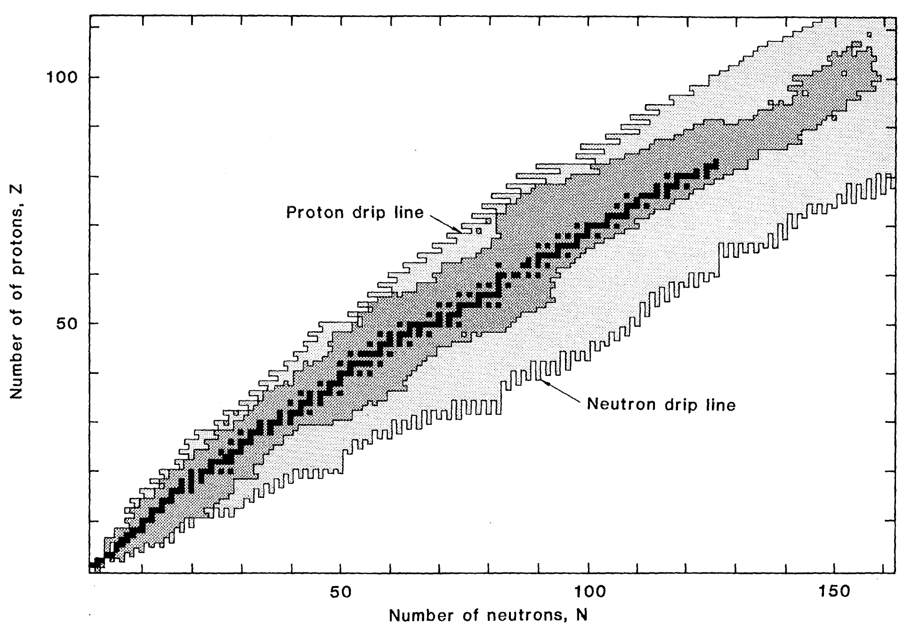

Fig. 1. Chart of the nuclides. The stable isotopes are represented by black squares. Moving out from the stable isotopes are areas representing isotopes that have already been synthesized and identified (*1*), isotopes that calculations indicate could exist for an observable period of time but have not yet been produced (*2*) and, finally, combinations of neutrons and protons not expected to adhere. The peninsula of observable nuclei undoubtedly extends for a short distance beyond the figure to the upper right; predictions in this region are tenuous at best.

Proton Radioactivity

Although unbound nucleons can lead to the immediate disintegration of a nucleus, this only occurs if enough energy is available. In the case illustrated, ^{151}Lu, the nucleon is a proton and is unbound by a little more than 1 MeV, yet ^{151}Lu has a half-life of 85 msec. To understand how an essentially unbound system can have such a relatively long life, we must look to the electromagnetic force, the third fundamental force (*9*) that plays a role in nuclear physics. Both the proton and the residual nucleus from which it is ultimately emitted are positively charged. Once these two fragments are actually separated from one another they will possess potential energy by virtue of the elecromagnetic repulsion that acts between objects with like charges. If this potential energy exceeds the nuclear energy initially available to the unbound proton, then the mismatch creates a barrier, a "Coulomb barrier," to the proton's emission.

According to classical physics, any deficiency between the energy available and that required would not simply delay the decay but would prevent it entirely. However, the electromagnetic potential energy depends inversely on the separation between the fragment centers, so it is quantum-mechanically possible for a proton to tunnel through the Coulomb barrier and materialize, so to speak, at a separation where the potential energy equals the nuclear energy available—1 MeV in our example. The half-life of such a decay depends very strongly on the severity of the mismatch or, in other words, on the distance that the proton must tunnel. Wherever nucleon emission is possible, it always competes with β-decay; consequently, if the nucleon's energy is too low, the competing process will predominate by occurring before emission can take place. If the nucleon's energy is too high, then the nucleus will disintegrate in an undetectably short time. Evidently the energy window that yields observable proton radioactivity is small, and the candidates, such as ^{151}Lu, are not particularly accessible.

These difficulties made proton radioactivity a tantalizing but elusive phenomenon. Alpha-particle radioactivity, in which a helium nucleus tunnels through the Coulomb barrier, can occur in nuclei near stability, even among isotopes that occur in nature. It was one of the first forms of radioactivity to be discovered. The first observation of proton emission (*10*), however, was not until 1970 and even at that was of a rather peculiar type. It arose not from the decay of a nuclear ground state but from the decay of an excited state in ^{53}Co that has a structure suited to the emission of protons in a tractable time scale. The parent nucleus was not even particularly far from the valley of stability. Though undoubtedly proton-radioactive, the ^{53}Co excited state did not appear to be the herald of a general phenomenon. The search for ground-state proton radioactivity went on as likely new isotopes were produced with fewer and fewer neutrons in their nuclei.

Success came in 1982 with the discovery of proton radioactivity from ^{151}Lu (*11*), the isotope we have been using as an example, and ^{147}Tm (*12*). The techniques used in their production and identification are illustrative of what is possible in the study of exotic nuclei. For both cases, the proton-radioactive nuclei were synthesized by heavy-ion fusion, in which the nuclei of two naturally occurring isotopes were brought together and fused to form a new nucleus containing most of the participants' nucleons. This is not as easy as it sounds, since the Coulomb barrier once again plays a role by causing the two positively charged nuclei to repel one another as they come into proximity. The barrier can certainly be overcome if one nucleus is projected at the other with sufficient kinetic energy, but this energy becomes a liability after fusion has taken place. The composite system seeks to dissipate its extra energy; and it may do so by breaking up or by otherwise changing its character through the ejection of nucleons.

This problem is not unlike the one faced by a golfer who tries to sink his putt in a hole that is perched at the top of a hill. If he hits the ball hard enough to surmount the hill, then he is in grave danger of overshooting the hole. The trick is to give the ball just enough energy.

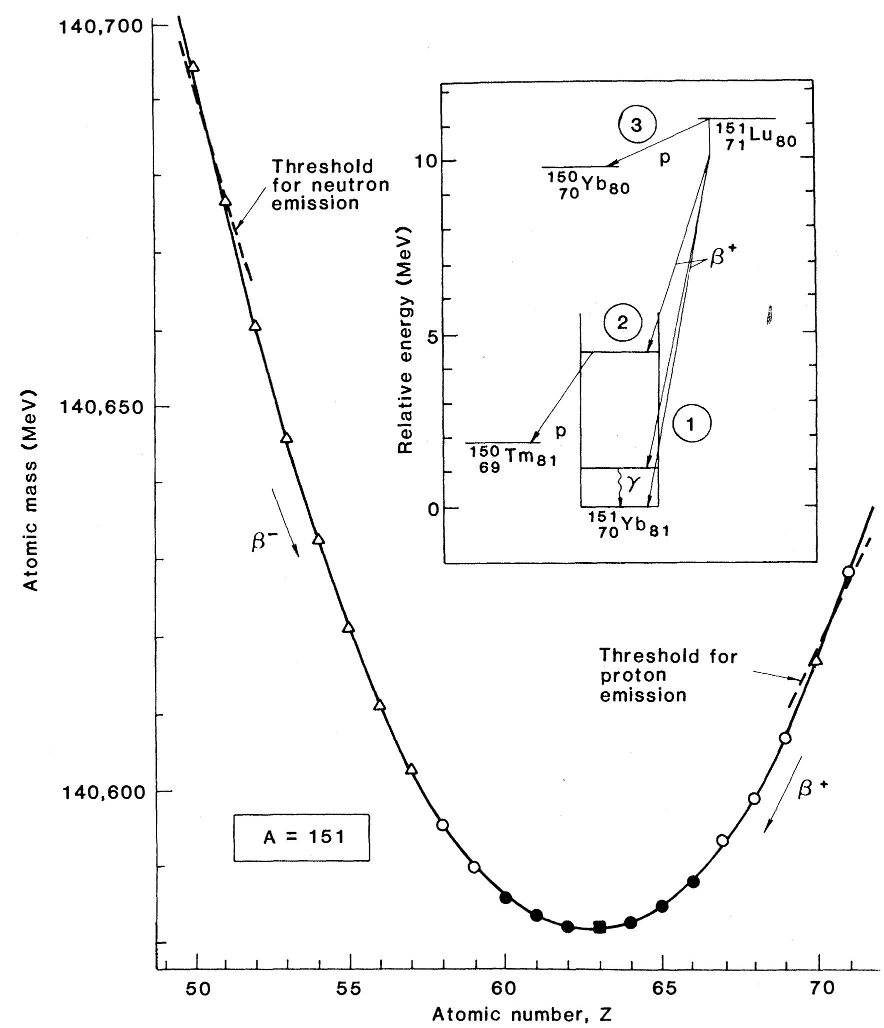

Fig. 2. Atomic masses of a series of isotopes that have 151 nucleons (neutrons and protons, $A = 151$) in their nuclei. The masses are given in energy units (MeV) to emphasize the energy released by decay between neighboring nuclei. The only stable isotope, $^{151}_{63}Eu_{88}$, is shown as a darkened square; the other isotopes whose masses have been measured (*4*) appear as darkened circles. All remaining masses shown come from predictions (*5*), with open circles representing nuclei that have been observed (*1*), and open triangles those that have not. The dashed lines show the approximate threshold at which a neutron or proton becomes energetically unbound by the nucleus. The inset illustrates three possible decay channels for the very neutron-deficient nucleus ^{151}Lu. Only the channel labeled 1 is the normal β-decay channel leading down the $A = 151$ mass parabola; the other two connect to an equivalent $A = 150$ parabola.

The ^{151}Lu nuclei were produced (*11*) by bombardment of a ruthenium target, which was approximately 0.5 μm thick and enriched in ^{96}Ru, with a beam of energetic ^{58}Ni ions from the UNILAC accelerator at Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Federal Republic of Germany. The actual reaction

$$^{96}_{44}Ru_{52} + ^{58}_{28}Ni_{30} \rightarrow ^{151}_{71}Lu_{80} + p + 2n$$

was most favored when the ^{58}Ni ions had 261 MeV of kinetic energy but, even at that, only 1 in about 10^{10} ions in the beam initiated the desired reaction. Other reactions took place concurrently in which different combinations of nucleons were ejected from the composite system before an identifiable heavy nucleus appeared. Thus, the synthesized ^{151}Lu nuclei had to be separated from the beam and a host of reaction products, most of them generated more prolifically.

The separation was accomplished by passing the reaction products, which recoil out of the thin target, through a velocity filter (*13*). This velocity filter was a combination of electric and magnetic fields that only allowed ions in a preselected velocity band to be transmitted. Although fusion products like ^{151}Lu have almost the same momentum as the beam, their mass is quite different and, therefore, their velocity is, too. They could pass through the filter with up to 40 percent efficiency while the ^{58}Ni beam and many reaction products did not; the suppression factor for the beam particles was as high as 10^{16}. The transmitted products implanted themselves in a silicon surface-barrier detector where nucleons that were subsequently emitted during decay could be observed. Figure 3A shows the energy spectrum obtained; it is the first reported observation of ground-state proton radioactivity. Its measured half-life, 85 ± 10 msec, testifies to the importance in this case of instantaneous processing of reaction products; chemical techniques, for example, would simply have been too slow for the purpose.

The second observed proton-radioactive isotope, ^{147}Tm, was produced (*12*) in a similar heavy-ion fusion reaction at the UNILAC accelerator, but the technique for isolating the product of interest was different. Reaction products recoiling from the thin target were stopped by a hot tantalum foil inside a thermal ion source (*14*). Since the average ion-source temperature was 2500°C, these atoms diffused back out of the catcher; they were then ionized, reaccelerated, and passed between the poles of a magnet, which separated them spatially according to their atomic mass. The entire apparatus is called an on-line isotope separator—"on-line" because it is directly coupled to a target undergoing bombardment.

This approach leads to a cleaner spectrum, as can be seen from Fig. 3B, because the collected sample is restricted to nuclei with 147 nucleons. The price paid in some cases is a longer time delay: not all elements diffuse rapidly out of a catcher foil; nor do they all ionize readily. However, this was not a serious problem for thulium; the observed isotope, ^{147}Tm, has a half-life of 420 ± 100 msec.

Although proton radioactivity is a newly observed phenomenon, it has already provided important information on a remote region of the nuclear chart (Fig. 1). Just how remote can be appreciated by noting that to reach ^{151}Lu from the lightest stable lutetium isotope would require the removal of 24 of the neutrons in that nucleus; and ^{147}Tm is 22 neutrons lighter than its corresponding stable isotope. Yet from the measured half-lives of these nuclei we can already limit the possibilities for their structure, and from their proton-decay energies we can stringently test predictions for their masses. We have opened a new window on nuclear structure, and that window is already being opened wider: already three more proton-radioactive nuclei have been reported, ^{109}I, ^{113}Cs, and ^{150}Lu (*15*).

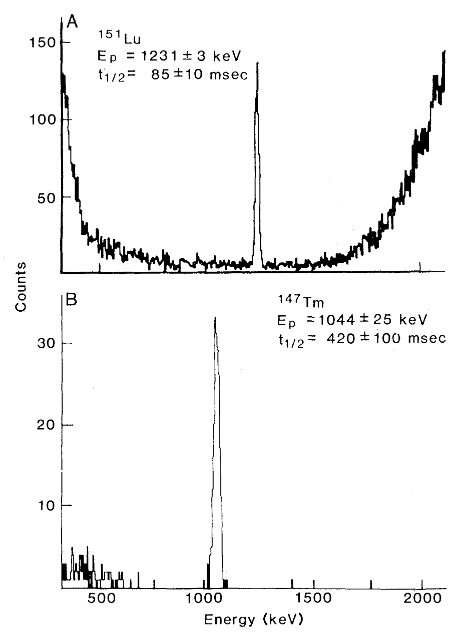

Fig. 3. (A) Energy spectrum of particles emitted in the decay of nuclei transmitted by a velocity filter (*13*) during the irradiation of a ^{96}Ru target with 261 MeV ^{58}Ni projectiles from the UNILAC (*11*). (B) Energy spectrum of particles emitted in the decay of nuclei transmitted by the on-line isotope separator during the irradiation of a ^{92}Mo target with 267 MeV ^{58}Ni projectiles from the UNILAC. The detection technique rejected particles with energy above about 2 MeV (*12*).

So far, we have followed the decay possibilities for exotic nuclei with the help of Fig. 2. As I have pointed out, the three decay channels illustrated there are, in principle, matched on the other side of the valley of stability by analogous decays that involve electrons (β^--decay) and neutrons. In practice, ground-state neutron radioactivity has not yet been observed. Since the Coulomb barrier is inoperative for the chargeless neutron, the only hindrance to the instantaneous ejection of an unbound neutron is the much weaker centrifugal barrier that arises from the fact that nuclei spin (*16*). As a result, fewer nuclei are expected to decay in a tractable time scale by neutron emission than by proton emission. In addition, the expected location of the neutron drip line is much farther from stability and more difficult to reach than the proton equivalent.

Beta-Delayed Multinucleon Decay

In yet another way, the three channels shown in the inset to Fig. 2 are not exhaustive. Excited states in ^{151}Yb, or in any other nucleus like it, even on the opposite side of the valley of stability, can be unbound to the emission of nuclear fragments other than a single nucleon. Alpha particles have already been mentioned. Two protons (*17*), two and three neutrons (*18*), and even tritons (*19*) have all been observed accompanying β-decay for the first time during the past 5 years. These multiparticle decays are expected to yield information over and above the usual nuclear data, especially about the low-energy interactions between the emitted particles themselves.

Although this promise is not yet fulfilled, it can be demonstrated with the β-delayed two-proton decay of $^{22}_{13}Al_9$. That isotope was synthesized (*17*) from a ^{24}Mg target in the 110-MeV ^{3}He beam of the 88-inch cyclotron at the Lawrence Berkeley Laboratory. The decay particles were identified as protons and measured in coincident pairs by two miniature detectors, each comprised of three silicon wafers, the thinnest of which is 24 μm thick. No special efforts were taken to isolate the isotope of interest since its characteristic decay and the specialized coincidence detection technique provided a unique signature for ^{22}Al. The energies of the observed events are shown in Fig. 4, together with the deduced decay scheme. The energy spectrum (Fig. 4B) shows that the two protons in combination carry off well-determined amounts of energy; their decay begins with the 14.04-MeV excited state of ^{22}Mg and concludes with the residual ^{20}Ne nucleus in either its ground state or first excited state.

The question—unanswered as yet—is whether the two protons are emitted together, presumably as a ^{2}He nucleus that subsequently breaks up, or in a sequential process in which the first proton leads to a definite state of ^{21}Na before the second proton is released. The energy distribution of the protons should be indicative: simultaneous two-proton emission should give rise to a broad distribution of energies, whereas sequential decay should lead to discrete energies. Unfortunately, although the proton energies cluster along the kinematic lines (Fig. 4A), the statistics are insufficient to establish that there are distinct groups. Experiments are already planned to settle the question through measurement of the angular correlations between detected protons (*20*). If a pair began the decay process together, then the partners' final trajectories should reflect that fact.

Data from other multiparticle decays might be expected to help resolve the ambiguity, but so far they have not. Only one other isotope has been observed to decay by β-delayed two-proton emission, $^{26}_{15}P_{11}$ (*21*), and it is a rather special case. Its protons must undergo sequential emission in order to conserve angular momentum, a consequence confirmed by the individual proton spectra. Beta-delayed multineutron emitters are also known, and they too have the option of decaying by paired or sequential emission. To date, the mechanism for two-neutron emission is no better understood than that for two-proton emission. The inability to detect neutrons efficiently and promptly has precluded the necessary measurements.

Before leaving neutron emission, however, some mention must be made of one of the richest emitters of them all, ^{11}Li. In recent studies, ^{11}Li was synthesized by 600-MeV proton bombardment of uranium in a uranium carbide target. The plethora of nuclear fragments produced by the bombardment was processed in the ISOLDE isotope separator at CERN (European Laboratory for Particle Physics) (*18*), and ^{11}Li was isolated at the rate of 25 atoms per second. Its half-life is only 8.7 msec. The results provided the first evidence for the emission of two and three neutrons as well as tritons. In all, six qualitatively different decay modes have been observed following the β-decay of ^{11}Li:

$^{11}_{3}Li_8 \xrightarrow{-\beta} {}^{11}_{4}Be_7$	(12 percent)
$^{10}_{4}Be_6 + n$	(81 percent)
$^{9}_{4}Be_5 + 2n$	(4 percent)
$^{8}_{3}Li_5 + t$	(0.01 percent)
$^{6}_{2}He_4 + \alpha + n$	(1 percent)
$2\alpha + 3n$	(2 percent)

As varied in its decay as ^{11}Li is, it is not the most extraordinary source of radioactivity. That title must surely go to ^{223}Ra, a naturally occurring radioactive isotope. It has long been known to decay by α-particle emission, but just this year it was discovered (*22*) that in one decay out of 10^9, ^{223}Ra emits a ^{14}C nucleus instead of an α particle. Never before, outside of the fission process, has anyone reported a nuclear fragment heavier than an α article to be emitted during radioactive decay.

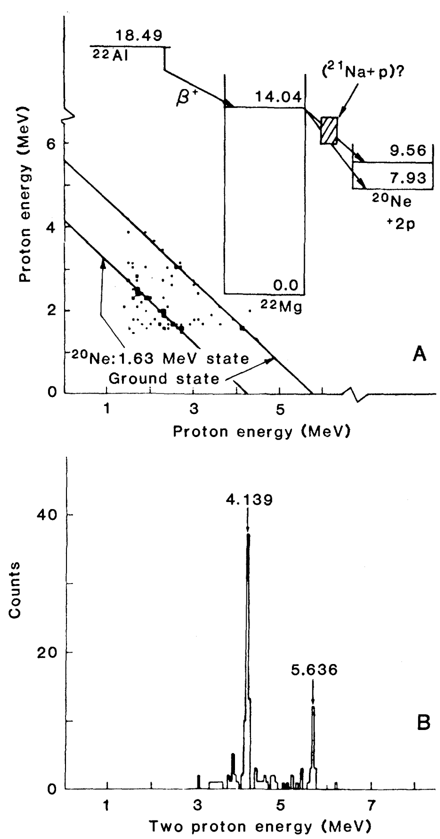

Fig. 4. (A) A proton-proton coincidence spectrum obtained following the β-decay of ^{22}Al. Kinematic lines corresponding to decay to the ground state and to the first excited state of ^{20}Ne are shown. Also shown is an abbreviated decay scheme; all levels are labeled by their energy, in MeV, measured relative to the ground state of ^{22}Mg. (B) Summed energy spectrum for the two-proton coincidences shown in (A).

Fundamental Applications: The Weak Force

So far, I have concentrated on the new phenomena observed among the exotic nuclei far from the valley of stability. However exciting these discoveries may be, their ultimate value will lie in what they can teach us about fundamental physics. With every extension to the chart of known isotopes, with every new decay process observed, the versatility of the nucleus as a microscopic laboratory is increased. The strong, weak, and electromagnetic forces all play a role in nuclei. To the extent that we can synthesize specific nuclei, even specific excited states of nuclei, we can use the nucleus as a well-controlled laboratory to study three of the basic forces of nature (*9*). This approach has been particularly fruitful for our understanding of the weak force.

Formally, the weak force can be considered as being made up of two components, or currents, classified according to their transformation properties. These are referred to as the vector and axial-vector currents. The vector component is governed by a conservation principle known as the conserved vector current (CVC) hypothesis (*23, 24*), which prescribes for the vector component a specific correspondence with the electromagnetic force and furthermore holds that its intrinsic strength is constant, being unaffected by the presence of the strong force. Precise verification of the constancy of the vector current has been accomplished through the observation of selected β-decay transitions in a variety of nuclei. The transitions selected were between states whose quantum numbers—specifically, spin parity and isospin of 0^+ and 1—require that only the vector current is involved, and the nuclei were chosen to cover a wide range of masses in order to vary the conditions of the strong force as much as possible.

The intrinsic strength of each individual transition is expressed as its *ft* value, a quantity that is determined not by a single measurement but by two and sometimes three separate experiments. To determine *ft*, one must measure the decay energy of the transition, the half-life of the parent state, and, if it has several possible decay branches, the fraction of the decays that populates the 0^+ final state. These challenging measurements have been made, with ever increasing precision, in a number of laboratories on at least three continents, notably at Harwell, England (*25*); Brookhaven, New York (*26*); Auckland, New

Zealand (*27*); and Chalk River, Canada (*28–30*).

The current level of precision in decay-energy measurements is a few parts in 10^5 (*27, 29*) while in half-lives it is a few parts in 10^4 (*26, 30*). Interestingly, the decay energy is not actually determined from the β-decay itself,

$$^{14}_{8}O_6 \rightarrow {}^{14}_{7}N_7 + e^+ + \nu$$

since the neutrino, ν, is difficult to observe. Rather, it is measured in an accelerator-induced reaction that essentially reverses the decay:

$$^{14}_{7}N_7 + p \rightarrow {}^{14}_{8}O_6 + n$$

or

$$^{14}_{7}N_7 + {}^{3}_{2}He_1 \rightarrow {}^{14}_{8}O_6 + {}^{3}_{1}H_2$$

Here the energies of the participants can be measured precisely, often by magnetic analysis. In the case of half-lives, perhaps the most important source of error is in the presence of undetected radioactive impurities, a common occurrence among accelerator-produced isotopes. Consequently, the recent measurements (*30*), which were taken for the first time on purified samples—obtained from the Chalk River on-line isotope separator (*31*)—represent a significant advance.

The present status of *ft*-value determinations is shown in Fig. 5. All relevant measurements have been incorporated through weighted averages, and small (~1 percent) radiative corrections have been calculated and applied (*32, 33*). Although eight transitions are involved, in nuclei whose masses differ by nearly a factor of 4, the $(ft)_R$ values agree to better than 1 percent. If this were as far as it went, however, the remaining scatter in the results could be taken to indicate that the weak force actually is being influenced by changes in the strong force, in disagreement with the CVC hypothesis. In fact, all indications are that even this scatter is removed when the electromagnetic force and its influence, not on the weak force itself but on the nuclear structure of the initial and final states of each transition, are accounted for. This correction, though small, requires a complex computation. The result appears as the stippled band in Fig. 5 (*34*). This band indicates the scatter expected from this effect. The breadth of the band corresponds to the estimated uncertainty due to the input parameters of the computation, though not to the possible inadequacy of the nuclear model used.

Comparison of the measured $(ft)_R$ values with the calculated values (Fig. 5) gives excellent agreement for the four cases below $Z = 20$, but some divergence for heavier nuclei. While the disagreement is never greater than 0.4 percent, it is still a matter of some concern. For the time being it seems likely that the nuclear shell model used in the computation (*34, 35*) is an inadequate representation for that purpose when $Z > 20$. Even so, the concordant four cases have already been used (*36, 37*) to extract a value for the vector coupling constant [$G'_V = (1.4150 \pm 0.0003) \times 10^{-49}$ erg cm^3], a fundamental measure of the strength of the vector component of the weak force in nuclei. That result, in conjunction with the analogous coupling constant for muon decay and the recently measured (*7*) mass of the Z^0 boson, yields direct information on the properties of quarks, the basic constituents of all subatomic particles. It is striking that the β-decays involved in this study release about 5 million electron volts of energy whereas the mass of the Z^0 boson is about 95 billion electron volts, yet both play essential roles in the result.

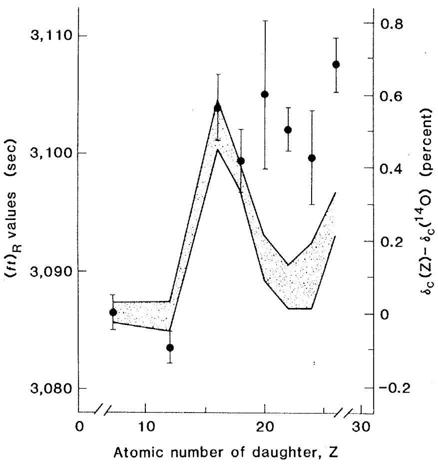

Fig. 5. Current status of measured $(ft)_R$ values (left-hand ordinate and points with error bars) compared with the calculated effects of analog symmetry breaking (right-hand ordinate and stippled band) in the nuclear states involved (*34*). The $(ft)_R$ values are weighted averages of all relevant data (*33, 36*) and incorporate radiative corrections (*32, 33*) as indicated by the subscript R. If the CVC hypothesis is valid and the nuclear effects are correctly calculated, then the experimental points should all lie within the stippled band.

The β-decay transitions used to extract the vector coupling constant were all between nuclear states with spin and parity 0^+. In such cases, the conservation of angular momentum requires only the vector current of the weak force to contribute. Through the exploitation of a more exotic decay mode, it has recently been shown that the vector current can also be probed in the decay of a 2^+ nuclear state, where the axial vector current also participates. The specific decay involved was that of ^{20}Na (*38*):

$$^{20}_{11}Na_9(2^+) \rightarrow {}^{20}_{10}Ne_{10}(2^+) + e^+ + \nu$$
$$\downarrow$$
$$^{16}_{8}O_8(0^+) + \alpha$$

Except for emitting the α particle instead of a proton, this process is the same as that represented by decay channel 2 in the inset to Fig. 2.

The essential feature of this decay is the emission of an α particle that follows each β-decay. Depending upon the momentum of the positron, e^+, and the neutrino, ν, the ^{20}Ne nucleus itself will recoil with characteristic momentum, which in turn will be imparted to the emerging α particle. Thus the energies of the positron and α particle and their relative directions of motion can be used to deduce the relative directions of the positron and its essentially unobservable companion, the neutrino. As an example, consider pairs of positrons and α particles traveling in opposite directions. If the neutrinos were emitted in the same direction as the positron, the α particle energy would be higher than if the neutrinos were emitted opposite to the positron. It is by measurement of the angular correlation between positron and neutrino that the effects of the vector and axial vector currents of the weak force can be distinguished.

A value has been obtained in this way for the vector coupling constant (*38*), which is statistically consistent with the result from $0^+ \rightarrow 0^+$ decays.

Future Development

Such applications, uniquely suited to the decay modes of exotic nuclei, are rapidly appearing in the wake of the first exploratory work. These applications have already reached a high degree of sophistication. Many provide much more detailed information than can be obtained with stable nuclei. For example, β-delayed proton decay has been used to time the life of excited nuclear states (*39*). The technique is sensitive to lifetimes in the range of 10^{-16} second, a span in which it has few competitors, and has been applied to a number of different nuclei (*40*).

The fundamental usefulness of exotic nuclei and their decay guarantees a continuing interest in the field. New heavy-ion accelerators—such as those at Darmstadt, Federal Republic of Germany; Caen, France; East Lansing, Michigan;

and Chalk River, Canada—will ensure that this interest is matched by an ever-increasing capability to synthesize new isotopes and to endow the nuclear laboratory with unprecedented flexibility.

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Muscle Contraction and Free Energy Transduction in Biological Systems

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One of the most ubiquitous properties of living systems is their ability to transform chemical free energy into motion. Muscle is highly specialized to perform this type of energy transduction, but motility also occurs in many important processes in cells. Ciliary motion, cytoplasmic streaming, and cell division are examples of the ability of cells to transform chemical free energy into mechanical work. Therefore, understanding the molecular basis for this type of free energy transduction is crucial to understanding the mechanism and regulation of many cellular processes.

Much of the available information about the mechanism of motile processes stems from structural, physiological, and biochemical studies on the mechanism of muscle contraction. Muscle contraction occurs when two sets of interdigitating filaments, the thin actin filaments and the thick myosin filaments, slide past each other (*1*). A widely accepted theory to explain this sliding process is the cross-bridge theory of muscle contraction (*1, 2*). This theory suggests that the sliding process is driven by cross-bridges that extend from the myosin filament and cyclically interact with the actin filament as adenosine triphosphate (ATP) is hydrolyzed (Fig. 1a). Although structural studies support the general concept of the cross-bridge theory, the exact mechanism whereby the chemical free energy of ATP hydrolysis is converted into mechanical work remains elusive. In this article we briefly review the development of cross-bridge models of muscle contraction from biochemical studies on the actomyosin adenosine triphosphatase (ATPase) activity. We also show how a current view of cross-bridge action is similar to the mechanism of other ATPase systems, such as active transport, and therefore illustrates the basic properties of ATP-driven free energy transduction.

Structure of Myosin and Actin

Both the actin and myosin filaments are polymeric structures (Fig. 1b) (*3*). Each globular actin monomer in the actin filament has a diameter of about 5.5 nm and is composed of a single polypeptide chain with a molecular weight of 43,000. Each myosin monomer in the myosin filament is composed of two heavy chains, each with a molecular weight of about 200,000, and four light chains, each with a molecular weight of about 20,000 (*3*). These polypeptide chains fold into three separate domains that have different functions (Fig. 1b). The subfragment-1 domain forms the two globular cross-bridges, which are about 15 nm long and 7 nm wide; the light meromyosin domain is involved in the aggregation of the myosin molecule into filaments, and the subfragment-2 domain provides a flexible connection between the myosin filament and the cross-bridges (*3*). As

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