Halo Nuclei

Nuclei having excess neutrons or protons teeter on the edges of nuclear stability, known as drip lines. Under this stress, some develop a halo

by Sam M. Austin and George F. Bertsch

For the past 50 years physicists have pictured the atomic nucleus—made of protons and neutrons—as a liquid drop that has a well-defined surface. But this is not always so. Researchers at a handful of laboratories have now witnessed an entirely novel structure: in certain nuclei, some of the constituent neutrons or protons will venture beyond the drop's surface and form a misty cloud, or halo, in much the same way that electrons form clouds around nuclei and make atoms. Not surprisingly, these extended nuclei behave very differently from ordinary ones. Normal nuclei are difficult to excite or break apart, but halo nuclei are fragile objects. They are larger than normal nuclei and interact with them more easily as well. In fact, the halo is a quantum phenomenon that does not obey the laws of classical physics. Thus, halo nuclei may well yield fresh insight into one of the central mysteries of physics, namely, that of nuclear binding.

Indeed, physicists have long puzzled over the possible combinations of neutrons and protons, or nucleons, that will stay together as a nucleus. This balance depends in rather subtle ways on how many neutrons and protons are involved and the forces acting among them. All nucleons attract one another, but only protons and neutrons can bind to each other in pairs, called deuterons. As a result, only those nuclei that contain roughly equal numbers of neutrons and protons are stable enough to occur naturally on the earth.

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Nuclei having unequal numbers of neutrons and protons exist as well, but their lifetimes are limited. Although they are bound—meaning it takes energy to remove one of their nucleons—they are not stable. Beta radioactivity can change them into a more stable species by transforming some of their neutrons into protons, or vice versa. Some of these transitions take place within milliseconds and others only after millions of years. But in general, if the nuclei are displayed on a graph so that the number of protons lies along one axis and the number of neutrons lies along the other, those farther away from the diagonal have shorter lifetimes [*see illustration on opposite page*].

At a certain distance from this diagonal—both above it and below it—the nuclei break up just as quickly as they form. No truly bound nuclei can exist beyond these borders, termed drip lines. The most exotic nuclei are those that lie just within the drip lines, on the edges of nuclear stability. Such extreme systems appear only in far more hostile environments than our own. They result from those reactions that synthesized the heavy elements in the universe and now power stellar explosions in novae, supernovae and x-ray bursters. Astrophysicists think that nuclei along the lower drip line are found in the crust of neutron stars.

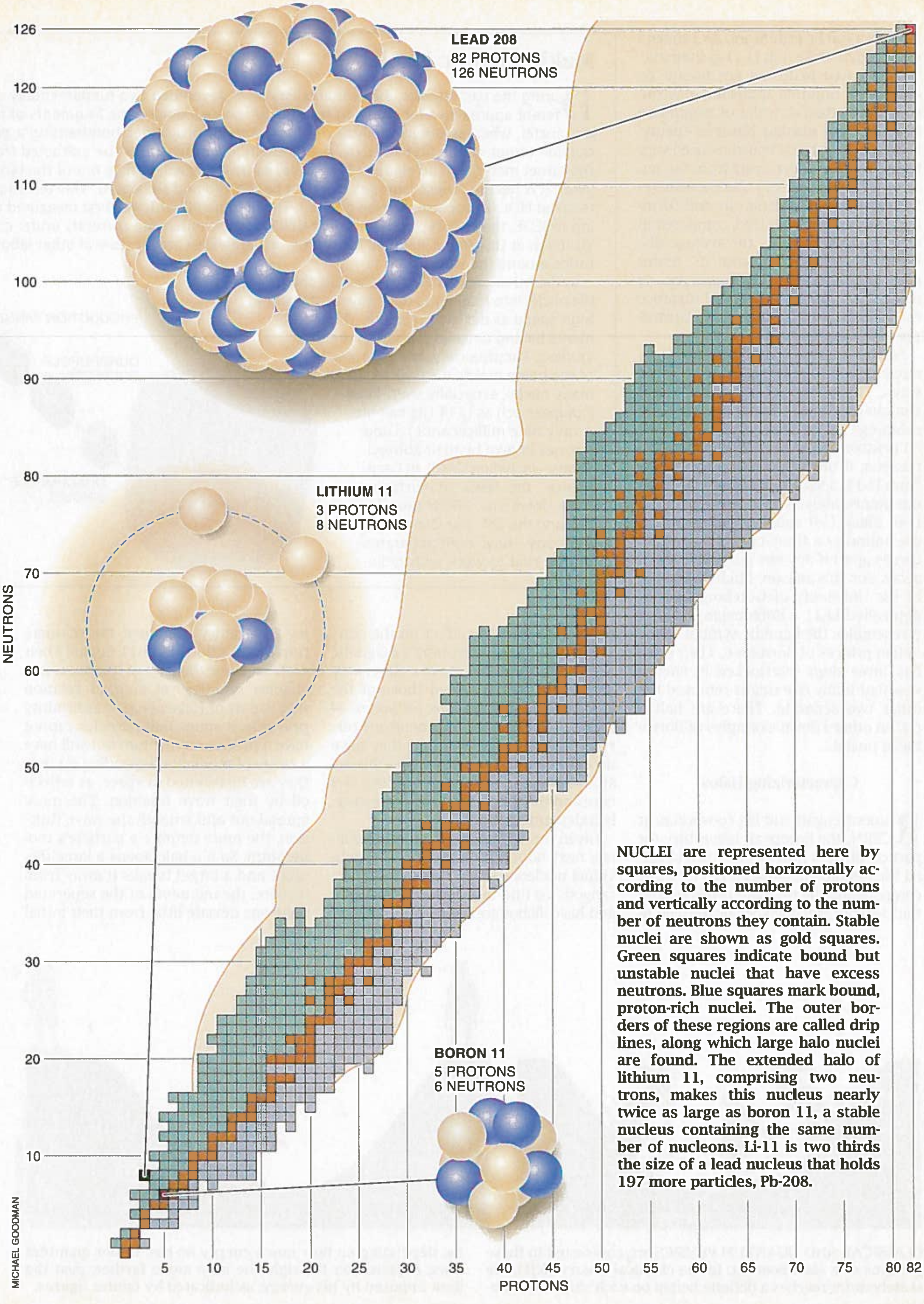
Early Evidence of Neutron Halos

Until a decade ago, physicists had few means for studying such nuclei. Then Isao Tanihata and his collaborators at Lawrence Berkeley Laboratory developed a technique for observing how unstable nuclei interact with other nuclei. This method has led to the discovery of halos in a variety of nuclei. To date, the most scrutinized halo nucleus is an isotope of lithium, Li-11, which has three protons and eight neutrons. Analyses of its fleeting structure have revealed a great deal about the surprising nature of halos in general.

Workers at Lawrence Berkeley Laboratory first discovered Li-11 in 1966, but not until more than a decade later did its unusual structure become evident. In 1985 Tanihata tried to measure its size. He collided ordinary nuclei at high energies to produce a beam of unstable isotopes in a process called projectile fragmentation. Next he placed a carbon foil in the beam. He then counted how many of the beam nuclei survived passage through the foil. This number reflects how likely was the chance of their interacting with nuclei in the target foil. Physicists express this probability by a measure called the cross section. Tanihata found that Li-11 nuclei had particularly large cross sections. The explanation that emerged was that the nuclei bore halos. Two neutrons in the Li-11 nucleus were bound so weakly that they roamed well beyond the core, where they were easily stripped away by the target.

It was an astonishing find. According to the laws of classical physics, a bound particle must stay within range of the core's forces. But in quantum mechanics, a remarkable effect called tunneling makes halos possible. To visualize this phenomenon, imagine a skateboarder in a trough-shaped arena [*see illustration on page 92*]. His total energy limits the distance he travels: the more energy he has, the higher he will go. He cannot rise any higher than the amount of energy he puts into his movement. In quantum mechanics the confinement is not so strict; even a lazy skateboarder will occasionally pop out of the arena. The amount of time he can spend there is limited, and it is related by Heisenberg's uncertainty principle to the extra energy he would need to get out. The lower the energy cost, the longer he can stay outside.

For an object as large as a person on a skateboard, the probability that tunneling will happen is unimaginably small, but on atomic and nuclear scales



NUCLEI are represented here by squares, positioned horizontally according to the number of protons and vertically according to the number of neutrons they contain. Stable nuclei are shown as gold squares. Green squares indicate bound but unstable nuclei that have excess neutrons. Blue squares mark bound, proton-rich nuclei. The outer borders of these regions are called drip lines, along which large halo nuclei are found. The extended halo of lithium 11, comprising two neutrons, makes this nucleus nearly twice as large as boron 11, a stable nucleus containing the same number of nucleons. Li-11 is two thirds the size of a lead nucleus that holds 197 more particles, Pb-208.

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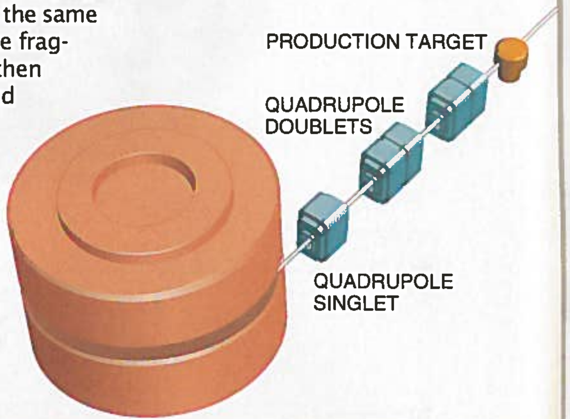
the effect can be significant. As Tanihata observed, the effect in Li-11 is dramatic. The last two neutrons are bound by only a few hundred thousand electron volts, more than an order of magnitude smaller than normal binding energy. Consequently, these neutrons need very little energy to move away from the nucleus. They can remain there a relatively long time, spreading out and forming a tenuous halo. Indeed, compared in size with other nuclei, the average distance of Li-11's halo from its center measures about five femtometers, or more than double the normal distance for a nucleus of its mass [*see illustration on preceding page*].

Further work revealed that the Li-11 nucleus was highly unusual in other ways. The isotope Li-10, which would contain one fewer neutron, is unbound, meaning that its three protons and seven neutrons will not hold together as a nucleus. If one neutron is taken away from Li-11, a second neutron will come out immediately as well, leaving behind Li-9. Thus, Li-9 and the two neutrons are bound as a three-body system that comes apart if any one particle is taken away. For this reason, Mikhail Zhukov of the University of Göteborg in Sweden called Li-11 a Borromean nucleus; it resembles the heraldic symbol of the Italian princes of Borromeo. Their crest has three rings interlocked in such a way that if any one ring is removed the other two separate. There are half a dozen other known examples of Borromean nuclei.

Making Exotic Nuclei

During the past decade, experimentalists have developed two fundamentally different approaches for studying halo nuclei. Some examine the fragments of target nuclei, whereas others analyze the fragments of projectiles bombarding a production target. In the first strategy, the interesting isotopes must be extracted from the target material. If an element is volatile, its isotopes will diffuse out of the target when it is heated. These isotopes can then be ionized and separated. This technique is called ISOL (isotope separation on line). The lifetime of Li-11 was first measured using ISOLDE, the ISOL-type laboratory at CERN. New facilities are currently under construction at Oak Ridge National Laboratory in Tennessee and at several other laboratories around the world.

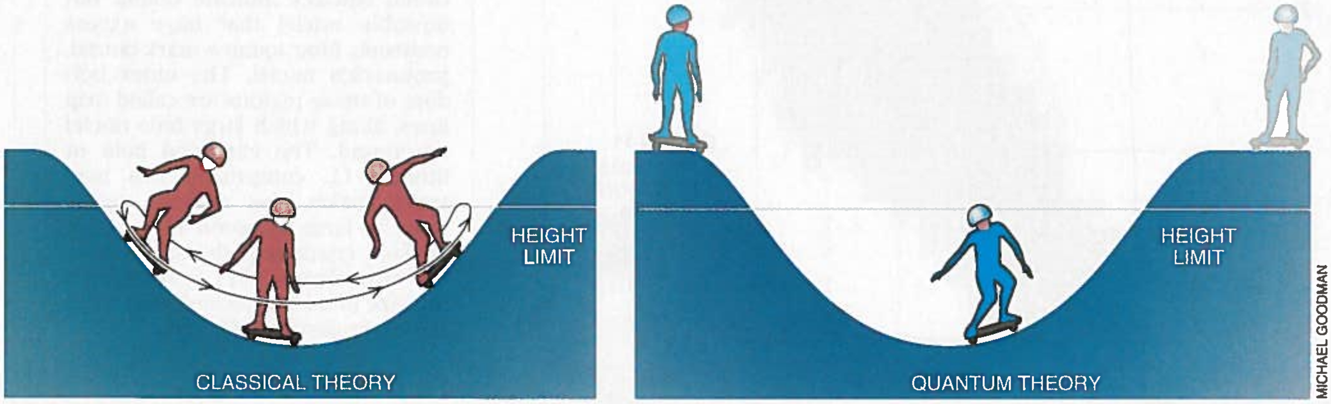
In the other tactic, the target breaks the projectile nuclei into fragments that move at the same high speed as did the projectile. Those fragments having unusual properties are then studied. Paradoxically, the high speed of the beam makes it easier to study many nuclei, especially short-lived isotopes such as Li-11 (its half-life is only nine milliseconds). Laboratories known by their abbreviations—including GANIL in Caen, France, the NSCL at Michigan State University, RIKEN near Tokyo and the GSI near Darmstadt, Germany—have built apparatus of this kind to work with radio-



Characterizing Halos

Rainer Neugart and his co-workers at CERN, the European laboratory for particle physics near Geneva, investigated the interaction between Li-11's three components (the two halo neutrons and the Li-9 core), testing specifically whether the halo had any effect on the core. They measured the isotope's magnetic and electrical properties in a clever way and found they matched those of the Li-9 nucleus [*see top box on pages 94 and 95*]. Because the halo neutrons carry no charge—and as a pair they have no spin or magnetic moment—this result supported the notion that the Li-9 core and the two-neutron halo are nearly independent objects.

Given this information, experimentalists next hoped to learn how the individual nucleons in Li-11 nuclei were arranged. To find out, Toshio Kobayashi and his collaborators at Lawrence Berkeley Laboratory examined the momentum distributions of Li-11 nuclei. Their motion under the laws of quantum mechanics satisfies yet another relation that is part of Heisenberg's uncertainty principle. It states that particles cannot have a precise momentum but will have a range of momenta depending on how they are distributed in space, as reflected by their wave function. The more spread out and smooth the wave function, the more definite a particle's momentum. So if a halo spans a large distance and a target breaks it away from its core, the momenta of the separated neutrons deviate little from their initial



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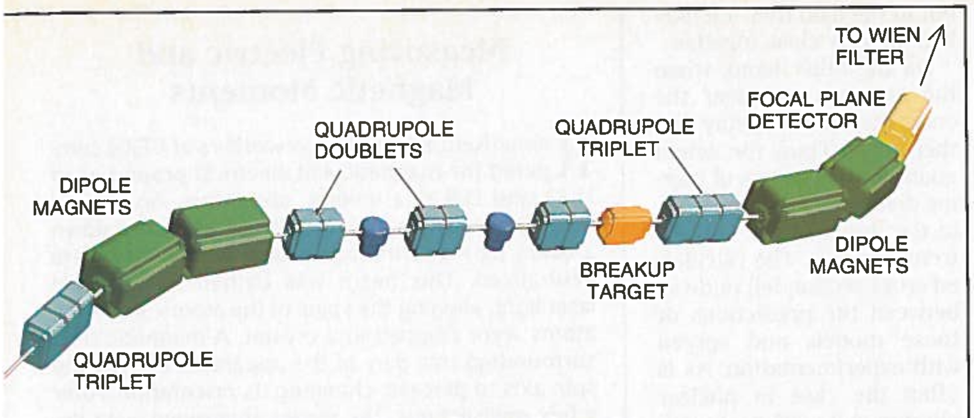
CLASSICAL AND QUANTUM PHYSICS are contrasted in these pictures of a skateboarder. In the classical theory (*left*), the skateboarder reaches a definite height on each side of the arena, depending on how much energy he has. Under quantum laws, depicted on the right, he may move farther, past the limit imposed by his energy, as indicated by fainter figures.



active beams and to study unstable nuclei.

In 1990 Bradley M. Sherrill and his associates built the Michigan State fragment separator, called the A1200. It filters out exotic nuclei by subjecting the fragment beam to various forces (*left*). Dipole magnets bend the beam according to the momenta and charges of the beam nuclei; doublet and triplet quadruple magnets focus the beam.

The beam can also be sent through a thin slab, which slows the nuclei by different amounts depending on their velocities and charges. In addition, the beam can be diverted to a Wien filter, a device that produces perpendicular electrical and magnetic fields; only nuclei of a chosen velocity pass through the filter. Finally, it is sometimes possible to measure the time a nucleus takes to pass through the separator, giving yet another measurement of its velocity. Armed with all this information, researchers have identified the individual nuclei passing through and measured their velocities and momenta as well.

momenta. They will travel nearly straight forward and at nearly the same velocity.

Kobayashi and his team took a slightly indirect approach to infer the halo's momentum. They produced reactions in which the halo neutrons were stripped from Li-11 and then observed the Li-9 core that traveled forward. Because Li-11's initial momentum is fixed, the spread in the core momentum had to match the spread in the neutron momentum. Using this relation, the investigators found that the momentum distribution was exceedingly narrow, about one fifth of that measured during the breakup of normal nuclei.

Later experiments at GANIL in Caen, France, led by Alex C. Mueller, gauged the deflection of the neutrons themselves rather than the core. Under these conditions, the neutrons from halo nuclei went forward in a cone about two degrees wide, whereas neutrons from ordinary nuclei came out in a cone some 10 degrees wide. Unfortunately, it was somewhat difficult to interpret these experiments quantitatively because elastic forces from the target had also deflected the particles.

A team at Michigan State University, consisting of Bradley M. Sherrill, Nigel A. Orr and one of us (Austin), found a way around this limitation. Elastic forces deflect the particles mainly sideways and hardly change the momentum component parallel to the beam direction. We realized that the influence of the halo would be clearest if we could measure the spread in the parallel momentum, but the beam of Li-11 we were using already had a momentum spread 10 times larger than the effect to be measured. Fortunately, the fragment separator at Michigan State, the A1200, allows an experimenter to disperse the beams and focus the particles on spots according to how much their momenta has changed rather than on their ultimate momenta [*see box on this and opposite page*]. In this way, the separator can single out the changes in momenta caused by the breakup.

Using this so-called energy-loss mode of operation, the Michigan State workers obtained a resolution much smaller than the width of momentum distribution they wished to measure. A beam of Li-11 struck a variety of targets, ranging in mass from beryllium to uranium, placed near the center of the device one at a time. The Li-9 nuclei resulting from these breakups showed a narrow momentum distribution; this width was nearly independent of the target mass. Because nuclear interactions mediated the breakup for light targets, whereas electrical, or Coulomb, forces influenced the breakup for heavy targets, we concluded that the result was independent of the reaction mechanism and directly reflected the structure of the halo. These results indicated that the radius of the Li-11 halo was more than twice that of its core.

Models and Predictions

While these experiments were going on, theorists were trying to understand the unique behavior of Li-11. They faced two large obstacles—and still do. First, the forces between nucleons are not known accurately enough to predict the subtle binding properties of halo nuclei. Second, even if those forces were known, today's computers do not have the speed or memory needed to solve the equations of quantum mechanics for 11 interacting nucleons. Nevertheless, physicists have developed simpler models that exhibit the main physical attributes of halo nuclei.

One attribute they try to capture in their models is the role of pairing in many-nucleon systems. In general, the pairing interaction is the attraction between the least bound particles in a system; it can radically affect the properties of that system. In metals, for example, the pairing between electrons gives rise to superconductivity. The pairing interaction is also of fundamental importance in almost every aspect of nuclear structure. It determines which nuclei are stable, and its presence promotes fluidity in such shape-changing processes as nuclear fission. Pairing in a dilute neutron gas can influence the properties of neutron stars, which depend on whether the neutrons act as a superfluid. And, finally, pairing causes the Borromean behavior.

A wide range of useful models has been developed, based on very different assumptions about pairing. P. Gregers Hansen of Aarhus University in Denmark and Björn Jonson of the Chalmers University of Technology in Sweden proposed one simple model in 1988. They assumed that the pairing between the two last neutrons in Li-11 was so strong that these nucleons could be treated as a single particle, named the dineutron.

The motion of this particle in the field of the Li-9 core is a two-body problem, which is relatively easy to solve. In fact, if the binding is weak—such that the two particles have little chance to interact—the wave function can be looked up in a textbook. Using this approximation, Hansen and Jonson derived formulas for the size of the halo, for the breakup probability of the nucleus in the electric field of a highly charged target and for the energy of the dineutron after the breakup. In such a simple model, however, they could not calculate the binding energy of the halo.

While an undergraduate student at Michigan State, James Foxwell investigated another extreme model under the guidance of one of us (Bertsch). In contrast to the dineutron picture, Foxwell's model ignores the pairing between neutrons completely. It assumes that each of the last two neutrons is independently bound to the core. A two-body problem is then solved for one neutron at a time. Foxwell calculated breakup probabilities and the energy of the excited system. Like the Hansen-Jonson model, Foxwell's approach requires knowing the binding energy ahead of time. Interestingly, these two very different strategies produced similar predictions of the fragility of Li-11, differing by only a factor of two in estimating its cross section.

Recent Work on Halos

Since then, theorists have constructed more sophisticated models, explicitly incorporating the forces giving rise to pairing. Because the three-body problem in quantum mechanics is now amenable to numerical solution on large computers, it was practical to treat Li-11 as a three-particle system. Henning Esbensen of Argonne National Laboratory calculated the Li-11 wave function with a realistic description of the interaction between the neutrons and the Li-9 core and a more approximate treatment of the pairing force. His wave function showed that when the neutrons are far out in the halo they are likely to be very close together.

On the other hand, when the neutrons are near the core, they tend to stay farther apart. Thus, the actual quantum mechanics of pairing describes behavior within the limits of the two extreme models. The calculated cross section fell midway between the predictions of those models and agreed with experimentation. As is often the case in nuclear physics, quite different models can be valid, and their domains of validity can even overlap. The three-body model was also successful in predicting the momentum spread in the Li-11 breakup measured at the Michigan State facility.

Ian Thompson of the University of Surrey and his co-workers made similar calculations. This group used a more realistic force between the neutrons but treated the neutron-core interaction more approximately. It also found that Li-11 is Borromean and has a large halo. Such consistent results have given us confidence that we understand the pairing between neutrons in a low-density environment, such as might be found in the crusts of neutron stars.

Now that a new aspect of nuclear behavior has been discovered and studied, one naturally asks the question, Where do we go from here? Clearly, halos affect many nuclear reactions. For example, experimentalists plan to measure reactions between Li-11 and protons to determine the probability that a proton will pick up two neutrons and form tritium. The correlation between the neutrons directly influences this probability, since the two neutrons must be close together in order to combine with a bombarding proton. By analyzing such reactions, we will be able to obtain

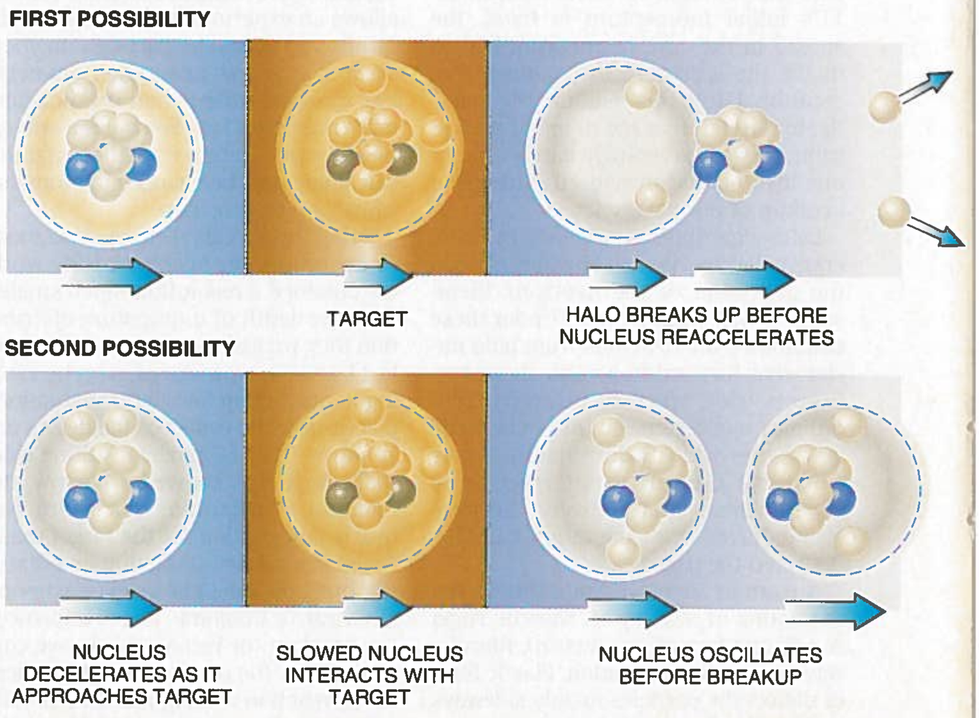
Measuring Electric and Magnetic Moments

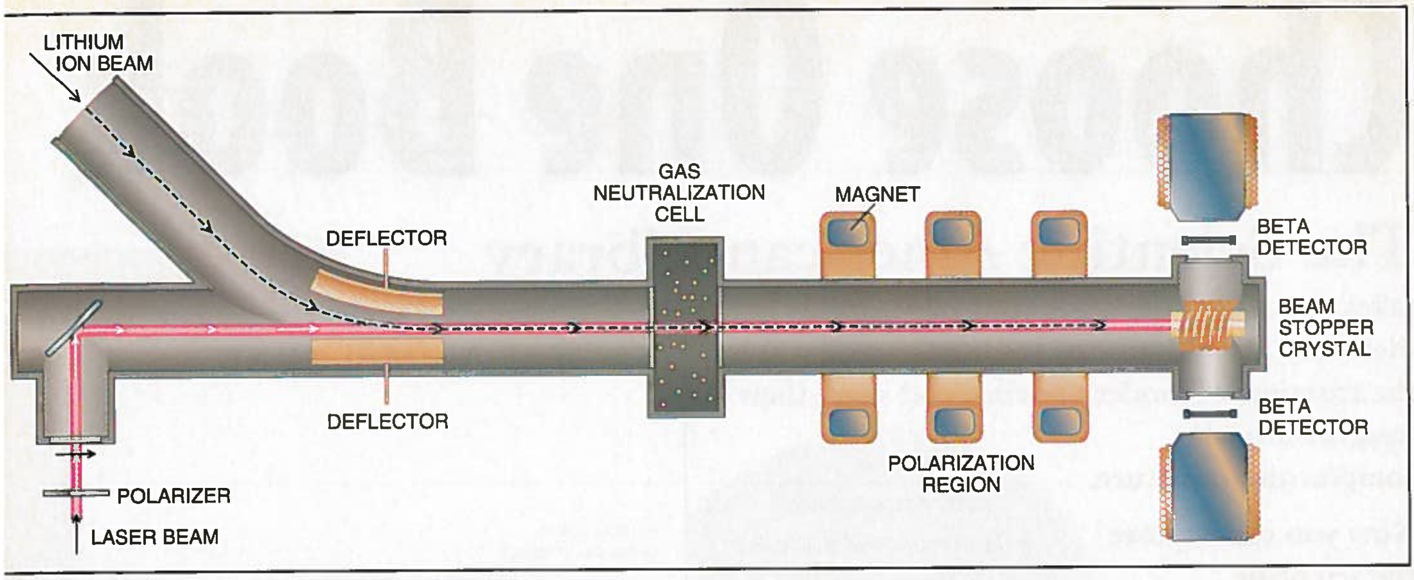
Rainer Neugart and his co-workers at CERN compared the magnetic and electrical properties of Li-11 and Li-9 in a unique apparatus. An electric field deflected ions from the ISOLDE separator down a beam pipe and through a gas, where they were neutralized. This beam was bathed in polarized laser light, aligning the spins of the atoms. Next, the atoms were stopped in a crystal. A magnetic field surrounding this part of the apparatus caused the spin axis to precess, changing its orientation. After a few milliseconds, the nuclei underwent beta decay, emitting electrons preferentially along the spin axis. From the emission directions of these decay electrons, the experimenters were able to deduce the electrical and magnetic properties of the nucleus.

How a Halo Is Lost

Aaron I. Galonsky and his collaborators at Michigan State University have investigated two contrasting pictures of how a nucleus loses its halo. In one picture, the halo neutrons are freed instantaneously when they interact with a target (*top*). In the other, the electric, or Coulomb, field generated by the target's charges sets the nucleus vibrating, with the charged core moving in one direction and the halo in another (*bottom*). To test these possibilities, Galonsky's group excited the Li-11 nucleus as gently as possible, passing the beam through a lead target, which is likely to produce Coulomb excitation. The researchers then measured the emission angles and energies of the two neutrons and Li-9 resulting from the breakup.

The energy absorbed was quite small and well defined. According to Heisenberg's uncertainty principle, therefore, the breakup of a vibrating





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a direct measure of these correlations.

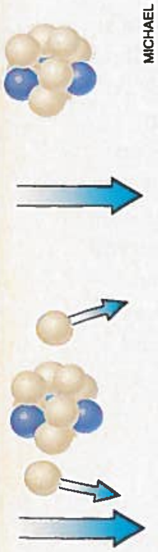
Experiments by Karsten Riisager and his collaborators at CERN have shown that halo nuclei exhibit unique properties when they undergo beta decay. They observed the Borromean nucleus helium 6, which has two protons and four neutrons. When this nucleus undergoes beta decay, one of its halo neutrons may turn into a proton. Normally this proton would remain bound to the nucleus, but in He-6 it can combine with its partner neutron in the halo and escape as a deuteron.

More important, physicists would like to study the halos of heavier nuclei. Most work to date has focused on two nuclei, Li-11 and an isotope of beryllium, Be-11, both of which are fairly easy to produce and isolate. New facilities are being planned to make heavier systems. But scientists have already begun to use their current equipment to look for halo nuclei having masses of about 20. Some are now analyzing the Borromean nucleus Be-14. Workers at Michigan State have measured the momentum distributions for an isotope of carbon, C-19, which bears seven more neutrons than does the most stable form, C-12. And researchers at GANIL have discovered C-22, having yet three more neutrons.

Theorists are also beginning to investigate the properties of drip-line nuclei that have more than two halo nucleons. In such systems the many-particle aspects of pairing become especially significant. In Borromean nuclei, these halos may be vastly larger than those seen in Li-11. Physicist Vitaly Efimov of the University of Washington has predicted such a phenomenon. He showed that when the interaction between the particles in a three-body system is almost strong enough to bind them two at a time, the system may have many extended halo states, potentially an infinite number of them.

Finally, weakly bound protons may also give rise to nuclear halos. Perhaps the best example is an isotope of boron, B-8, which contains one very loosely bound proton. This proton is even less well bound than the neutrons in Li-11, and its halo is quite possibly aspherical. To determine the characteristics of B-8's halo, teams at several laboratories are measuring the nucleus's parallel momentum distribution.

Astrophysicists are particularly interested in the nucleus B-8 because in the sun it produces easily detected neutrinos. A serious anomaly has arisen because the observed number of neutrinos from the decay of B-8 in the sun is much less than predicted. Understanding the exact nature of this nucleus may well provide clues to this mystery. The study of nuclei near the drip lines will surely yield further surprises. But already halos have taught us quite a bit about what takes place at the outer limits of stability.



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system should take a relatively long time. But the workers found that Li-11 broke up quickly, as though the neutrons were freed instantaneously on collision. They inferred this fact from a seemingly unrelated observation: in comparing the velocities of the Li-9 core and the two neutrons, the neutrons moved more slowly. At first, it was puzzling that the neutrons should be slower if the breakup process was so gentle.

The explanation lay in the timing of the breakup itself. Because Li-11 is charged, it decelerates as it approaches the target's Coulomb field and then reaccelerates as it departs. In the oscillatory picture the breakup takes such a long time that the Li-9 nucleus would travel well beyond the target's Coulomb reach before it could occur. But in an instantaneous breakup, Li-9 is separated near the target, where it is subject to Coulomb reacceleration. In contrast, the uncharged neutrons are not affected by the electric field and so move more slowly, as observed. Hence, Galonsky's group concluded that the Li-11 nucleus had lost its halo when it passed the target.

FURTHER READING

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