New source. Japan's Radioactive Isotope Beam Factory should crank out more unbound nuclei.

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NUCLEAR PHYSICS

Fathoming Matter's Heart Unbound

Going to extremes, physicists hunt for "unbound" nuclei that don't stick together at all

Ordinarily, the protons and neutrons in an atomic nucleus bind to one another with ferocious strength. The might of that binding explains why alchemists never found a way to change lead into gold: That would require prying apart the nucleus of one element to change it into another. Now, however, some physicists are eagerly creating odd nuclei that are so loosely built they are hardly nuclei at all. These rare beasts may provide a better understanding of the heart of matter.

In recent decades, experimenters have used particle accelerators to produce ever-more-unstable and fleeting radioactive nuclei. The new work pushes this exploration to its logical extreme with the creation of "unbound nuclei"—puffs of protons and neutrons so loosely jumbled together that there is literally nothing to keep them intact, not even momentarily. Some unbound nuclei could yield insights into stellar explosions that forge many of the heavy elements we see on Earth today. Others may stretch current theories of nuclear structure until they snap and thus yield new insights.

"In some sense, it's the most extreme test of our theories of nuclear structure," says Nigel Orr of the Laboratory for Corpuscular Physics (LPC) in Caen, France, one of three dozen physicists who gathered recently for a workshop on the subject.* Sydney Gales, director of the National Heavy Ion Accelerator (GANIL) in Caen, says: "We are discovering that there is a whole new kind of loosely formed matter. The physics is completely new."

So far, experimenters have snared a handful of the oddities. But interest in them is growing, as new accelerators now powering up or in planning should cough out many more.

Crossing the line

The study of unbound nuclei crosses a conceptual frontier. Researchers map nuclei on a chart resembling a crossword puzzle, with the number of protons increasing from bottom to top and the number of neutrons increasing from left to right (see diagram, p. 1425). The 255 stable nuclei form a diagonal "valley of stability," with their unstable radioactive brethren, less and more neutron-rich, to the left and right. In pursuing unbound nuclei, physicists strive to make nuclei ever richer in neutrons and, ultimately, to push across the "neutron drip line," beyond which binding is impossible. On the near side of this line, each nucleus can minimize its energy, at least temporarily, by forming a tight clump. On the far side, a nucleus can always reduce its energy by falling apart, so there is no energy barrier to hold the thing together.

Interest in unbound nuclei builds on the study of other strange-but-bound nuclei, says Angela Bonaccorso, a theorist with the Italian National Institute of Nuclear Physics in Pisa. In the 1980s, scientists discovered that the bound nucleus lithium-11, which has three protons and eight neutrons, possesses an unusual structure in which two of its neutrons form a diffuse "halo" roughly 10 times the radius of the nucleus's core. Oddly, one halo neutron can't stick without the other: Remove one to form lithium-10 (three protons and seven neutrons) and the other flies out, too. Lithium-10 is unbound.

This means that the drip line zigzags as unbound lithium-10 lies between bound lithium-9 and lithium-11. Similarly, unbound beryllium-13 lies between bound beryllium-12 and beryllium-14, and unbound helium-7 and helium-9 interleave with bound helium-6 and helium-8. These interlopers are barely unbound; if their lowest energy state were just slightly lower, they'd stick together.

Such unbound nuclei challenge established theories of nuclear structure. Protons and neutrons cling to one another through the strong force, and most theories assume that each particle whizzes about in a static force field determined by the average distribution of all the others. Such "mean field" models predict the existence of energy "shells"—like those for the electrons in an atom—into which the protons and neutrons stack.

In these barely unbound nuclei, the mean-field approach comes up short. That's because the precise energy of the entire system depends on the details of the continual jumbling of the protons and neutrons. In that case, the notion of a shell—which assumes that the energy can be calculated from an unchanging average distribution of the particles—is no longer strictly valid, says Horst Lenske, a theorist at the Justus Liebig University Giessen in Germany. In fact, Lenske says, whether a nucleus is bound may depend on the precise and exceedingly complicated dynamics of all the interacting protons and neutrons.

If theorists can account for these dynamics, then they might better understand all nuclei, Bonaccorso says. The basic shell model has been embellished in various ways to help account for dynamical effects and deal with specific nuclei. Insights from unbound nuclei might tie these ad hoc fixes together more coherently. "We are constructing theories that are far more general," Bonaccorso says.

Depends on how you look at it

Studying unbound nuclei is not easy, however. The experiments require intense beams of radioactive nuclei to make these rare beasts and sophisticated detection schemes to snare the fragments released as they fly apart in less than

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*Unbound Nuclei Workshop, University of Pisa, Italy, 3–5 November 2008.

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a trillionth of a nanosecond. An unbound nucleus also presents a challenge because its properties depend on how it is produced.

For example, physicists expect that lithium-10 consists of a lithium-9 core with a halo neutron whizzing around it, and they want to know the exact "state" of that far-flung neutron. To determine that, LPC's Orr and his team fired beryllium-11 nuclei (with four protons and seven neutrons) through a carbon target in experiments at GANIL. A few of the collisions plucked one proton out of the beryllium nucleus to make a lithium-10 nucleus. That would instantly break into a lithium-9 nucleus and a neutron, and the experimenters would look for those pieces.

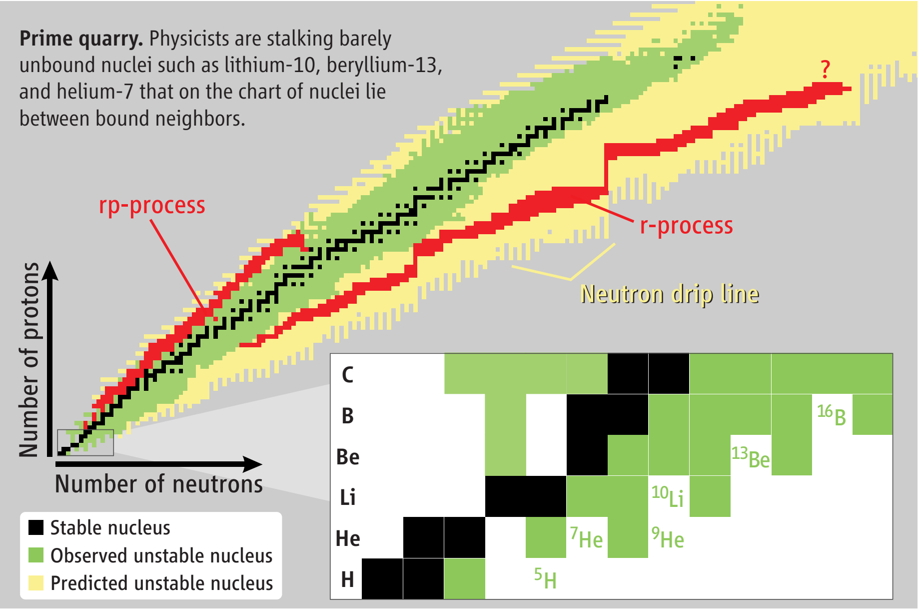
By measuring the energy with which the neutron and lithium-9 sped apart, researchers could probe their interactions; any pushing or shoving between them should create a peak in the energy spectrum. That spectrum would thus reveal the original state of the lithium-10 nucleus. Looking at the energy spectrum, Orr and his team found a broad peak that suggested the ejected neutron began in a state in which it had no angular momentum—a so-called s-state.

However, Haik Simon of the Helmholtz Center for Heavy Ion Research (GSI) in Darmstadt, Germany, and colleagues took a different approach to make lithium-10. They fired rare lithium-11 nuclei at a carbon target to try to knock one neutron out of the lithium nucleus. They then examined the resulting lithium-10 much as Orr did and observed an energy spectrum comprising three overlapping peaks. That suggests that the lithium-10 sometimes emerged in an s-state, sometimes in a p-state with one unit of angular momentum, and sometimes in a d-state with two units.

In spite of the incongruous results, there is an underlying consensus, Simon says. Both experiments show that, in spite of its infinitesimally brief existence, lithium-10 has a structure with well-defined energy states. They both also show that the lowest energy ground state is the s-state, as theory predicted. "Here we're getting quite clear," Simon says. "It has now been resolved."

But not all unbound nuclei are so straightforward. Takashi Nakamura of the Tokyo Institute of Technology and colleagues see signs of a more complicated situation in unbound beryllium-13 (four protons and nine neutrons). In experiments at the Institute of Physical and Chemical Research's (RIKEN's) Nishina Center for Accelerator-Based Science in Wako, Japan, Nakamura and colleagues produced beryllium-13 by shooting beryllium-14 nuclei through a liquid hydrogen target to chip one neutron out of the incoming nucleus.

When the beryllium-13 fell apart, the researchers measured the energy spectrum of the rebounding pieces and observed a peak. But that peak seems to have the wrong energy and shape to be the expected s-state and may be a p-state, Nakamura says. That suggests that in beryllium-13, the quantum state of the beryllium-12 core is somehow altered, or "collapsed," by the mere presence of the extra neutron, he says. Deciphering how the core is deformed is the sort of challenge theorists hope will lead to new insights.



Prime quarry. Physicists are stalking barely unbound nuclei such as lithium-10, beryllium-13, and helium-7 that on the chart of nuclei lie between bound neighbors.

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Stellar explosions run backward

A nucleus can also become unbound if it absorbs too much energy, and such overamped nuclei may play starring roles in stellar explosions. In a blast called a nova or in a more-powerful one called an x-ray burst, heavier nuclei form when lighter ones rapidly absorb protons, in the so-called "rp-process." For example, a magnesium-22 nucleus can absorb an energetic proton to make an aluminum-23 nucleus, which quickly spits out a photon to shed its excess energy.

Reproducing that interaction is difficult. However, RIKEN's Tohru Motobayashi and colleagues have found an easier way to run it backward. They fire aluminum-23 nuclei through a lead target. As an aluminum nucleus passes through a lead nucleus's electric field, it absorbs a "virtual" photon from the field. That unbinds the aluminum-23 and it splits into magnesium-22 and a proton.

The researchers measured the energy with which the magnesium-22 and proton flew away from each other. They found three overlapping peaks in the energy spectrum, the lowest at about 500 kiloelectron volts. Such details suggest that the forward process requires relatively high temperatures and densities and may play a bigger part in more-energetic explosions. "Our result implies that this process does not contribute so much to the nova but that it is important for the x-ray burst," Motobayashi says.

The study of unbound nuclei is likely to grow, given the new facilities coming online or in planning, researchers say. Two years ago, the Nishina Center revved up the massive superconducting cyclotron that powers the lab's Radioactive Isotope Beam Factory (*Science*, 15 December 2006, p. 1678). When fully functional, it will provide beams more than 1000 times as intense as those at older facilities. GSI is building a synchrotron-based facility that will power up in the middle of the next decade (*Science*, 2 November 2007, p. 738), and in December 2008, the U.S. Department of Energy chose Michigan State University in East Lansing to host its proposed linear-accelerator-based facility (*Science*, 19 December 2008, p. 1777).

With much more intense beams, researchers should be able to climb drip lines to make unbound elements up to aluminum or silicon, says Tokyo Tech's Nakamura. Motobayashi says it should also be possible to study overenergized nuclei involved in an astrophysical progression called the r-process, in which lighter nuclei gobble up neutrons and which is thought to forge half the nuclei heavier than iron.

Exactly what unbound nuclei will reveal remains to be seen. Of course, the allure of the unknown is also leading nuclear physicists to test the bounds of their field. **–ADRIAN CHO**