Physicists Explore the Driplines

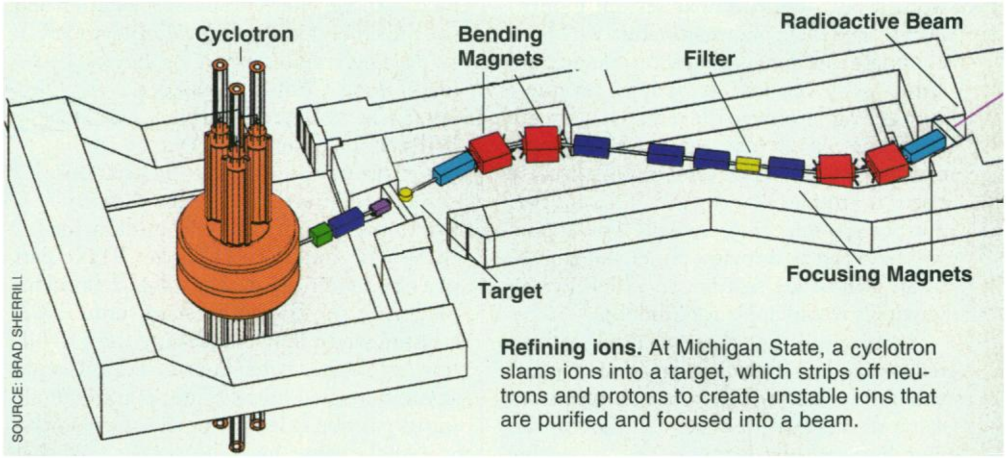
By creating and studying beams of short-lived exotic nuclei, researchers hunt for clues to the structure of the nucleus and the metabolism of stars

For the better part of a century, nuclear physicists have plied their trade using the 270-odd stable and long-lived nuclei—the known elements and their isotopes—that exist on the planet. To one growing group of physicists, though, that's like contenting oneself with a single dish from a smorgasbord. Nearly 20 times more atomic nuclei can, in theory, exist, at least for the few microseconds physicists need to study their properties and maybe even harness them for technological uses. Many of these highly unstable nuclei, sporting unusual ratios of protons to neutrons, live briefly in out-of-the-way places like the surfaces of neutron stars and the cores of supernovae. But they had remained beyond the province of earthly study.

Recently, however, advances in accelerator and detector technology have made these exotic nuclei into the star players of a burgeoning field of nuclear physics. By now its practitioners have created and studied more than 3000 of them. Some, like an exotic isotope of lithium containing eight neutrons for its three protons, represent an entirely new form of matter, giving new insights into the principles of nuclear structure. Others have offered glimpses of the processes that, operating in stars or supernovae, spawned the elements known on Earth.

The lure of this new territory drew more than 200 nuclear physicists and astrophysicists to Michigan State University (MSU) in East Lansing during the last week of May, when they gathered to discuss the state of their field at the Third International Conference on Radioactive Nuclear Beams. The talk was of nuclei poised at the very edge of stability, on the so-called nuclear driplines, and of the latest sightings along these frontiers, such as a possible endpoint for an element-building process in stars. And, inevitably, participants dreamed about the next step: moving from the trickles of exotic nuclei produced so far to more intense beams, which could create new superheavy elements, form new semiconductor devices, or even forge rare isotopes on demand for medical diagnosis and treatment.

In the short life of nuclear physics with radioactive nuclei, researchers have found two different ways of turning particle accelerators—often built for other purposes—to the task of making these nuclei. The more common method is known as the ISOL method, for Isotope Separator On Line, and was developed at CERN, in Geneva. The idea, says Helge Ravn of CERN, is to break up nuclei in a target by bombarding it with high-energy protons, creating radioactive fragments that have to be extracted using chemical or solid-state methods. An alternative, the fragmentation method—practiced at MSU and at laboratories in Japan, France, and Germany—smashed a beam of large, stable nuclei into a thin target. As the fragmented nuclei pour out the other side, they are separated in a mass spectrometer.



Refining ions. At Michigan State, a cyclotron slams ions into a target, which strips off neutrons and protons to create unstable ions that are purified and focused into a beam.

Both techniques can produce nuclei like chromium-43, with 24 protons and just 19 neutrons, instead of the 26 to 30 of stable chromium, and cadmium-130, with 48 protons and 82 neutrons, 16 more than mundane stable cadmium. In these skewed nuclei, the balance of forces at work in a stable nucleus is thrown off. One force, the strong nuclear force, powerfully yokes together the protons and neutrons, but its range is extremely short. The other, the electromagnetic repulsion between the positive charges of the protons—known as the Coulomb force—is weaker but has a longer range. Add more protons to a stable nucleus, and the Coulomb force works to rend it apart. Add more neutrons, and the strong force has trouble holding it together. The upper and lower limits of the proton-to-neutron ratio are the extremes of stability—the driplines.

Exploring the driplines. To study these nuclei, researchers do anything from smashing them into other targets and watching how they shatter, to trapping them in front of an array of detectors and observing their decays. One goal is to learn about nuclear structure. As Conrad Gelbke, head of MSU's National Superconducting Cyclotron Laboratory, explains, "When you push nuclear structure off the line of stability, you have a chance to learn much about your nuclear interactions." Brad Sherrill of MSU describes one way to probe an exotic nucleus: "Ring it like a bell and see how it vibrates." Experimentalists set up these resonances, he says, by letting an exotic nucleus "fly by a nucleus with a lot of protons. Then the Coulomb force will push on the protons in the unstable nucleus, and start them vibrating."

Nuclei at the limits of stability have turned out to have structures that would never have been forecast by nuclear theory, which researchers describe as an inexact art. Such was the case when a team of Japanese researchers, led by Kenzou Sugimoto and Isao Tanihata of RIKEN, explored the properties of lithium-11 in the mid-1980s. The researchers were using the Lawrence Berkeley Laboratory's Bevalac accelerator, shooting a beam of oxygen-18 into a beryllium target. The oxygen shattered in the target, and a grab-bag of exotic isotopes of helium and lithium popped out the other side. From the debris the researchers isolated beams of lithium-11—nuclei containing lithium's usual complement of three protons, but eight neutrons instead of the usual four.

As the researchers studied this short-lived outrider, which has a half-life of about 10 milliseconds, they discovered that it broke the three cardinal rules of nuclear size and structure that, says Tanihata, "were [until recently] always written in the first 10 pages of every textbook." Unlike every other nucleus ever studied, lithium-11 does not have a size proportional to one-third its mass (rule #1), a sharply defined surface (rule #2), or a uniform mixture of protons and neutrons throughout the nucleus (rule #3). Instead, Tanihata and his colleagues found when they scattered lithium-11 nuclei off another element, its protons are clumped in the core of the nucleus, with the neutrons surrounding the core in a halo that seemed to fade from the density of nuclear matter to the density of free neutrons. This halo extends far beyond what, by rights, should be the limits of the nucleus. Says Mike Nitschke of Lawrence Berkeley, "[It] came out of the blue, a completely unexpected phenomenon, not predicted by any model, or any theory."

Five years later, researchers at East Lansing were still debating the exact form of lithium-11. By now, most agree that it has a core of lithium-9—three protons and six neutrons—surrounded by a halo of two neutrons. The question, says Tanihata, is how the neutrons in the halo interact: "Some people say the neutrons form a di-neutron, that they're stuck together going around the core. Others say that there's a neutron on each side." What's fascinating, he adds, "is that lithium-9 and one neutron don't…stick together, and two neutrons by themselves don't stick together. Only when you have all three parts together is it bound."

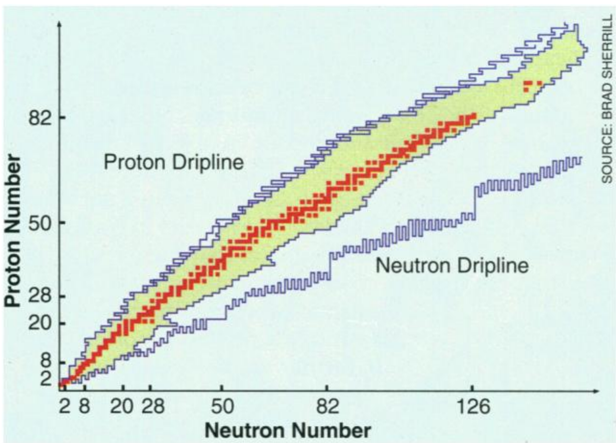
While theorists struggle to explain why this should be, the two neutrons in the halo provide a unique opportunity for experimentalists to study what's known as neutron matter, says Tanihata. Until the creation of lithium-11, matter composed only of neutrons was theorized to exist only in neutron stars, where it is far out of reach of experiment, leaving physicists trying to determine its properties—such as the equation of state, which is the relationship between pressure and volume—to extrapolate from nuclear theory. But the surface layer of lithium-11, says Tanihata, "would be a very nice place to experiment on neutron matter."

Stars in their eyes. Such astrophysical applications, in fact, account for much of the interest now focused on exotic nuclei. Radioactive beams open a window into the processes that forge elements in the stars because many of these nuclei are intermediate steps in the element-forming processes. By studying their lifetimes, decay pathways, and propensity to react with other elements, researchers hope to learn how fast and how far up the ladder of elements each process can go.

Lighter elements are created, generally within stars, in what's known as the CNO (for carbon-nitrogen-oxygen) cycle, in which helium nuclei fuse together one by one to make these successively heavier elements. But if the stellar environment gets hot enough, in the neighborhood of 100 million degrees, says Grant Mathews of Lawrence Livermore National Laboratory, the CNO cycle may become a jumping off point for the rapid proton, or *rp*, process, which builds heavier elements by adding individual protons one by one to the growing nucleus.

The *rp* process, proposed in 1981 by Stan Woosley of the University of California, Santa Cruz and Richard Wallace, now of Los Alamos National Laboratory, ignites during novae—thermonuclear flareups in white dwarf stars—on the surfaces of neutron stars, and in other extremely hot environments. There oxygen can fuse with an additional alpha particle, which turns it into neon. If the neon captures a proton before it decays, says MSU's Sherrill, "you break out of the cycle and get heavier nuclei beginning to be formed. These heavier nuclei capture protons, and you move right up the table of the elements." The process cannot continue indefinitely, however, because the steady addition of protons without a balancing complement of neutrons eventually leads to a nucleus at the proton dripline. The question is, when?

For the past few years, Sherrill and his colleagues have been mapping the proton dripline in search of the end of the *rp* process, which theorists predicted would lie in the neighborhood of arsenic-65. "What we do is take a beam of krypton atoms," says Sherrill, "and smash it into nickel atoms at 40% of the speed of light. It's possible to knock just enough protons and neutrons out of the krypton to make never before produced isotopes." In December 1991, Sherrill and his colleagues reported that they had created arsenic-65 and it was relatively stable, as was



Virgin territory. Only 3000 of the more than 5000 theoretically predicted nuclei have been created in the laboratory *(yellow)*; only about 270 exist in nature *(red)*.

the next likely termination point, bromine-69. A third potential termination, krypton-72, was known to be stable.

This year, the MSU workers moved up another notch and tried to create rubidium-73. This nucleus, however, lay beyond the dripline, as other researchers had suspected. "That implies the termination point for this process [at krypton]," says Sherrill. "If we're right, somewhere up in the heavens, a neutron star is feeding on matter from its companion and making these nuclei, up to krypton-72, but that's probably where it stops."

In still fiercer astrophysical environments, another process takes over, spawning elements even further up the periodic table—the *r* process, or rapid neutron process. This process is thought to take place in the interiors of supernovae, where the explosion generates a flux of neutrons that, for a few seconds, can reach a quadrillion per second per square centimeter. Some of the neutrons in this storm stick to nuclei, pushing them toward the neutron dripline. After every few additions, a growing nucleus undergoes beta decay, in which it releases an electron and one of the neutrons changes to a proton. That moves the nucleus one step up the elemental ladder. The *r* process, which yields nuclei on the neutron-rich side of stability, can form all the elements up to uranium.

For years, says Mathews, astrophysicists have been asking experimentalists to help them chart the *r* process by studying the half-lives and decays of the nuclei on the neutron-rich side of stability. But that territory is much harder to explore than the proton-rich side, because neutrons are less tightly bound than protons. "If you smash something into a nucleus," says Mathews, "the simplest thing to happen is for a bunch of neutrons to come out of the nucleus, and that leaves you on the proton-rich side." Because the reactions leading to nuclei on the neutron dripline are rare, the only way to get enough to study is to create as many reactions as possible, says Tanihata, which requires more intense beams than are available today.

Existing facilities, explains Dave Morrissey of MSU, don't allow intense radioactive beams to be studied safely. "Our facility was designed 15 years ago," he says, "and the field only took off in the last five to 8 years. We…would have designed the machine differently had we known we were going to do this." Besides wanting a facility with the radiation shielding needed to study more intense beams, researchers would also like to be able to accelerate nuclei produced by the ISOL method to study interactions that are now out of reach. To do so, they need two accelerators: a primary machine firing protons into a target, and a secondary accelerator to accelerate the exotic nuclei that spew from the target.

For now, only a Belgian facility at Louvain-la-Neuve produces secondary beams, using refurbished equipment, and the Oak Ridge National Laboratory is in the process of building such a facility by reconfiguring old machines. Researchers are now trying to drum up support for a larger facility, called the Isospin Laboratory. (Isospin is the term for the neutron to proton ratio, which makes it a politically attractive euphemism for radioactivity.) The lab, which promises, says

Nitschke, "perhaps two to three orders of magnitude increase in intensity, at a cost of more than $50 million and less than $200 million," was first proposed in 1989 as part of the Department of Energy's Nuclear Science Advisory Committee long-range plan.

If such a machine gets built, it may have constituents well beyond physicists—nuclear chemists, for example. Walter Loveland of Oregon State University points out that with an intense enough beam, researchers could routinely produce elements like 104 and 106. These elements have already been identified, earning them a place in the periodic table, but the proton-rich isotopes made so far have a half-life of barely a few minutes. Theorists predict that isotopes richer in neutrons could have a 10-fold longer half-life.

Chemists would love to get their hands on longer-lived isotopes, explains Loveland, because these heavy exotics break the rules of ordinary chemistry. In these heavy elements, he says, "the nucleus is so heavy and the electrons so tightly bound around it" that the electron velocities become relativistic—they approach the speed of light. "Once electrons become relativistic in behavior," he says, "the kinds of chemistry we talk about to students doesn't work any more. If we can get significant quantities of nuclei which stay around for a while, it will mean an awful lot for both atomic physics and chemistry."

Then there is the Holy Grail of nuclear chemistry, which is creating hitherto undiscovered superheavy elements above element 109, a territory theorists speculate might harbor stable elements. As Tanihata explains, researchers have been trying to make these fragile superheavies by colliding heavy nuclei, such as nickel and bismuth—but instead of sticking together, the colliding nuclei generally shatter. If researchers could generate beams of neutron-rich heavy isotopes with neutron halos like that of lithium-11, says Tanihata, "you might be able to make a soft landing." The halo might act as a kind of atomic-scale cushion for the collision.

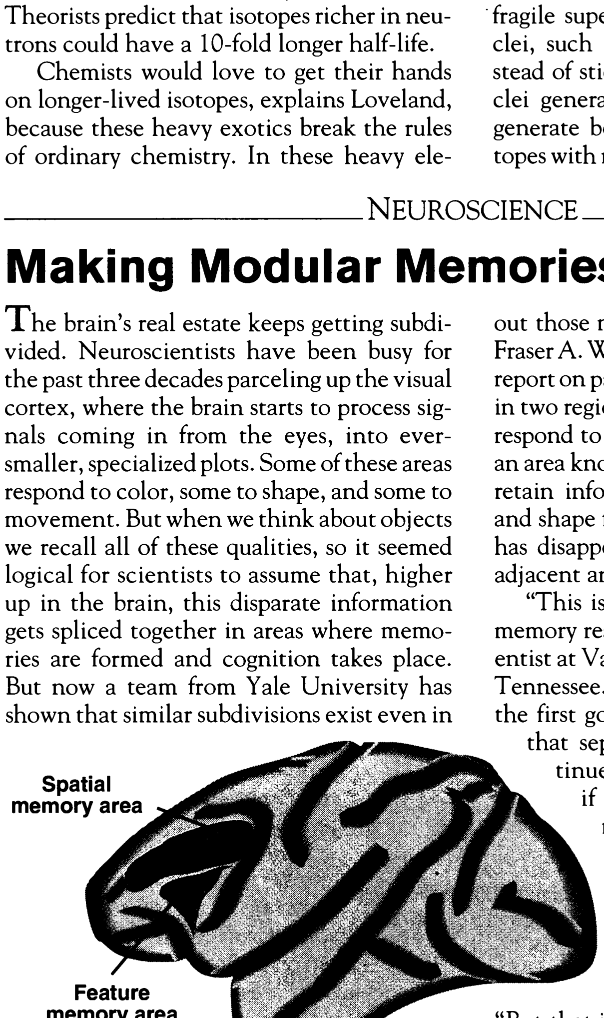
Applied scientists will also be lining up, judging from their interest so far. Ravn says that 30% of the projects at ISOLDE, at CERN, are already in applied science: efforts to make new semiconductor devices, by doping semiconductors with radioactive nuclei that can then decay into other elements, or to develop and study new radioisotopes for diagnostics and cancer treatment. Adds Sherrill, "As the science develops, we'll be able to give you nuclei of any element and any half-life to use in whatsoever science you want—biology, medicine, condensed matter, whatever. You say, 'I have a process that lasts 10 milliseconds.' We say, 'Okay, here's a 10-millisecond nucleus, or a whole bunch of nuclei.'" Exotic nuclei will be exotic no more.

–Gary Taubes

NEUROSCIENCE

Making Modular Memories

The brain's real estate keeps getting subdivided. Neuroscientists have been busy for the past three decades parceling up the visual cortex, where the brain starts to process signals coming in from the eyes, into ever-smaller, specialized plots. Some of these areas respond to color, some to shape, and some to movement. But when we think about objects we recall all of these qualities, so it seemed logical for scientists to assume that, higher up in the brain, this disparate information gets spliced together in areas where memories are formed and cognition takes place. But now a team from Yale University has shown that similar subdivisions exist even in the prefrontal cortex, which is involved in forming temporary, working memories. Some areas chiefly respond to "what" an object was, while others respond to "where" it was located.



Memory maps. Areas in the prefrontal cortex seem to recall different aspects of an image.

ILLUSTRATION: L. OWENS

"Memory is modular; it's not all in one device," says neuroscientist Patricia Goldman-Rakic, one of the researchers. "This is the first physiological evidence separating out those modules." She and her colleagues Fraser A. Wilson and Séamas P. Ó. Scalaidhe report on page 1955 of this issue that neurons in two regions in monkeys' prefrontal cortex respond to different visual cues. Neurons in an area known as the inferior convexity (IC) retain information about an object's color and shape for a short period after the object has disappeared from view. Neurons in an adjacent area encode an object's location.

"This is really right on the forefront" of memory research, says Jon Kaas, a neuroscientist at Vanderbilt University in Nashville, Tennessee. Kaas notes that these results are the first good functional evidence showing that separate perceptual pathways continue into the prefrontal cortex. And if further studies reveal working memory centers tied to the other senses, Kaas believes it would suggest that memories are divided up by their qualities much like image qualities—motion and shape, for example—are divided up in other cortical regions. "But that is a big if," he says.

Researchers had already traced out a physical path of neuronal connections going from spatial areas in the visual cortex, in the rear of the brain, up to the prefrontal cortex. They had also discovered a similar path leading from visual areas that react to features. Wilson and his colleagues then set out to determine whether function matched anatomy. They began by teaching monkeys two different visual tasks. In one, the monkeys were trained to stare at a spot in the center of a video screen while an image flashed at one of several locations on the screen and then disappeared. A few seconds later, a cue on the screen signaled the monkeys to move their gaze to where the image had been, an indication that they retained the information about its location. In the second test, the location of the image—a square—remained constant, but the pattern within the square changed. The monkeys were trained to wait until the image disappeared, and then move their eyes to the left if they saw one pattern or to the right if they saw another, indicating they remembered information about an object's features.

Throughout the tests, the researchers used microelectrodes implanted in the monkeys' prefrontal cortex to record the activity of individual neurons in the IC and in an adjacent area that surrounds a feature called the principal sulcus. The investigators found that when they kept the image the same but changed its location, neurons surrounding the sulcus became active during the delay period, while neurons in the IC tended to remain quiet. But when the image's pattern varied and its location remained constant, the delay period brought neurons in the IC to life, but the neurons around the sulcus didn't respond.

Finding that working memory is specialized in at least two ways, say other scientists, shows that such memories appear to form in a parallel fashion, and that there's no central memory manager putting everything together. "The assumption in the past has sort of been that there will be a next level [of processing] that will reintegrate everything," says John Allman, a neurophysiologist at the California Institute of Technology. "But there just isn't much evidence for that."

–Robert F. Service

Robert F. Service is a science writer in New York City.