An Element of Stability

Three teams of nuclear physicists are racing to disprove that as superheavy elements get bigger, they are always more unstable. In their sights is element 114, which is postulated to be exceptionally long-lived

DARMSTADT, GERMANY—Physicists in three labs around the world are gearing up for an expedition to a remote island, where they hope to find a bit of relief from the unstable world they are used to. Getting there will hardly be a pleasure cruise, however. In fact, it is shaping up to be an all-out race, and the first to arrive could capture one of physics's biggest prizes.

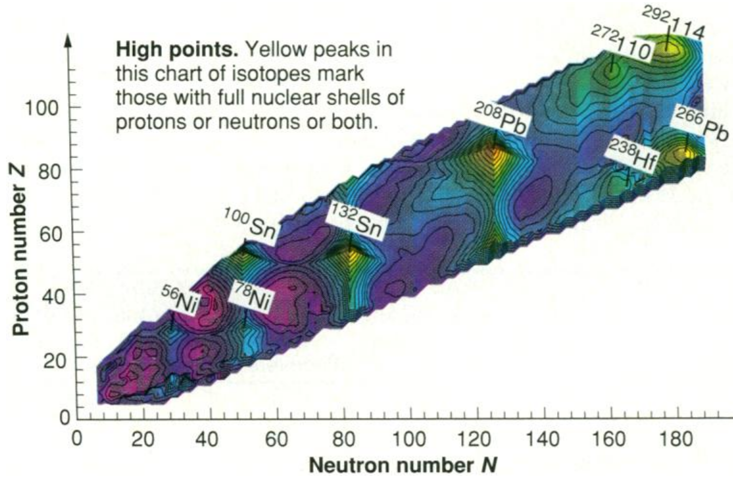
This tantalizing territory is a so-called "island of stability" that is postulated to exist around the superheavy element 114. The explorers who are hoping to reach this island are relying on theoretical extrapolations for evidence that it even exists. But if they find it, the discovery "would revolutionize the fields of heavy-element nuclear physics and nuclear chemistry," says Ken Gregorich, a nuclear chemist at Lawrence Berkeley National Laboratory (LBNL) in California, one of the three labs that are about to embark on the search.

The chart for this voyage is the periodic table of elements. Like all maps it looks simple, but hides a wealth of complexity. Each of the 112 elements currently in the table has a collection of shadowy siblings, isotopes with different numbers of neutrons in their nuclei. While all the isotopes of a particular element have essentially identical chemical properties, their nuclear characters can be very different—for example, many are highly radioactive with half-lives measured in microseconds.

Nature provides us with 94 different elements, up to and including plutonium, but since 1940 physicists have used nuclear reactors and particle accelerators to produce new elements with ever greater numbers of protons and neutrons in their nuclei. They have forged 20 elements, but the task is getting harder and harder and the elements more and more unstable—the latest, element 112, lasts a mere 280 microseconds.

Theorists predict, however, that this trend toward instability will take an upturn as they approach element 114. One particular isotope of 114, theorists say, is situated at the center of an island of stability, with many of the isotopes around it more stable than the superheavy isotopes that researchers can make today. That's the promised land that is beckoning labs in California, Germany, and Russia. But the race is more than just an intellectual one. One laboratory, the Institute for Heavy Ion Research (GSI) here in Darmstadt, has dominated this field for the past 2 decades, indisputably discovering five of the last six known elements. But soon GSI will have some real competition: LBNL and the Joint Institute for Nuclear Research (JINR) in Dubna, near Moscow—both of which have long histories of forging new elements—are putting the finishing touches on new facilities and will soon join GSI in pursuit of the superheavies.

All three institutes are planning experiments to forge superheavy elements as early as next spring, efforts that will be discussed at a meeting on 27 and 28 October of the Welch Foundation for Chemistry in Houston. "Element 114 is still the Holy Grail of this field," says nuclear theorist Rayford Nix of Los Alamos National Laboratory (LANL) in New Mexico.



High points. Yellow peaks in this chart of isotopes mark those with full nuclear shells of protons or neutrons or both.

PETER MOLLER/LANL

Magic quest

These nuclear navigators are taking their bearings from the arrangement of protons and neutrons in atomic nuclei. Currently, nuclear theory says that they form themselves into concentric "shells"—akin to the electron shells that surround the nucleus—with neutrons in one set of shells and protons in another. Each shell has a particular number of spaces for particles, and just as a complete electron shell makes for a chemically very stable element—one of the noble gases—a full nuclear shell gives that nucleus added stability. Helium, oxygen, calcium, tin, and lead, for example, each have a full shell, or "magic number," of protons. So should element 114. Lead-208 is the largest known isotope that is "doubly magic," also possessing a magic number of neutrons (126). Theorists predict that the next magic number of neutrons is likely to be 184, so the isotope that researchers at GSI, LBNL, and Dubna have their sights set on is the doubly magic element ^{298}114. Isotopes in the vicinity of ^{298}114 are expected to have half-lives lasting up to years. This is "one of the fundamental predictions of modern nuclear theory," says Dubna nuclear physicist Alexander Yeremin.

The hunt for the doubly magic 114 began in the 1960s, when physicists first suggested that closed nuclear shells might lead to stable superheavy elements. Some physicists were then predicting that ^{298}114's half-life might even be millions of years. "There was a lot of enthusiasm," says GSI director Hans Specht, "because some theoreticians felt that these elements would have exotic properties"—ones that could lead to new materials, fuels, or even weapons.

But after just a few years' attempts to reach it, the island of stability seemed farther away than ever. The discovery of elements 104 to 106—whose first known isotopes had half-lives measured in milliseconds—suggested that the size of still heavier ones would overwhelm the predicted stabilization of closed shells and split apart, or fission, instantly after formation. Conjuring fleeting glimpses of elements beyond 106 would require accelerators with more energy and detectors more sensitive than were available at existing facilities.

At that time, the favored technique for creating superheavy elements was "hot fusion," which involved smashing beams of helium and other light elements into a target made of a heavy element such as plutonium: In this reaction, each new fused nucleus must "cool off" by shedding neutrons. In the early 1970s, Dubna researchers pioneered a new approach, dubbed "cold" fusion, in which they fired a beam of moderately sized isotopes, such as cobalt, at the heavier stable elements lead or bismuth in the hope the two would have just enough energy to fuse. The Dubna group managed to produce isotopes of fermium (100) and rutherfordium (104), but their calculations suggested that to forge elements heavier than 106, cold fusion would require an additional burst of energy—an "extra push"—to get the atoms to fuse. "Many people believed that cold fusion would never work," says GSI physicist Gottfried Münzenberg. In the end, Dubna shelved the technique.

There were, however, no experimental data to back the extra-push theory, so while Dubna abandoned cold fusion, GSI took a gamble on the technique. "They believed in our method and adopted it," says Dubna team leader Yuri Oganessian. In the mid-1970s, GSI physicists led by Peter Armbruster set up a beamline for cold fusion and constructed a new detector, dubbed the Separator for Heavy Ion Reaction Products (SHIP), to weed out the rare superheavy isotopes from the showers of collision debris. Their bet paid off in 1981, when they fired a chromium beam at a rotating bismuth target and detected the predicted signature of element 107: a unique chain of alpha-particle decays. "Each decay chain has its own fingerprint," says GSI team leader Sigurd Hofmann.

Dubna's postulated "extra push" turned out to be unnecessary: Within 3 years, cold fusion had delivered elements 108 and 109 to the GSI group. However, the collisions that spawned each successive element were rarer.

To extend the periodic table even further, GSI embarked on a program in 1989 to increase the sensitivity of the SHIP detector 10-fold, finishing their modifications in 1994. That year, all three labs claimed to have created element 110—GSI and Berkeley via cold fusion, and Dubna via hot fusion. Who was first remains unresolved, but, in contrast to years past when there were bitter disputes between the labs over priority and the right to name new elements, most members of the three groups now favor deciding on a name for element 110 together. Later that year, however, GSI researchers had the limelight to themselves again when they forged 111, and in February 1996 the group fused zinc with lead to create 112—an event so rare it took about 3×10^{18} zinc ions fired at the lead to create two atoms of element 112.

Since then GSI scientists have been running experiments to calculate the exact beam energy it will take to create 113 from a beam of zinc-70 blasted at bismuth. The group will try for 113 next spring and, if successful, will next try to forge ^{283}114 from a beam of germanium ions and a lead target—an experiment that will push their equipment's sensitivity to its limit. "114 is at the borderline of possibility," says Specht.

Back in the race

If GSI manages to create element 114 next spring, the 169-neutron version it is shooting for would still have fewer neutrons and be far less stable than the doubly magic ^{298}114. Aiming to get even closer to this isotope is the Berkeley team, headed by LBNL's Gregorich and including two éminences grises of nuclear physics, Glenn Seaborg and Albert Ghiorso. Last fall, LBNL brought in GSI's Victor Ninov as a visiting scientist to help design its new $600,000 Berkeley Gas-filled Separator (BGS), which is expected to be ready for test runs in February 1998, after the lab finishes installing new magnets in its 88-inch (224-cm) cyclotron. One of the first BGS experiments, set for next fall, will aim to prove that LBNL was the first to create 110; the group will reproduce and extend the original work—whose partial decay chain suggested a sighting of one atom of element 110.

Later next year, the Berkeley group plans to bombard plutonium-244 with calcium-48 in an attempt to create element 114 with 174 neutrons. Such an isotope would be closer to ^{298}114, and should be far more stable than the version GSI will try to make. The LBNL team could also change its target to curium-248 in an attempt to make element 116 with 176 neutrons, also thought to be in the island of stability. "The BGS will have the best sensitivity for these reactions," says Gregorich. But he acknowledges that the timetable depends on the untested BGS: "We haven't even found the bugs yet."

Also in the hunt for a stable version of 114 is the Dubna group, which, like LBNL, is finishing an upgrade. In collaboration with researchers at Lawrence Livermore National Laboratory (LLNL) in California, Dubna will use hot fusion to try to forge superheavies. The group has installed a new ion source for its cyclotron and is now working to jack up the intensity of its calcium-48 beam, a project it expects to complete next month. "We hope that the [new] source will make more efficient use of the very rare and expensive calcium-48," says Livermore's Ron Lougheed. Early next year, Dubna will launch a series of experiments to produce neutron-rich versions of elements 110, 112, and 114. By producing a more neutron-rich version of 114, says Lougheed, "we may have a better chance at discovering how much stability these spherical shells add to element 114."

A dark horse in the race is Argonne National Laboratory (ANL) in Illinois, which by the end of the year will have finished installing a new ion source on its ATLAS accelerator. Some time next year, Argonne researchers hope to join the hunt for superheavy elements. However, acknowledges Argonne physicist Walter Henning, "we do not have the experience that the other laboratories have. ... I don't count us a favorite to win this race." Henning tips GSI to be the clear favorite.

No matter which country plants its flag first, scientists are excited about having the island of stability in their sights. If such elements are discovered, says Gregorich, they "are sure to be the center of study for a large part of the nuclear physics and nuclear chemistry communities for many years." For physicists, measuring the decay properties of these elements should provide new insights into how the atomic nucleus sticks together, while chemists would have a virtual terra incognita of how these stable superheavies might chemically react with other elements. Further in the future are attempts to create superheavies such as element 126, which some nuclear-shell theories suggest could be even more stable than 114. Beyond 126, says GSI nuclear chemist Matthias Schädel, "theoretical models simply aren't good enough to predict what might happen."

–Richard Stone

ELEMENTAL DISCOVERIES

Atomic number	Name	Discoverer	Year discovered	Half-life of longest lived isotope
93	Neptunium#	LBNL	1940	2.14 million years
94	Plutonium#	LBNL	1940	82 million years
95	Americium	LBNL	1944	7370 years
96	Curium	LBNL	1944	15.6 million years
97	Berkelium	LBNL	1949	1400 years
98	Californium	LBNL	1950	900 years
99	Einsteinium	LBNL, ANL, LANL	1952	1.29 years
100	Fermium	LBNL, ANL, LANL	1952	100.5 days
101	Mendelevium	LBNL	1955	51.5 days
102	Nobelium	JINR	1966	58 minutes
103	Lawrencium	LBNL, JINR	1961	3.6 hours
104	Rutherfordium	LBNL, JINR	1969	1.1 minutes
105	Dubnium	LBNL, JINR	1970	34 seconds
106	Seaborgium	LBNL, LLNL	1974	20 seconds
107	Bohrium	GSI	1981	102 milliseconds
108	Hassium	GSI	1984	1 second
109	Meitnerium	GSI	1982	70 milliseconds
110	?	GSI, LBNL, JINR*	1994	8.6 milliseconds
111	?	GSI	1994	1.5 milliseconds
112	?	GSI	1996	280 microseconds

Exists in trace quantities in nature in uranium ores. * Priority in dispute.

SOURCES: GSI; LANL; R. C. BARBER *ET AL.*, *PROG. PART. NUCL. PHYS.* 29, 453–530 (1992)