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Three first-ever atomic nuclei created at NSCL; new super-heavy aluminum isotopes may exist

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Page from an NSCL logbook used in the experiment that successfully created three super-heavy isotopes of magnesium and aluminum. The partially visible scrawled phrase "Let the celebrations begin!" reflects the excitement about the discovery. Credit: NSCL

Researchers at Michigan State University's National Superconducting Cyclotron Laboratory, NSCL, have created three never-before-observed isotopes of magnesium and aluminum. The results not only stake out new territory on the nuclear landscape, but also suggest that variants of everyday elements might exist that are heavier than current scientific models predict.

The findings appear in the October 25 issue of the journal *Nature*.

"It's been a longstanding project since the beginning of nuclear science to establish what isotopes can exist in nature," said Dave Morrissey, University Distinguished Professor of chemistry and one of the paper's authors. "This result suggests that the limit of stability of matter may be further out than previously expected; really, it shows how much mystery remains about atomic nuclei."

Particles that comprise atomic nuclei, protons and neutrons, are held together by the nuclear force. One of the four fundamental forces that collectively describe the interactions of all matter in the cosmos, the nuclear force, has been the subject of scientific inquiry since the 1930s.

Despite much progress in nuclear physics during the subsequent decades, understanding of how the nuclear force and other effects play out inside nuclei is far from complete. For example, even today scientists aren't sure exactly what combinations of protons and neutrons can make up most atomic nuclei.

One way experimental nuclear physicists explore this issue is by using accelerator facilities to create reactions that, in effect, kluge together piles of protons. An element is defined by its number of protons. For example, hydrogen has one proton; helium, two protons; oxygen eight protons, uranium, 92 protons. Whenever physicists establish a new proton limit, they invariably garner attention for conjuring new elements. In October 2006, a team of Russian and American scientists generated worldwide headlines for creating an element with 118 protons, the most protons ever recorded in a single nucleus.

Another way to probe nuclear stability is to see how many neutrons can be loaded onto nuclei of more quotidian elements, which is the focus of much of the work at NSCL. Elements can exist as different isotopes, which contain the same number of protons but different numbers of neutrons. As an example, the most abundant stable isotope of carbon has six protons and six neutrons. However, trace amounts of carbon-13 and carbon-14 – with seven and eight neutrons respectively – also can be found on Earth.

The neutron-limit, referred to as the neutron-dripline, is a basic property of matter. Yet remarkably, despite more than a half-century of inquiry, scientists know the dripline location only for the eight lightest elements, hydrogen to oxygen. So one very basic question – what's the heaviest isotope of a given element that can exist" – remains unanswered for all but eight of the hundred or so elements on the Periodic Table.

In an experiment that ran earlier this year at NSCL, researchers successfully created and detected three new super-heavy isotopes of magnesium and aluminum: magnesium-40, with 12 protons and 28 neutrons; aluminum-42, 13 protons and 29 neutrons; and aluminum-43, 13 protons and 30 neutrons. If the everyday version of aluminum were a 160-pound adult, aluminum-43 would be a muscular, 255-pound heavyweight.

"Evidence of particle stability for magnesium-40 obtained at NSCL is a major step in the field of rare isotope physics," said Hiro Sakurai, chief scientist at RIKEN in Japan, who was not involved in the research. The RIKEN research institute in Saitama, Japan, is home to the world's most powerful accelerator facility for creating radioisotope beams.

The fleeting appearance of these three nuclear newcomers is significant for several scientific and technical reasons.

First, when is comes to magnesium, the results indicate that the dripline extends at least as far as, and possibly beyond, magnesium-40. The isotope wasn't detected in several dripline-focused experiments conducted around the world since 1997 and the research community had begun to suspect that it was beyond the bounds of stability. Though it's difficult to compare across disciplines, physicists' success in detecting three magnesium-40 isotopes in the course of an 11-day experiment is roughly similar to the achievement of biologists who finally snap an image of an elusive and thought-to-be-extinct animal after years of traipsing through the jungle.

"The discovery of the hitherto unknown heaviest magnesium and aluminum isotopes at NSCL is a milestone in rare isotope research and is a great accomplishment for the worldwide scientific community exploring unstable nuclei close to the so-called neutron dripline," said Horst Stocker, director of Gesellschaft fur Schwerionenforschung, GSI, who was not involved in the research. Darmstadt, Germany-based GSI is one of the world's top accelerator facilities for producing heavy-ion beams for research.

Second, aside from being a similarly interesting outlier, aluminum-42 carries added importance since it is a near-dripline nucleus with an odd number of neutrons. Isotopes of lighter elements that toe the edge of existence generally have even numbers of neutrons due to the fact that neutrons naturally pair up inside nuclei. With an even number of neutrons, the nuclei in effect have a tidy, complete set of such pairs that collectively form a sort of energetic scaffolding that increases stability.

According to one of the leading theoretical models, aluminum-42 shouldn't exist. That it does suggests that the dripline may in fact tilt in the direction of more novel, neutron-rich isotopes, an implication that will help to extend nuclear theory and point the way to future experiments.

The NSCL result "alters the landscape of known nuclei, it alters our understanding of the forces that bind nuclei into stable objects, and it has important implications for future attempts with next-generation facilities to map the evolution of nuclear structure and existence into the most weakly bound nuclei," said Rick Casten, D. Allan Bromley Professor of Physics at Yale University, also not involved in the research.

The experimental technique itself also is noteworthy. Creating and measuring rare isotopes is always needle-in-a-haystack work that requires researchers to hunt for a few desired nuclei from a swarm of fast-moving and mostly known and therefore less interesting particles. But in this experiment, NSCL researchers achieved a hundred- to thousand-fold boost in their ability to filter out what can be thought of as junk. They did so by essentially jury-rigging the facility to filter the beam twice. The result was an ability to detect and measure isotopes so rare that they represent less than one in every million billion particles that passed by the detectors.

The dual filtering process, more properly known as two-stage separation, is a fixture in most new and planned facilities for rare isotope beam research, including the proposed upgrade of NSCL. This experiment marks one of the first uses of two-stage separation in the world and the first time the technique has been tried at NSCL, which typically filters and purifies particles only once in its A1900 separator.

NSCL detectors returned just one blip of data consistent with the existence of aluminum-43. This generally isn't enough to count as a discovery, according to the conventions of nuclear science. However, more than 20 instances of its immediate neighbor, aluminum-42, were observed. Because of this relative abundance and the fact that, due to pairing, the 30 neutrons in aluminum-43 should prove more stable than the 29 neutrons in aluminum-42, the solitary signature of aluminum-43 etched in the data logs carries more than usual amount of credibility.

"Experiments such as these are paving the way into the new era of nuclear structure studies that technological developments are opening to investigation for the first time ever," said Yale's Casten.

Source: Michigan State University