

Neutron-rich magnesium undergoes unexpected transitions

The structure of an exotic isotope near the edge of stability strays from that of its lower-mass counterparts.

The first model of the nucleus envisioned it as a structureless liquid drop of protons and neutrons. In 1949 Maria Goeppert Mayer and Hans Jensen upended that picture by introducing the nuclear shell model: Like electrons in a nuclear potential, protons and neutrons too experience a central potential generated by the other nucleons and therefore, as quantum particles, must exist in discrete energy levels.¹ For their discovery, Goeppert Mayer and Jensen shared half of the 1963 Nobel Prize in Physics (see *PHYSICS TODAY*, December 1963, page 21).

Today researchers can use heavy-ion accelerators to study much more exotic nuclides than the more easily accessible ones that inspired the nuclear shell model. Experiments have shown that low-atomic-number nuclei with nearly equal numbers of protons and neutrons are well described by the model. As proton-neutron asymmetry increases, however, the model's mean-field approximation breaks down, and corrections to the nuclear potential change the shell structure and its energy levels.

With 12 protons and 28 neutrons, magnesium-40 exists at the edge of nuclear stability. In a new study of the nuclide's nuclear excitations, a multi-institute team of researchers using the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center in Wako, Japan, has found that the nuclear structure of ^{40}Mg does not follow the trends established by lighter Mg nuclides.² Gamma-ray spectroscopic measurements of the first two excited states of ^{40}Mg uncovered energies much lower than those predicted by current models and experimental trends. The researchers tentatively attribute the discrepancy to weak binding of the out-



ermost neutrons, but it is not yet clear whether accounting for that in theoretical calculations will reproduce the observed transition energies.

The outer limit

The shell model predicts that particular so-called magic numbers—2, 8, 20, 28, 50, 82, or 126—of neutrons (N) or protons (Z) make for especially stable nuclei because they have a filled outer shell. Because of the energy gap between shells, the first excitation in a nucleus with a

FIGURE 1. THE RADIOACTIVE ISOTOPE projectile separator BigRIPS enabled researchers to isolate enough magnesium-40 for gamma-ray spectroscopy. The separator was part of the upgrade to RIKEN's facility in 2007 and is used to separate the isotopes produced by the primary beam's breakup into secondary beams. BigRIPS allows for higher-intensity beams than its predecessor, RIPS, because of its larger apertures and two-stage separation scheme. (Photo courtesy of RIKEN Nishina Center.)

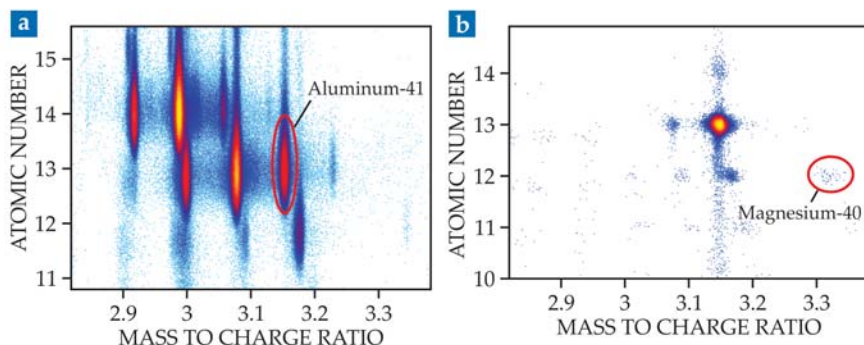


FIGURE 2. THE RADIOACTIVE ISOTOPE BEAM FACTORY AT RIKEN uses a high-intensity calcium-48 beam to generate exotic isotopes. **(a)** A beam of aluminum-41 nuclei (circled in red) can be clearly identified after the breakup of the primary ^{48}Ca beam on a beryllium target. **(b)** A small number of nuclei from the ^{41}Al beam lose a proton after interacting with a reaction target and become magnesium-40. As excited states in those nuclei quickly transition to the ground state, they emit gamma rays whose energies provide insight into the nuclear structure. (Adapted from ref. 2.)

magic number of protons or neutrons requires more energy than in a non-magic nucleus. (The experimental observation of that feature was crucial to Goeppert Mayer and Jensen's insight regarding the nuclear structure.)

But magic numbers are not always so magic. As the number of nucleons strays from the most stable configurations, correlations between them become important and the mean-field nuclear potential changes. Correlation effects lead to so-called islands of inversion, where having a magic number of nucleons no longer means that the ground state has a filled outer shell.³ Instead, the shells overlap and nucleons begin to fill the next shell before the previous one is complete. The large gap between the ground state and the first excitation disappears.

Magnesium needs eight more neutrons than protons to reach what was thought to be its first magic number, $N = 20$. But it turns out that 20 is not a magic number for Mg, because ^{32}Mg is on an island of inversion. That change in the energy levels accompanies a change in the nuclear shape from a sphere to a prolate, or elongated, spheroid. Spectra of nuclides from ^{32}Mg to ^{38}Mg indicate that the nucleus retains its prolate shape as more neutrons are added.

Neutrons can't be added indefinitely. Beyond a certain threshold, known as the drip line, the nuclear potential is not strong enough to bind another neutron, even in a metastable state (see the article by David Dean, *PHYSICS TODAY*, November 2007, page 48). Scientists were unclear whether they had reached the drip

line with ^{38}Mg ; the lighter ^{37}Mg showed extremely weak binding, and what would be the outermost neutron in ^{39}Mg is actually unbound. But nucleon pairing is energetically favorable, so an isotope with even N can be bound even if its lighter odd- N neighbor is not. When ^{40}Mg was finally observed as a bound state⁴ in 2007, it showed itself to be an even more neutron-rich Mg nuclide for studying the effects of weak binding on the nuclear structure.

Piling on neutrons

The ^{40}Mg experiment at RIBF was conducted in December 2016. Products from the breakup of a calcium-48 beam, which is popular for nuclear experiments because it has a magic number of protons and neutrons and a large neutron-to-proton ratio (see *PHYSICS TODAY*, June 2010, page 11), were directed to a two-stage projectile fragment separator, BigRIPS, shown in figure 1. The separator isolated an aluminum-41 beam from the products. After hitting a reaction target, most of that secondary beam reached the spectrometer at the end of BigRIPS unchanged; however, a small population of the ^{41}Al nuclei lost a proton and became ^{40}Mg . As shown in figure 2, only a tiny fraction of the intense primary beam actually ends up forming that neutron-rich species.

Such exotic, heavy nuclei are now easier to create since RIKEN's 2007–08 facilities upgrade. The researchers knew that they needed an intense primary ^{48}Ca beam to produce enough ^{40}Mg downstream for gamma-ray spectroscopy.

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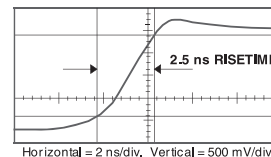
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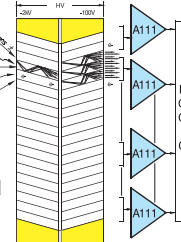
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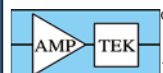
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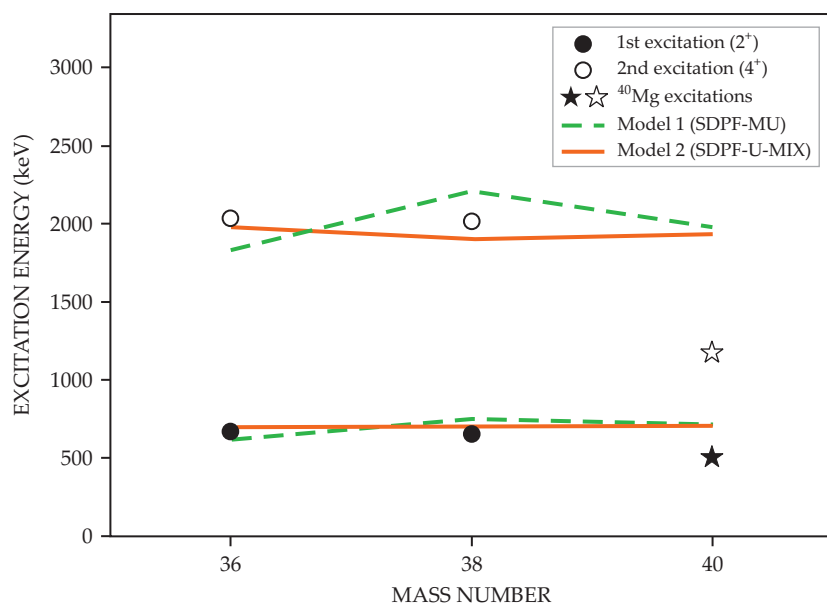


FIGURE 3. THE FIRST TWO EXCITATIONS in magnesium-36 and magnesium-38 (circles) agree with theoretical calculations predicting a prolate nuclear shape (green and orange lines). The same shape is expected to persist in ^{40}Mg , but measurements of the nuclide's first two excitations (stars) deviate far from both the trends of lighter nuclei and theoretical predictions. (Adapted from ref. 2.)

"Everything about measuring a gamma-ray spectrum depends on statistics," the paper's lead author, Heather Crawford of Lawrence Berkeley National Laboratory (LBNL), pointed out. "The only place where this is currently possible is RIBF."

The LBNL team initially attempted to do gamma-ray spectroscopy on ^{40}Mg in 2010, but that run was cut short due to problems with RIBF's cyclotron. A second scheduled experiment in 2014 was ultimately canceled. Everything finally fell into place in 2016: "We had an amazing beam intensity and stability at RIBF, and nature was kind to us with two populated excited states in ^{40}Mg ," said Crawford. "It was really about patience in waiting for the measurement to happen."

As a calibration, the researchers first remeasured the energies associated with the first two excited states in ^{36}Mg and ^{38}Mg . The values matched both previous experiments and theoretical calculations of the excited state energies, as shown in figure 3. But the energies from ^{40}Mg , shown as stars in the figure, deviated far from predictions: At about 500 keV, the first transition, which was tentatively ascribed to the first excited state decaying to the ground state, was 20% lower than expected. The second transition, about 670 keV higher, was nearly 50% lower

than expected and so far from any theoretical predictions that it is unclear which excited state could have generated it.

Mysterious transitions

A nuclear shape change could explain the deviation from predictions: If the ^{40}Mg nucleus was an oblate spheroid or had triaxial deformation, its expected energy levels would shift. However, in their truncated 2010 experiment,⁵ the same researchers measured the two-proton removal cross section from silicon-42 to generate ^{40}Mg . The production yield supported the idea that, like lighter nuclides, ^{40}Mg should be a prolate spheroid.

In the absence of such a dramatic nuclear shape change between ^{38}Mg and ^{40}Mg , the discrepancy could also stem from the coupling of outer neutrons to the rest of the nucleus. The weakly bound outer neutrons in near-drip-line nuclei can generate a long tail known as a halo in the distribution of nuclear material. First observed in lithium-11, the extended structures have since been observed in other nuclei. But as Crawford points out, not all weakly bound nucleons form halos; they must also be in a low-angular-momentum, single-particle orbital that allows them to spend time away from the core. "This is part of why these nuclei are interesting," she says.

"Halos have been observed, but how they modify other aspects of structure is not so clear."

Most halo studies have been restricted to smaller nuclei with fewer than 20 neutrons. With 28 neutrons—more than twice the number of protons— ^{40}Mg is the most neutron-rich nucleus with that many neutrons to be studied. It is also the heaviest isotope with such weakly bound nucleons to be probed using gamma-ray spectroscopy.

With two weakly bound neutrons, ^{40}Mg could be viewed as a ^{38}Mg nucleus surrounded by a two-neutron halo. If that picture is correct, how do those halo neutrons couple to the rest of the nucleus? Experiments and theory agree that for lighter nuclei the first excitation is the 2^+ state with positive parity and overall spin $J = 2$, followed by a second excitation to the 4^+ state with $J = 4$. In those nuclei, the 4^+ state emits a gamma ray as it decays into the 2^+ state, which then subsequently decays into the 0^+ ground state with the emission of a second gamma ray. But as Crawford notes, the 4^+ state may no longer be the second excitation in ^{40}Mg : "It's possible that the weak binding may push the second 2^+ state down in energy, as we speculate in the paper, but honestly we don't know for sure the nature of the second state."

Whatever their cause, the unexpectedly low excitation energies in ^{40}Mg show that the current models fail to accurately describe nuclear structures as the nuclei become heavier and further from stability. Improvements like those at RIKEN's RIBF are enabling researchers to perform measurements on increasingly exotic nuclei, which will help them understand how collective effects can change the nuclear shape and energy levels far from stability. A better understanding of neutron binding may also elucidate the rapid neutron capture that forms heavy isotopes in stars.

Christine Middleton

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