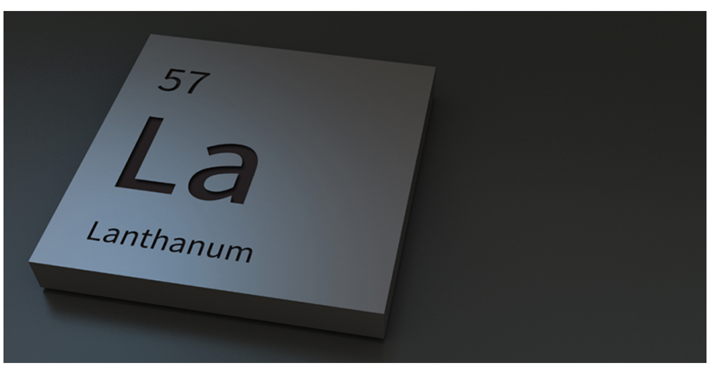
Lanthanum Less Abundant Than Previously Thought

Measurements related to the production of lanthanum in stars where elements are thought to form via the "*i* process" indicate that less of the element is produced than models predict.

By Katherine Wright

The past decade has seen significant advances in the observational capabilities of astronomical telescopes. With those advances have come beautiful pictures of the cosmos and an increasing number of unexpected findings, including observations that indicate there were more bright galaxies in the early Universe than anyone predicted (see **News Feature: JWST Sees More Galaxies Than Expected**). Recent data also suggest that some stars contain more of certain elements than models allow (see **Research News: Heavy Element Quandary in Stars Worsened by New Nuclear Data**). Solving such element-abundance problems is key to understanding the origin of the Universe's heavier constituents. Artemis Spyrou of Michigan State University and Dennis Mücher of the University of Cologne, Germany, have now measured a neutron-capture cross section for a nuclear reaction relevant to a nucleosynthesis pathway known as the *i* process [**1**]. The data help constrain models and could allow astrophysicists to fill in missing puzzle pieces about how stars cook up elements.



By experimentally determining the neutron-capture cross section of barium-139, researchers have revised downward their predictions of the stellar abundance of one the isotope's decay products—lanthanum.
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Most of the Universe's heavier elements form in stars via a neutron-capture process. Until recently, element abundances measured by astronomers could be explained by the two most studied of these processes: the slow neutron-capture process, or "*s* process," and the fast neutron-capture process, or "*r* process." "Almost all the observations agreed with the models," Spyrou says. Then new telescopes came online, and stars with unexpected element ratios popped into view.

These observations led researchers to start exploring a lesser-known neutron-capture pathway called the intermediate process, or "*i* process." The pathway was first predicted in the 1970s but went by the wayside, as it wasn't needed to explain the data that were then available.

As its name suggests, the properties of the *i* process sit between those of the *s* and *r* processes. For example, in stars where elements form by the *s* process, a nucleus might capture one neutron every few hundred years. The *s* process typically involves relatively stable nuclei that can live for days or months before decaying. At the other end of the scale, where the *r* process is relevant, the nuclei are highly unstable. Here, nuclei capture neutrons significantly more frequently—every second or less—and decay times are also less than a second. Between these extremes sits the *i* process, with relevant timescales of a few tens of minutes. "The *i* process is intermediate in every way," Spyrou says.

Traditional measurements of neutron-capture cross sections are made by bombarding a target with a neutron beam. Studying the *i* process in this way is tricky, however, because the short half-lives of the relevant isotopes make it impossible to incorporate them in a stable target. An alternative method would be to form the isotope of interest into a beam and fire it into a target of unbound neutrons, but such a target is impossible to make. “Direct measurements are just not feasible at the moment,” Spyrou says.

To study the *i* process, Spyrou, Mücher, and their colleagues measured the decay of a beam of cesium-140 into barium-140. During this decay, a neutron is converted into a proton, and the resulting barium-140 nucleus then emits a gamma ray, which the researchers detected. These gamma-ray measurements allowed them to indirectly infer the neutron-capture cross section of barium-140, a property that relates to the probability that a nucleus of an isotope will absorb an incoming neutron. “It’s an indirect measurement, but we can learn just about everything we need to using it,” Spyrou says.

One of the things that can be learned is the production probability of isotopes of other elements, such as lanthanum-139. This isotope forms through the decay of barium-139, whose neutron-capture cross section can be determined from the barium-140 experiments. A wealth of astrophysics observations exists for lanthanum, making it an ideal candidate for constraining the outputs of nucleosynthesis models. It was measurements of lanthanum that highlighted problems with the *s* and *r* processes in explaining recent data. The team’s experiments indicate that the neutron-capture cross section of barium-139 is larger than nuclear theory models currently predict. That larger cross section means that barium-139 is more likely to capture a neutron and transmute into other elements, leading to a smaller probability of this isotope decaying into lanthanum-139. The result therefore implies a lower lanthanum abundance compared to previously predicted values for stars where the *i* process dominates.

With this data in hand, Spyrou, Mücher, and their colleagues were able to constrain the barium–lanthanum ratio for which the *i* process is relevant, significantly reducing uncertainties for astronomical observations. “The neutron-capture cross sections relevant for the *i* process are almost exclusively experimentally unknown,” says Arthur Choplain, who studies the neutron-capture process at Université libre de Bruxelles. He says it’s “exciting” to see such measurements for barium and lanthanum because of their importance for nucleosynthesis models. Choplain hopes that the team’s approach could be used to measure the neutron-capture cross section of other isotopes. Each such measurement could, he says, “progressively increase the accuracy of our *i*-process models and eventually allow more reliable comparisons between models and observations.”

Spyrou, Mücher, and their colleagues are now planning studies along those lines. They also plan to measure the neutron-capture cross section of cesium-137, another isotope important for the *i* process. This pathway is particularly attractive to study, Mücher says, as “it is probably the only *i*-process isotope for which we can measure the reaction cross section directly.”

Katherine Wright is the Deputy Editor of ***Physics Magazine***.

REFERENCES

1. A. Spyrou *et al.*, “First study of the $^{139}\mathrm{Ba}(n,\gamma)^{140}\mathrm{Ba}$ reaction to constrain the conditions for the astrophysical *i* process,” **Phys. Rev. Lett. 132, 202701 (2024).**