Cosmic understanding: Identifying distinctive signatures of heavy elements

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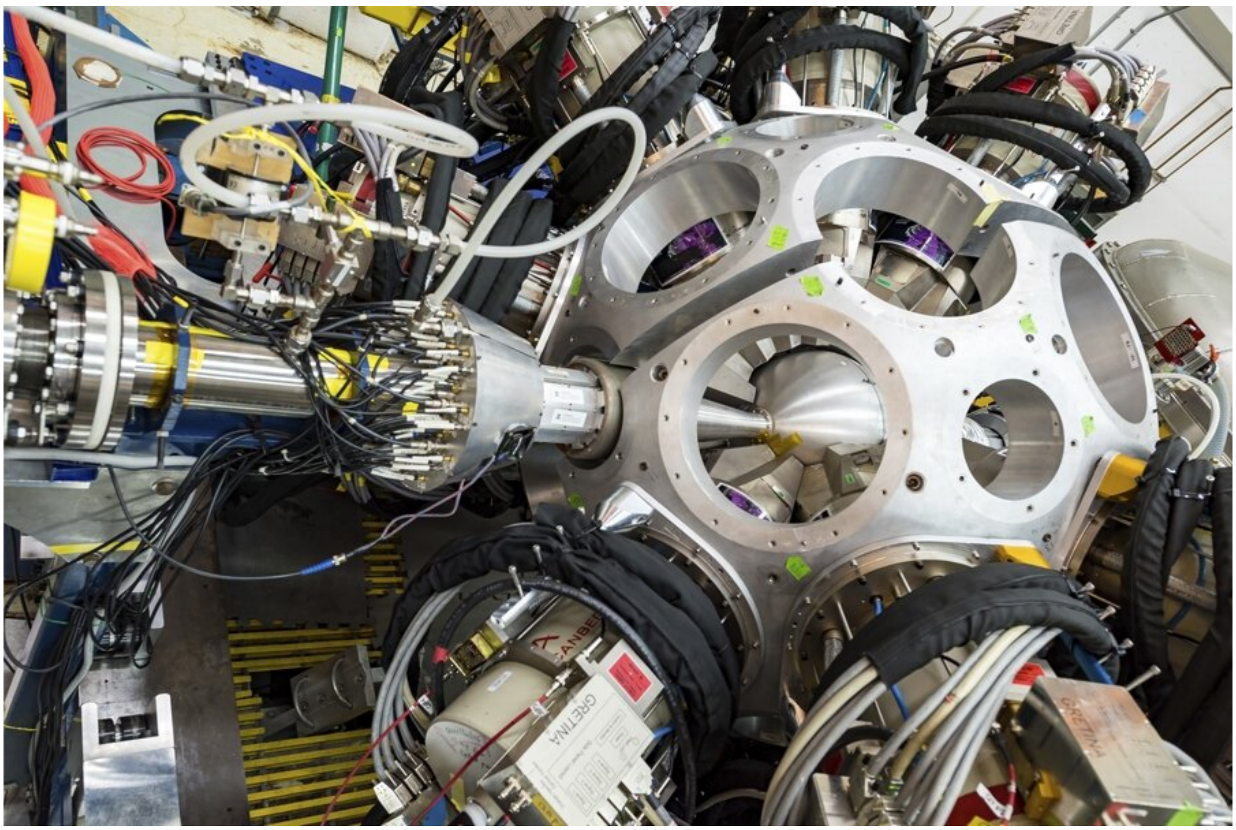

Using the ATLAS Office of Science user facility at Argonne National Laboratory, nuclear scientists are investigating how heavy elements in the universe formed. Credit: Argonne National Laboratory

At the Department of Energy's Argonne National Laboratory, in a side room off the ATLAS nuclear particle accelerator, Jason Clark sits on an upper platform to do his work. The cramped space requires head-ducking and watching-your-step to navigate. Particles stream though metal piping weaving in and out of the room. Perched atop that metal platform, a device with a tiny Canadian flag taped to it plucks a single particle from the stream, which Clark then studies to understand the origin of the elements.

In another building at Argonne, in a room packed with servers, a supercomputer named BEBOP churns away. The room is cold, as most server rooms are, chilled by the deafeningly loud fans required to keep the servers from overheating. Among BEBOP's many tasks, the supercomputer runs simulations programmed by Rebecca Surman's theoretical nuclear astrophysics group at the University of Notre Dame. These complex simulations inform Clark's research. The two collaborate to find the distinctive signatures of heavy elements.

ATLAS occupies a basement in one of Argonne's many buildings, with particle streams going in and out of funky corners housed by cinder blocks. Navigating the space takes careful attention and a knowing guide. At the end of odd corridors and behind walls that minimize radiation, experiments with lots of detectors of all types pick up particles for the many scientists working in the ATLAS DOE Office of Science user facility to study.

"It's a unique window into nuclear physics," notes Surman.

Clark conducts his work mainly in the room housing the CAlifornium Rare Isotope Breeder Upgrade (CARIBU). Here Clark and the team of researchers working with him seek to understand the bigger question: Where do elements heavier than iron come from?

As Clark noted, "These are the same isotopes that could be produced in supernovae or neutron star mergers." Understanding the way these elements form provides insight into processes that occur in these galactic events. The interest in these unique, fundamental processes that produce heavy elements drive the questions in the lab.

Modeling the making of elements

Take any astronomy class in any university in the country. The mantra is always the same: Elements lighter than iron are formed in the cores of stars; elements heavier than iron are formed in stellar explosions. While the former rings true, the latter is not always, or at least not exclusively, true. Some of these heavier elements form when stars explode, but other astrophysical processes not yet completely understood also play a role in forming new elements.

New elements form when groups of nuclei, made up of protons and neutrons, come together to form new things. Forming new elements takes many paths, using combinations of protons and neutrons in light and sometimes heavy elements. This is the process known as fusion.

The simplest case of fusion brings together two protons and two neutrons to make helium. If you combine two helium atoms together, you get the four protons and four neutrons making up a beryllium nucleus. This process, known as nucleosynthesis, continues this way in the cores of stars, light elements coming together to form more complex, heavier elements. However, stars have limits on how much they can fuse together. Eventually stars stop fusing together elements when they get to iron.

Surman's research involves "reverse engineering" the formation of elements heavier than iron. These elements can form by rapid captures of neutrons, making combinations of neutrons and protons so extreme they have never been seen in laboratories on Earth. Exotic nuclei like these decay back to stable elements like gold and platinum.

"When astronomers measure the relative amounts of heavy elements in the solar system and other stars, they note that the abundances form a universal pattern," Surman explained. However, researchers have struggled to identify conclusively what astrophysical event causes this universal pattern.

Reverse engineering attempts to use this universal pattern to "predict" the properties of exotic nuclei required to replicate this pattern in astrophysical simulations. Different astrophysical events have different characteristic properties such as temperature, neutron densities, and others. Each reverse engineering prediction of nuclear data produces distinct properties for each possible astrophysical event.

Picking out which processes can be a daunting task. So how does Surman and the team make these decisions?

Supercomputers help.

Mathematical nucleosynthesis models can be complicated and too clunky for a person to run through by hand. In fact, some models are so complicated that an entire building full of desktop computers could not run it efficiently. Surman's model requires this level of complexity.

With small elements like helium, there are only so many ways you can combine protons and neutrons to make a helium nucleus. As the elements get heavier, the options grow exponentially. So Surman uses a method called a Markov chain Monte Carlo to weed through the possibilities.

If you hear "Monte Carlo" and think of a casino in a particular James Bond movie, you are not far off. The method is named after that casino in Monaco. Attaching the idea to a casino is somewhat appropriate. Monte Carlo simulations produce a random selection of all the possible outcomes of a complicated process using random numbers, just like slot machines do.

In the case of this model, randomized combinations of protons and neutrons make choosing paths a lot simpler. The testing can happen over a broader swathe of options without a researcher deciding on every option. Initially, the research group chooses some nuclear data and astrophysical conditions. Then they run a nucleosynthesis simulation with these starting conditions and compare the resulting pattern of abundances to the universal pattern.

Then the Monte Carlo simulation introduces variations to the masses of the nuclei in the model. For each set of varied nuclear data, the team reruns the nucleosynthesis simulation. Each run checks how well the simulated and actual abundance patterns agree with each other and if that agreement has improved. Then they start the process all over again and repeat these steps until an excellent match is found.

"We then repeat this entire process for different astrophysical environments, leading to distinct sets of 'reverse-engineered' masses," Surman noted.

To achieve agreement between results, Surman says it takes about 40 runs through the model. To be extra sure, they run the model 50 times. At that point, they can approach the variation with certainty. And then, if the variation is testable by CARIBU, measurements of these nuclear properties taken by Clark can help answer this longstanding mystery.

Trapping particles for measuring masses

The natural second step in the research is to check the predicted properties experimentally. While the astrophysical processes that produce heavy elements are beyond the capability of many facilities, the processes modeled by Surman are within the capabilities of CARIBU. Surman's results inform Clark's work with CARIBU.

The sheer number of nuclei involved in the astrophysical processes preclude Clark's ability to blindly pick which nuclei to measure. Moreover, ATLAS and CARIBU require significant resources to run. And some of the particles produced by CARIBU are very exotic and thus very rare.

"With low production and low yield, you just have to be very efficient," Clark said of this particular challenge. Rather than haphazardly look for results that may or may not be in ideal regions, Surman communicates what "region" to look in without getting into specifics.

It's like someone asked you to guess where they went on their summer vacation. Instead of just handing you a globe and telling you to pick a place, they tell you they spent time on a beach, narrowing the possibilities considerably. The integrity of the search still holds, but the narrowed possibilities make the search more targeted. So without a precise target, Clark conducts experiments to measure the masses of nuclei in the region communicated to him.

The process starts with CARIBU, which contains a thin plate with californium that is constantly producing a range of heavy elements. These heavy elements are extracted, separated out, and then directed up to the device called the Canadian Penning Trap (CPT) mass spectrometer.

Sitting near the two-story ceiling, the CPT whirs along, capturing nuclear particles from the stream. It snags a heavy ion with its magnetic and electric fields. Then the device measures the mass of the particle. After the measurements are completed by Clark, only then does he compare notes with Surman. Ideally, the results would match up to what is predicted by the nucleosynthesis model.

So far, the researchers have had some interesting results. A long-standing theory predicted a high-mass impact event such as two neutron stars merging could provide the right conditions to make heavy elements. In August of 2017, a group of researchers at the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected an event that would later be identified as a neutron star merger. Detection of this event confirmed that neutron star mergers produce heavy elements like those studied by Surman and Clark.

To understand this process better, Clark and Surman studied the isotopes of both samarium and neodymium. As usual, Surman employed her "reverse engineering" nucleosynthesis model and Clark measured particle masses with the CPT. The results converged nicely, showing that the masses both predicted and measured were consistent with elements produced by a neutron star merger. Clark and Surman are looking to explore this further as the research moves forward.

As Clark noted, conducting these experiments requires efficiency and a targeted approach. While CARIBU has been useful to probe some of these possible environments for making elements, the ability to probe heavier elements will be used to explore this research further. This research can help to target experiments at future nuclear physics accelerators such as the forthcoming Facility for Rare Isotope Beams (FRIB), which is set to begin running experiments in 2022.

The basic nuclear science of how heavy elements can form provides a stepping-stone to understanding the origin of the elements. Every experimental run gets closer to a deeper understanding of nucleosynthesis. But without answering the question of how heavy elements can form, that ultimate goal is not achievable.

"We want to understand all of nuclear physics," Surman said, "and at the heart is the need to understand this problem."

Provided by US Department of Energy

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