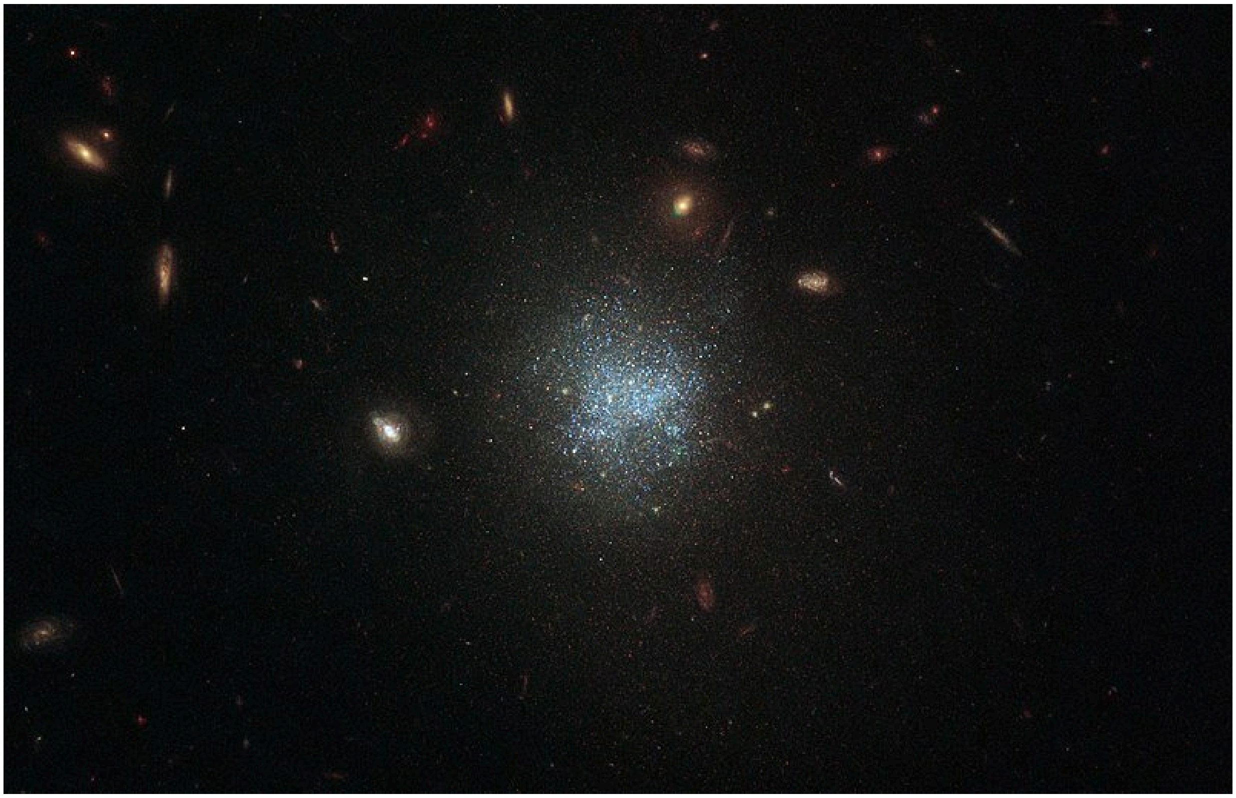
Halos and dark matter: A recipe for discovery

July 23 2022, by Matt Davenport



This Hubble Space Telescope image centers on what's known as a low surface brightness, or LSB, galaxy (blue), surrounded by more familiar-looking galaxies (yellow). Astrophysics believe that more than 95% of the matter found in LSBs is dark matter. Credit: ESA/Hubble & NASA, D. Calzetti

About three years ago, Wolfgang "Wolfi" Mittig and Yassid Ayyad went looking for the universe's missing mass, better known as dark matter, in the heart of an atom.

Their expedition didn't lead them to dark matter, but they still found something that had never been seen before, something that defied explanation. Well, at least an explanation that everyone could agree on.

"It's been something like a detective story," said Mittig, a Hannah Distinguished Professor in Michigan State University's Department of Physics and Astronomy and a faculty member at the Facility for Rare Isotope Beams, or FRIB.

"We started out looking for dark matter and we didn't find it," he said. "Instead, we found other things that have been challenging for theory to explain."

So the team got back to work, doing more experiments, gathering more evidence to make their discovery make sense. Mittig, Ayyad and their colleagues bolstered their case at the National Superconducting Cyclotron Laboratory, or NSCL, at Michigan State University.

Working at NSCL, the team found a new path to their unexpected destination, which they detailed June 28 in the journal *Physical Review Letters*. In doing so, they also revealed interesting physics that's afoot in the ultra-small quantum realm of subatomic particles.

In particular, the team confirmed that when an atom's core, or nucleus, is overstuffed with neutrons, it can still find a way to a more stable configuration by spitting out a proton instead.

Shot in the dark

Dark matter is one of the most famous things in the universe that we know the least about. For decades, scientists have known that the cosmos contains more mass than we can see based on the trajectories of stars and galaxies.

For gravity to keep the celestial objects tethered to their paths, there had to be unseen mass and a lot of it—six times the amount of regular matter that we can observe, measure and characterize. Although scientists are convinced dark matter is out there, they have yet to find where and devise how to detect it directly.

"Finding dark matter is one of the major goals of physics," said Ayyad, a nuclear physics researcher at the Galician Institute of High Energy Physics, or IGFAE, of the University of Santiago de Compostela in Spain.

Speaking in round numbers, scientists have launched about 100 experiments to try to illuminate what exactly dark matter is, Mittig said.

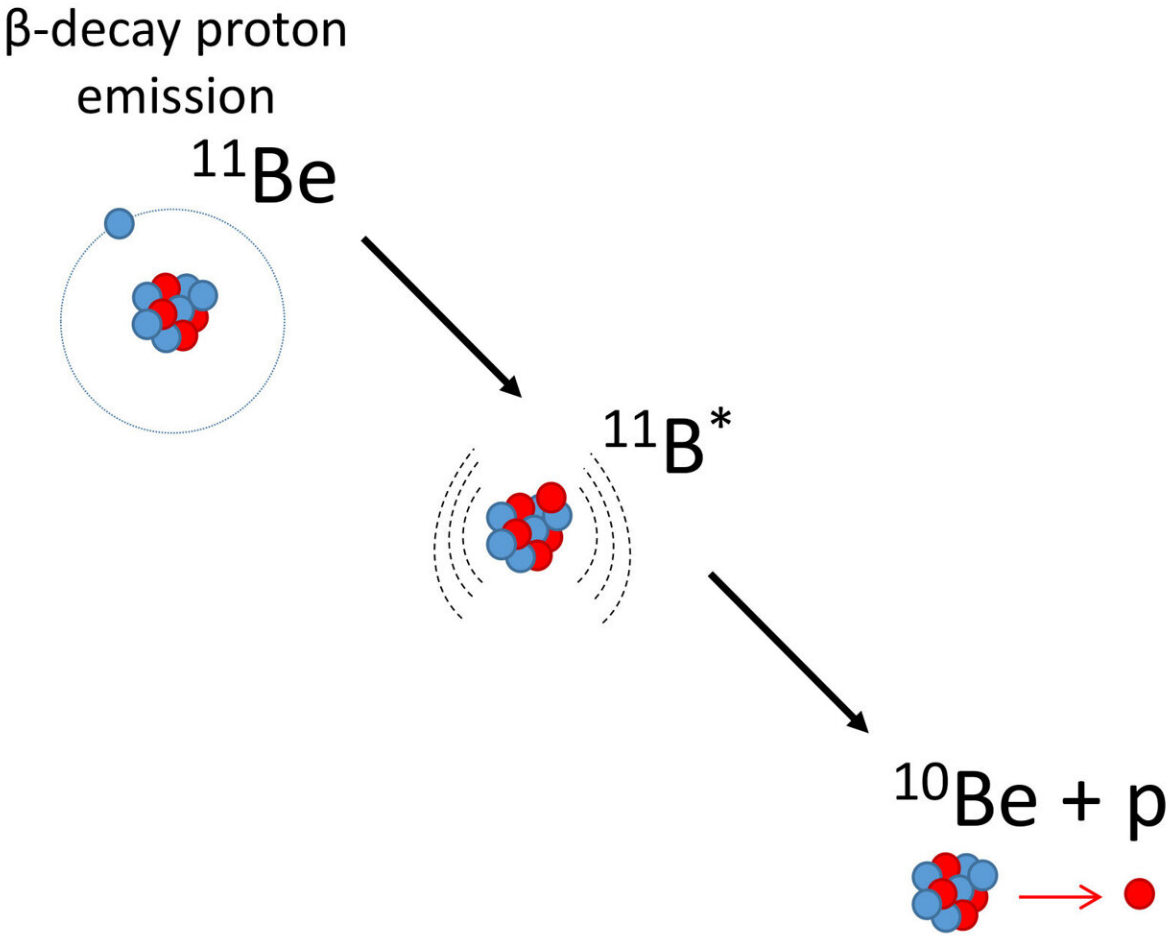
"None of them has succeeded after 20, 30, 40 years of research," he said.

"But there was a theory, a very hypothetical idea, that you could observe dark matter with a very particular type of nucleus," said Ayyad, who was previously a detector systems physicist at NSCL.

This theory centered on what it calls a dark decay. It posited that certain unstable nuclei, nuclei that naturally fall apart, could jettison dark matter as they crumbled.

So Ayyad, Mittig and their team designed an experiment that could look for a dark decay, knowing the odds were against them. But the gamble wasn't as big as it sounds because probing exotic decays also lets researchers better understand the rules and structures of the nuclear and quantum worlds.

The researchers had a good chance of discovering something new. The question was what that would be.



In the team's experiment published in 2019, beryllium-11 decays through beta decay to an excited state of boron-11, which decays to beryllium-10 and a proton. In the new experiment, the team accesses the boron-11 state by adding a proton to beryllium-10, that is, by running the time-reversed reaction.

Help from a halo

When people imagine a nucleus, many may think of a lumpy ball made up of protons and neutrons, Ayyad said. But nuclei can take on strange shapes, including what are known as halo nuclei.

Beryllium-11 is an example of a halo nuclei. It's a form, or isotope, of the element beryllium that has four protons and seven neutrons in its nucleus. It keeps 10 of those 11 nuclear particles in a tight central cluster. But one neutron floats far away from that core, loosely bound to the rest of the nucleus, kind of like the moon ringing around the Earth, Ayyad said.

Beryllium-11 is also unstable. After a lifetime of about 13.8 seconds, it falls apart by what's known as beta decay. One of its neutrons ejects an electron and becomes a proton. This transforms the nucleus into a stable form of the element boron with five protons and six neutrons, boron-11.

But according to that very hypothetical theory, if the neutron that decays is the one in the halo, beryllium-11 could go an entirely different route: It could undergo a dark decay.

In 2019, the researchers launched an experiment at Canada's national particle accelerator facility, TRIUMF, looking for that very hypothetical decay. And they did find a decay with unexpectedly high probability, but it wasn't a dark decay.

It looked like the beryllium-11's loosely bound neutron was ejecting an electron like normal beta decay, yet the beryllium wasn't following the known decay path to boron.

The team hypothesized that the high probability of the decay could be explained if a state in boron-11 existed as a doorway to another decay, to beryllium-10 and a proton. For anyone keeping score, that meant the nucleus had once again become beryllium. Only now it had six neutrons instead of seven.

"This happens just because of the halo nucleus," Ayyad said. "It's a very exotic type of radioactivity. It was actually the first direct evidence of proton radioactivity from a neutron-rich nucleus."

But science welcomes scrutiny and skepticism, and the team's 2019 report was met with a healthy dose of both. That "doorway" state in boron-11 did not seem compatible with most theoretical models. Without a solid theory that made sense of what the team saw, different experts interpreted the team's data differently and offered up other potential conclusions.

"We had a lot of long discussions," Mittig said. "It was a good thing."

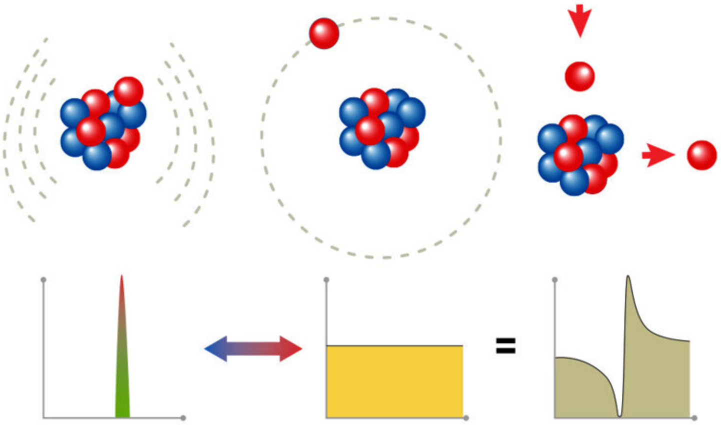
As beneficial as the discussions were—and continue to be—Mittig and Ayyad knew they'd have to generate more evidence to support their results and hypothesis. They'd have to design new experiments.

The NSCL experiments

In the team's 2019 experiment, TRIUMF generated a beam of beryllium-11 nuclei that the team directed into a detection chamber where researchers observed different possible decay routes. That included the beta decay to proton emission process that created beryllium-10.

For the new experiments, which took place in August 2021, the team's idea was to essentially run the time-reversed reaction. That is, the researchers would start with beryllium-10 nuclei and add a proton.

Collaborators in Switzerland created a source of beryllium-10, which has a half-life of 1.4 million years, that NSCL could then use to produce radioactive beams with new reaccelerator technology. The technology evaporated and injected the beryllium into an accelerator and made it possible for researchers to make a highly sensitive measurement.



In an open quantum system, a discrete, or isolated, state, analogous to boron-11 (left), mixes with an adjacent continuum of states, related to beryllium-10 (middle), which results in a new “resonant” state (right). Credit: Facility for Rare Isotope Beams

When beryllium-10 absorbed a proton of the right energy, the nucleus entered the same excited state the researchers believed they discovered three years earlier. It would even spit the proton back out, which can be detected as signature of the process.

"The results of the two experiments are very compatible," Ayyad said.

That wasn't the only good news. Unbeknownst to the team, an independent group of scientists at Florida State University had devised another way to probe the 2019 result. Ayyad happened to attend a virtual conference where the Florida State team presented its preliminary results, and he was encouraged by what he saw.

"I took a screenshot of the Zoom meeting and immediately sent it to Wolfi," he said. "Then we reached out to the Florida State team and worked out a way to support each other."

The two teams were in touch as they developed their reports, and both scientific publications now appear in the same issue of *Physical Review Letters*. And the new results are already generating a buzz in the community.

"The work is getting a lot of attention. Wolfi will visit Spain in a few weeks to talk about this," Ayyad said.

An open case on open quantum systems

Part of the excitement is because the team's work could provide a new case study for what are known as open quantum systems. It's an intimidating name, but the concept can be thought of like the old adage, "nothing exists in a vacuum."

Quantum physics has provided a framework to understand the incredibly tiny components of nature: atoms, molecules and much, much more. This understanding has advanced virtually every realm of physical science, including energy, chemistry and materials science.

Much of that framework, however, was developed considering simplified scenarios. The super small system of interest would be isolated in some way from the ocean of input provided by the world around it. In studying open quantum systems, physicists are venturing away from idealized scenarios and into the complexity of reality.

Open quantum systems are literally everywhere, but finding one that's tractable enough to learn something from is challenging, especially in matters of the nucleus. Mittig and Ayyad saw potential in their loosely bound nuclei and they knew that NSCL, and now FRIB could help develop it.

NSCL, a National Science Foundation user facility that served the scientific community for decades, hosted the work of Mittig and Ayyad, which is the first published demonstration of the stand-alone reaccelerator technology. FRIB, a U.S. Department of Energy Office of Science user facility that officially launched on May 2, 2022 is where the work can continue in the future.

"Open quantum systems are a general phenomenon, but they're a new idea in nuclear physics," Ayyad said. "And most of the theorists who are doing the work are at FRIB."

But this detective story is still in its early chapters. To complete the case, researchers still need more data, more evidence to make full sense of what they're seeing. That means Ayyad and Mittig are still doing what they do best and investigating.

"We're going ahead and making new experiments," said Mittig. "The theme through all of this is that it's important to have good experiments with strong analysis."

More information: Y. Ayyad et al, Evidence of a Near-Threshold Resonance in B11 Relevant to the β -Delayed Proton Emission of Be11, *Physical Review Letters* (2022). DOI: 10.1103/PhysRevLett.129.012501

Provided by Michigan State University

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