Extremely sensitive experiment shows no hint of a key radioactive decay

Physics experiment searches for a decay with a half-life older than the Universe's.

The Standard Model of physics, which explains the properties and interactions of the fundamental particles, does a phenomenal job with the things it gets right, and there's nothing that it obviously gets wrong. But that's not to say it doesn't have its issues. There are a variety of rather fundamental topics that it doesn't cover at all, like why neutrinos have a mass and what constitutes dark matter.

A variety of extensions of the Standard Model deal with these topics, but they're entirely theoretical—we don't have experimental evidence for them. This week, one of the most exquisitely sensitive tests yet to look for validation of alternative versions of the Standard Model has been reported, and it has turned up blank. The test had to be sensitive, as it was looking for a radioactive decay with a half-life at least 15 orders of magnitude longer than the age of the Universe.

Spinning antiparticles

The issue being tested has to do with one of the more notable missing pieces of the Standard Model. There's obviously a lot more matter than antimatter present in our Universe, and the Standard Model gives few hints as to why that should be, since it mostly treats matter and antimatter as functionally equivalent. A number of extensions have been proposed that do produce a matter-filled Universe, but many of them rely on a specific and peculiar idea about neutrinos.

That idea involves neutrinos being their own antiparticles. Rather than there being two distinct types of a particle, like an electron and a positron, regular and anti-neutrinos differ only in terms of their spin. The idea was first proposed back in the 1930s by Ettore Majorana, and they're called Majorana particles in his honor. But we have yet to identify any particle that displays this sort of behavior. Still, neutrinos have done so many other weird things that if you had to pick a candidate for being a Majorana particle, they'd be high on the list.

So, if we could show that neutrinos are their own antiparticles, then it would provide significant support for these extensions to the Standard Model and thus a possible explanation for our matter-dominated Universe.

The problem is that working with neutrinos (or anti-neutrinos) is extraordinarily difficult. Neutrinos only interact with matter extremely rarely—trillions pass through you every second, but you'll interact with maybe three of them in your entire life. Plus, as noted above, matter and antimatter are largely interchangeable within the Standard Model, mostly differing in terms of charge. Neutrinos aren't charged at all.

So researchers have identified a situation where nature would run the test for us. Beta decay is a type of radioactive decay that converts a neutron to a proton and releases both an electron and a neutrino in the process. There's a relatively rare type of decay, called a double-beta, in which this happens to two neutrons at once. This double-beta process would then produce two identical neutrinos.

If neutrinos are their own antiparticle, however, then these two neutrinos could still collide and annihilate. The result would be a radioactive decay that released two electrons but no neutrinos: a neutrinoless double-beta.

Rarest of the rare

So all we have to do is look for a neutrinoless double-beta decay. Sounds easy until you realize that these decays should be staggeringly rare. Theoretical predictions suggest that their half-life should be "at least 15 orders of magnitude longer than the age of the Universe," as the researchers behind the new work put it.

Of course, you can search for rare events by increasing their frequency (that's how we found neutrinos, after all). Simply adding more of an element that undergoes this sort of decay will up the odds. But improving the chances of spotting a neutrinoless double-beta decay is only half the battle. You also have to be really good at ignoring anything else that might look like one. And it's this half of the equation that is the story behind the new results.

That's because detecting the decays is the (relatively) easy part. One of the isotopes that undergoes double-beta decays is ^{76}Ge. Germanium happens to be a good semiconductor, and we make particle detectors out of semiconductors all the time (the Large Hadron Collider uses several). So, the source and the detector are one and the same in this experiment. And it's possible to enrich germanium for its radioactive isotope, increasing the probability of detection.

But if you tried to run the experiment on a typical lab bench, you'd never spot any decays because the semiconductor would be pummeled by the debris of cosmic rays hitting our atmosphere and swamped by the decay of the radioactive elements that are naturally all around us. Controlling this background noise is the big challenge.

Seeking silence

To reduce the noise, the people behind the GERmanium Detector Array (GERDA) experiment put their hardware underground in the Gran Sasso facility in Italy. This blocks much of the cosmic rays and provides the same shielding as 3,500 meters of water. But some high-energy muons from cosmic rays could still potentially get through all that rock. So the authors placed a large particle detector between their hardware and the sky, allowing them to determine when muons were coming through. Any data collected at those times is discarded.

But both the rocks and the detector hardware itself contain radioactive elements. Some of this is handled by further shielding. The entire hardware is embedded in a large tank of water that has been purified based on its isotopes, so none of the radioactive form of hydrogen is present. External particles originating outside the tank should also produce flashes of light as they bump into water molecules, so the tank has detectors to pick up these events. Again, signs of external particles cause the data collected at this time to be dumped.

The water surrounds a tank of chilled liquid argon that the detectors reside in. This serves both to chill the detector to its operating temperature and as another way of identifying background events. The argon acts like the water, in that it will emit flashes of light if particles or radiation bumps into an argon atom. So again, the argon is watched by detectors, all of them nearly a meter away from the experimental hardware, since the detectors, too, may contain radioactive elements.

The net result is that anything picked up by the experimental hardware that's not seen by any of the other detectors almost certainly originated in the experimental hardware itself. The setup is so effective, in fact, that the GERDA team thinks that, over six months of operation, not a single background event was left in the data.

Double-beta MIA

That's not to say the researchers didn't observe anything. In the data discarded due to indications of background radiation, they were able to identify peaks that correspond to radioactive potassium that was impossible to remove from the water and instruments. And, in the experimental detector itself, radioactive decays that produced neutrinos were quite common, allowing them to confirm that the hardware was working as expected.

What didn't show up were signs of a neutrinoless double-beta decay. This places a hard limit on the probability of the decay's half-life at over 10^{25} years. If neutrinos are Majorana particles, then their mass can't exceed 0.33 electronVolts. That mass is rather important, and we'll get back to it below.

If the researchers run this experiment for another few years, they expect they can up the limit to 10^{26} years. And they're thinking of expanding the experiment out to 1,000 kg of Germanium, which would let them push the limit to 10^{28} years.

Of course, all that says definitively is that the decays, if they exist, are extraordinarily rare. It's really the mass limit that becomes significant. With the large detector, the neutrino mass limit could be dropped to less than 20 milli-electronVolts. But, critically, this is not the only way we have of getting at the neutrino's mass. If the next version of GERDA sets that limit, and some other experiments tell us that neutrinos weigh more than that, then we know something's seriously wrong with the entire idea of neutrinoless double-beta decays.

Experimentalists, apparently, are patient enough that the 100-plus members of the GERDA team are willing to wait years just to provide part of a potential answer, all while knowing that the theorists will take just a few months to come up with entirely new ideas for the Standard Model if that answer eliminates the existing ones.

https://arstechnica.com/science/2017/04/latest-test-for-a-standard-model-replacement-comes-up-empty/