The Germanium Detector Array at Gran Sasso, Italy, is one of a number of experiments hunting for signs of neutrino-less double-β decay in atomic nuclei.

BETA TEST

Debate rages over whether researchers have managed to see an exceptionally rare form of radioactivity. Experiments this year should finally settle the issue.

BY EDWIN CARTLIDGE

Once every 10 trillion trillion years or so, certain atomic nuclei might just break the rules. As two of their neutrons undergo an otherwise normal decay, changing into protons and spitting out electrons, they might fail to release the normal by-products: ghostly particles called neutrinos.

To have any chance of detecting this rare 'neutrino-less double-β decay', physicists have to collect a few trillion trillion atoms of an appropriate isotope — tens or even hundreds of kilograms' worth — put their sample deep underground so that it is isolated from cosmic rays and conventional radioactivity, then spend years counting potential decay events until they are sure that any signals they see aren't noise. It is an intricate and painstaking process, but several collaborations around the world are doing it, and some could even come up with an answer by the end of the year.

A definitive sighting, says Ettore Fiorini, a particle physicist at the University of Milano-Bicocca in Italy, would be "one of the most important discoveries in physics in the past 100 years". It would mean that the charge-less, almost mass-less neutrino is its own antiparticle, making it unlike any other fundamental particle. The discovery would allow physicists to finally pin down the mass of the neutrino, and it might even help them to understand why matter exists at all (see 'Decay tactics').

But even if the decay is not seen, a definitive result would settle a controversy that has beset the neutrino-physics community since 2001, when Hans Klapdor-Kleingrothaus and his colleagues at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, claimed to have seen the phenomenon in a detector at Italy's Gran Sasso National Laboratory[1]. Many physicists think that the Heidelberg group simply mistook ordinary radioactivity for the exotic process. Even some researchers working on the experiment, including a team from the Kurchatov Institute in Moscow, didn't believe the claim and left the collaboration in protest.

But the Heidelberg group has refused to back down. That's not surprising, says Stefan Schönert, a physicist at the Technical University Munich in Germany and spokesman for another experiment at Gran Sasso, the Germanium Detector Array (GERDA). If the claim were to be confirmed, he says, "the Nobel prize would go to Klapdor-Kleingrothaus".

"There is nothing that I could point to that would say he is obviously wrong," adds Steven Elliott, a neutrino physicist at the Los Alamos National Laboratory in New Mexico. "But this is clearly a dramatic claim, so people tend to be sceptical. What we want is really hard-core proof of whether he is right or wrong."

CRYSTAL CLEAR

The challenge is how to get that proof. Nothing in this business is easy — as even the detector at the centre of the controversy demonstrated. Known as the Heidelberg–Moscow experiment, it was built from 11.5 kilograms of germanium that had been enriched to 86% germanium-76 from the natural proportion of 7%. The team chose this isotope because it is one of only about a dozen known to undergo ordinary double-β decay, so it was automatically eligible for neutrino-less decay. Germanium is also a semiconductor, which allowed the material to serve as both source and detector — any electrons emitted would deposit their energy in the surrounding crystal as an observable pulse of current.

The experiment started generating data in 1990. The researchers' first and most obvious challenge was to shield the ^{76}Ge from any background radiation that could mimic the signal. The 1,400 metres of rock lying above the Gran Sasso lab blocked out cosmic rays[2]. And the researchers screened out most of the radioactivity from the surrounding rock using thick shields of lead and copper. They also made the components of the experiment from materials that have low natural radioactivity.

Their second challenge was to distinguish between the different types of double-β decay. The half-life for neutrino-less double-β decay, assuming that it happens, was estimated at the time to be longer than 10^{22} years. The researchers therefore expected to see no more than a few thousand neutrino-less events per year in their 11.5 kilograms of ^{76}Ge; ordinary double-β decay, which at the time was thought to have a half-life in the order of 10^{20} years, would generate at least 100 times more events. And the decay products — a pair of electrons — would look identical. Any neutrinos would effectively be invisible, flying out of the detector without leaving a trace.

To identify neutrino-less decay, physicists need to measure the energy of the electrons. In ordinary double-β decay, the total energy is shared between the electrons and the neutrinos in a way that changes randomly from one decay to the next. The electron energies are therefore spread across a wide range of values. But in neutrino-less decay, the electrons take up all the energy so the energy spectrum should show a sharp peak at a single value — at 2,039 kiloelectronvolts (keV) in the case of ^{76}Ge.

That is exactly what Klapdor-Kleingrothaus and his colleagues claimed to have seen. They announced that almost 10 years of data-taking had produced a peak containing about 15 events right at the expected energy — and that there was only a 3% chance that the peak was due to a statistical fluctuation in background radiation[1]. Neutrino-less double-β decay, they claimed, had been found.

But critics — and there have been many — are not so sure. Their biggest concern is that the team did not adequately account for the multitude of other peaks in the data, most of which are from background radioactivity that no experiment can ever fully screen out.

In 2002, Elliott and 25 other physicists said as much in a letter[3] to *Modern Physics Letters A*, the journal that had published the result. They weren't convinced, for instance, that the Heidelberg researchers had correctly attributed some of the peaks to bismuth-214 in the rocks surrounding the lab and in the detector components. And if the team couldn't prove that, the critics said, then how could it claim to know what caused the feature at 2,039 keV?

The Heidelberg group's response was to collect another three years' data, taking extra care in the measurement and identification of the bismuth-214 peaks[4]. The researchers also tracked every surge of energy that was deposited in their detector, measuring the rise and fall of the electrical current over several hundred nanoseconds. At that timescale, the energy released in both ordinary and neutrino-less double-β decay should form a single pulse, whereas background radioactivity tends to generate multiple pulses, making it easier to distinguish signals from background.

ENRICO SACCHETTI

The components of the Germanium Detector Array are made from materials with low radioactivity.

This analysis eliminated much of the background noise, as well as four of the events in the 2,039 keV peak, but allowed the team to claim a greatly improved statistical significance for the remaining 11 events. In 2006, the researchers announced[4] that the peak was consistent with a half-life of 2.2×10^{25} years for neutrino-less double-β-decay in ^{76}Ge, and with a neutrino mass of about 0.3 eV. "There is a signal at the right energy and we show that the events in the signal are of single-site nature," says Klapdor-Kleingrothaus, referring to the single-pulse energy deposit. "More than that you cannot do."

Sceptics remain unconvinced; arguments still rage about whether the background radiation had been properly accounted for. But the experiment was closed down in November 2003, and no other double-β-decay detector had the sensitivity to test the team's conclusions. Only now has a new generation of experiments begun to reach that level.

Perhaps the one that has come closest is EXO, the Enriched Xenon Observatory, which is about 650 metres underground at the US Department of Energy's Waste Isolation Pilot Plant in Carlsbad, New Mexico. EXO is looking for neutrino-less double-β decay in 200 kilograms of liquid xenon enriched in xenon-136. Last month, collaboration member Jacques Farine of Laurentian University in Sudbury, Canada, told delegates at the Neutrino 2012 conference in Kyoto, Japan, that the experiment had seen no evidence of the neutrino-less decay in data collected between September 2011 and April 2012. The finding[5], the collaboration says, amounts to "the almost complete refutation" of the Heidelberg claim.

Or maybe not. EXO used a different isotope from that used in the Heidelberg–Moscow experiment, and there is considerable uncertainty about how the different nuclear structures affect the rates of neutrino-less double-β decay. This gives the Heidelberg team wiggle room even if the negative results continue at EXO, and at two other competing experiments: the KamLAND-Zen project in the kilometre-deep Kamioka mine in Japan, which also uses ^{136}Xe, and the Cryogenic Underground Observatory for Rare Events (COURE) detector in Gran Sasso, which uses tellurium-130.

But there would be no such wiggle room if GERDA were also to see nothing. GERDA uses the same sample of enriched germanium that was monitored in the Heidelberg–Moscow experiment, as well as some similarly enriched material salvaged from the International Germanium Experiment, which was operated by a collaboration of US, Russian, Spanish and Armenian physicists at the Canfranc Underground Laboratory under the Pyrenees Mountains in the 1990s. GERDA has much lower levels of background events than its predecessor, Schönert says, partly because the materials close to the germanium are purer, so it will quickly equal and then surpass the Heidelberg–Moscow experiment's sensitivity. Having started up in November 2011, it should have acquired enough data to "rule Klapdor-Kleingrothaus in or out" by late 2012 or early 2013, he says.

MATTER OF SCALE

But even a negative result from GERDA would not necessarily kill the idea. It could simply mean that the decay is rarer than the Heidelberg group claimed — in which case researchers will need much bigger detectors to identify it. Michel Sorel, a physicist at the Spanish National Research Council in Valencia, and physics coordinator of the Neutrino Experiment with a Xenon Time Projection Chamber (NEXT) detector in the Canfrac laboratory, estimates that several tonnes of material could be needed. A number of the existing collaborations are planning to upgrade their detectors to reach the multi-tonne scale, but Sorel believes that the cost of building them — US$100 million to $200 million each — means that only one such experiment is ever likely to be realized.

In the meantime, however, Sorel is eager to see the Heidelberg claim tested with the existing detectors. "Most of the community was against the claim and probably still is," he says. "But people take it seriously and that is why germanium experiments like GERDA were built."

Verification of the Heidelberg claim would be "fantastic", Schönert says, because experiments could then be dedicated to investigating the mechanisms behind neutrino-less double-β decay. Physicists know that one mechanism is a 'virtual' neutrino that leaps from one neutron to the other too quickly for them to observe. But another might be one of the long-sought 'supersymmetrical' particles that physicists have hypothesized as extensions to the standard model of particles and forces.

The important thing now, says Schönert, is that physicists working on double-β-decay experiments keep their competitive streaks in check. "It is not important who rules out or confirms Klapdor-Kleingrothaus first," he insists, "but that the data are of high quality. We have to try and keep to the spirit of the community, and not be the loudest shouter." ■

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2. Nosengo, N. *Nature* **485,** 435–438 (2012).
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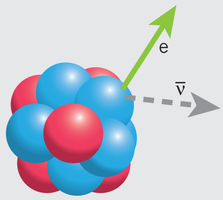
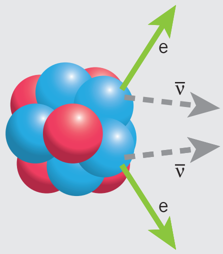
DECAY TACTICS

The three types of β decay and why they matter.



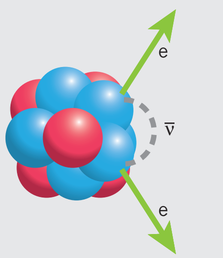
Standard β decay

This phenomenon occurs when a neutron (blue) spontaneously emits an electron (green arrow) and an antineutrino (grey arrow) and turns into a proton (red). For neutrons that roam freely outside a nucleus, the half-life for this process — the time needed for half the neutrons to decay — is about 10 minutes. But for neutrons in unstable nuclei, the half-life can be just a few thousandths of a second.



Double-β decay

This process occurs in some otherwise stable nuclei that contain even numbers of neutrons and protons. These isotopes become even more stable when two of their neutrons simultaneously convert into protons, emitting two electrons and two antineutrinos. This process was first observed in 1987. Its half-life varies from one isotope to the next, but is at least 10^{18} years.



Neutrino-less double-β decay

The 'neutrino-less' form of double-β decay is theoretically possible in the same nuclei if the two emitted antineutrinos can annihilate one another (grey curve), so that neither can escape to the outside. Technically the description should be 'antineutrino-less', but the terms neutrino and antineutrino are often used interchangeably. The half-life for this process is at least 10^{25} years.

Massive solutions

A confirmed observation of neutrino-less double-β decay would have large implications for particle physicists. For example, the annihilation is possible only if neutrinos and antineutrinos are the same particle. This would make the neutrino the first example of a 'Majorana' particle, named after the Italian physicist Ettore Majorana, who predicted its existence in the 1930s. In addition, the emission of two electrons with no balancing antineutrinos would violate a symmetry principle known as the conservation of lepton number. That, in turn, could help researchers to come up with theories beyond the 'standard model' of elementary particles.

The discovery would provide the first direct measurement of a neutrino's mass, which can be determined from the decay's half-life. Experiments have shown that the mass must be larger than zero, but have not been able to calculate its absolute value. Knowing the mass would help astronomers to work out how primordial neutrinos influenced galaxy formation. Galaxies formed from clumps of heavy, slow-moving particles that started drawing together as a result of their mutual gravity almost immediately after the Big Bang. But neutrinos move at close to the speed of light, so they would have remained a near-uniform haze that would have slowed down this accretion, thanks to the combined gravity of all those tiny masses. The more mass that neutrinos have, the slower that galaxies would have formed.

Finally, the discovery could help physicists to understand why the Universe seems to be made up almost entirely of matter, even though equal amounts of antimatter were presumably created at the time of the Big Bang. The idea is that in the early Universe, particles had a slight preference for decaying into matter over antimatter, and, because matter and antimatter annihilate each other, that would have left only matter. Those particles — much heavier partners of the neutrino — could exist only if neutrinos are Majorana in nature. **E.C.**