



Underground neutrino experiment sets the stage for deep discovery about matter

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If equal amounts of matter and antimatter had formed in the Big Bang more than 13 billion years ago, one would have annihilated the other upon meeting, and today's universe would be full of energy but no matter to form stars, planets and life. Yet matter exists now. That fact suggests something is wrong with Standard Model equations describing symmetry between subatomic particles and their antiparticles. In a study [published](#) in *Physical Review Letters*, collaborators of the MAJORANA DEMONSTRATOR, an experiment led by the Department of Energy's Oak Ridge National Laboratory, have shown they can shield a sensitive, scalable 44-kilogram germanium detector array from background radioactivity.

This accomplishment is critical to developing and proposing a much larger future experiment—with approximately a ton of detectors—to study the nature of neutrinos. These electrically neutral particles interact only weakly with matter, making their detection exceedingly difficult.

“The excess of matter over antimatter is one of the most compelling mysteries in science,” said John Wilkerson of ORNL and the University of North Carolina, Chapel Hill. Wilkerson leads the MAJORANA DEMONSTRATOR, which involves 129 researchers from 27 institutions and 6 nations. “Our experiment seeks to observe a phenomenon called ‘neutrinoless double-beta decay’ in atomic nuclei. The observation would demonstrate that neutrinos are their own antiparticles and have profound implications for our understanding of the universe. In addition, these measurements could provide a better understanding of neutrino mass.”

In a 2015 report of the U.S. Nuclear Science Advisory Committee to the Department of Energy and the National Science Foundation, a U.S.-led ton-scale experiment to detect neutrinoless double-beta decay was deemed a top priority of the nuclear physics community. Nearly a dozen [experiments have sought neutrinoless double-beta decay](#), and as many future experiments have been proposed. One of their keys to success depends on avoiding background that could mimic the signal of neutrinoless double-beta decay.

That was the key accomplishment of the MAJORANA DEMONSTRATOR. Its implementation was completed in South Dakota in September 2016, nearly a mile underground at the [Sanford Underground Research Facility](#). Siting the experiment under nearly a mile of rock was the first of many steps collaborators took to reduce

interference from background. Other steps included a cryostat made of the world's purest copper and a complex six-layer shield to eliminate interference from cosmic rays, radon, dust, fingerprints and naturally occurring radioactive isotopes.

"If you're going to search for neutrinoless double-beta decay, it's critical to know that radioactive background is not going to overwhelm the signal you seek," said ORNL's David Radford, a lead scientist in the experiment.

There are many ways for an atomic nucleus to fall apart. A common decay mode happens when a neutron inside the nucleus emits an electron (called a "beta") and an antineutrino to become a proton. In two-neutrino double-beta decay, two neutrons decay simultaneously to produce two protons, two electrons and two antineutrinos. This process has been observed. The MAJORANA Collaboration seeks evidence for a similar decay process that has never been observed, in which no neutrinos are emitted.

Conservation of the number of leptons—subatomic particles such as electrons, muons or neutrinos that do not take part in strong interactions—was written into the Standard Model of Physics. "There is no really good reason for this, just the observation that it appears that's the case," said Radford. "But if lepton number is not conserved, when added to processes that we think happened during the very early universe, that could help explain why there is more matter than antimatter."

Many theorists believe that the lepton number is not conserved, that the neutrino and the antineutrino—which were assumed to have opposite lepton numbers—are really the same particle spinning in different ways. Italian physicist Ettore Majorana introduced that concept in 1937, predicting the existence of particles that are their own antiparticles.

The MAJORANA DEMONSTRATOR uses germanium crystals as both the source of double-beta decay and the means to detect it. Germanium-76 (Ge-76) decays to become selenium-76, which has a smaller mass. When germanium decays, mass gets converted to energy that is carried away by the electrons and the antineutrinos. "If all that energy goes to the electrons, then none is left for neutrinos," Radford said. "That's a clear identifier that we found the event we're looking for."

The scientists distinguish two-neutrino versus neutrinoless decay modes by their energy signatures. "It's a common misconception that our experiments detect neutrinos," said Jason Detwiler of the University of Washington, who is a co-spokesperson for the MAJORANA Collaboration. "It's almost comical to say it, but we are searching for the *absence* of neutrinos. In the neutrinoless decay, the released energy is always a particular value. In the two-neutrino version, the released energy varies but is always smaller than for neutrinoless double-beta decay."

The MAJORANA DEMONSTRATOR has shown that the neutrinoless double-beta decay half-life of Ge-76 is at least 10^{25} years—15 orders of magnitude longer than the age of the universe. So it's impossible to wait for a single germanium nucleus to decay. "We get around the impossibility of watching one nucleus for a long time by instead watching on the order of 10^{26} nuclei for a shorter amount of time," explained co-spokesperson Vincente Guiseppe of the University of South Carolina.

Chances of spotting a neutrinoless double-beta decay in Ge-76 are rare—no more than 1 for every 100,000 two-neutrino double-beta decays, Guiseppe said. Using detectors containing large amounts of germanium atoms increases the probability of spotting the rare decays. Between June 2015 and March 2017, the scientists observed

no events with the energy profile of neutrinoless decay, the process that has not yet been observed (this was expected given the small number of germanium nuclei in the detector). However, they were encouraged to see many events with the energy profile of two-neutrino decays, verifying the detector could spot the decay process that has been observed.

The MAJORANA Collaboration's results coincide with new results from a competing experiment in Italy called GERDA (for GERmanium Detector Array), which takes a complementary approach to studying the same phenomenon. "The MAJORANA DEMONSTRATOR and GERDA together have the lowest background of any neutrinoless double-beta decay experiment," said Radford.

The DEMONSTRATOR was designed to lay the groundwork for a ton-scale experiment by demonstrating that backgrounds can be low enough to justify building a larger detector. Just as bigger telescopes collect more light and enable viewing of fainter objects, increasing the mass of germanium allows for a greater probability of observing the rare decay. With 30 times more germanium than the current experiment, the planned one-ton experiment would be able to spot the neutrinoless double-beta decay of just one germanium nucleus per year.

The MAJORANA DEMONSTRATOR is planned to continue to take data for two or three years. Meanwhile, a merger with GERDA is in the works to develop a possible one-ton detector called [LEGEND](#), planned to be built in stages at an as-yet-to-be-determined site.

LEGEND 200, the LEGEND demonstrator and step towards a possible future ton-scale experiment, will be a combination of GERDA, MAJORANA and new detectors. Scientists hope to start on the first stage of LEGEND 200 by 2021. A ton-scale experiment, LEGEND 1000, would be the next stage, if approved. "This merger leverages public investments in the MAJORANA DEMONSTRATOR and GERDA by combining the best technologies of each," said LEGEND Collaboration co-spokesperson (and long-time MAJORANA spokesperson up until last year) Steve Elliott of Los Alamos National Laboratory.

The title of the *Physical Review Letters* paper is "Search for Neutrinoless Double Beta Decay in ^{76}Ge with the MAJORANA DEMONSTRATOR."

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