Neutrino experiments look to reveal big answers about how these fundamental particles interact with matter

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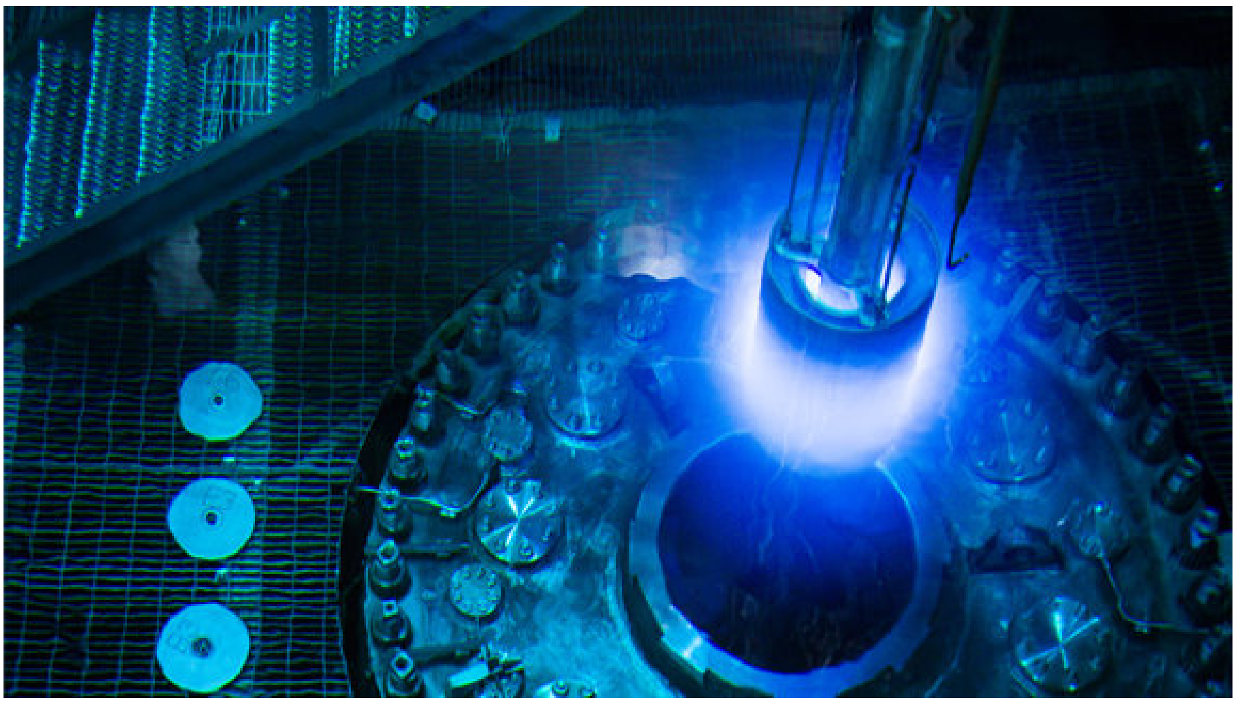


The High Flux Isotope Reactor (HFIR), a DOE user facility at Oak Ridge National Laboratory, provides antineutrinos for the PROSPECT experiment. This photo shows the process of refueling HFIR. Credit: US Department of Energy

Except in horror movies, most scientific experiments don't start with scientists snooping around narrow, deserted hallways. But a tucked-away location in the recesses of the Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL) provided exactly what Yuri Efremenko was looking for.

Efremenko, an ORNL researcher and University of Tennessee at Knoxville professor, is the spokesperson for the COHERENT experiment, which is studying neutrinos. The team uses five particle detectors to identify a specific interaction between neutrinos and atomic nuclei. The most abundant particles in the universe, neutrinos are extremely light and have no electric charge. They interact very little with other particles. In fact, trillions pass through the Earth every second, leaving no impression. Needless to say, they're notoriously difficult to detect.

At first, the team surveyed a bustling area near the Spallation Neutron Source (SNS), a DOE Office of Science user facility at ORNL in Tennessee. The neutrons the SNS produces drive 18 different instruments that surround the SNS like spokes on a wheel. The SNS also produces neutrinos, which fly off in all directions from the particle accelerator's target. But putting the neutrino detectors on the same floor as the SNS would expose the devices to background particles that would increase uncertainties.

"We were really fortunate to go into the basement one day," said David Dean, ORNL's Physics Division Director. After moving some water barrels to the side and conducting background tests, they were in business. The basement location would protect the machines from exposure to background particles. Once scientists installed the experiment's detectors, they nicknamed the hallway "Neutrino Alley."

The experiment, called COHERENT, poses a stark contrast to most other neutrino experiments. To catch a glimpse of these miniscule particles, most experiments use incredibly large machines, often in remote locations. One is located at the South Pole, while another shoots neutrino beams hundreds of miles to a far detector. Besides its mundane location, COHERENT's main detector is barely bigger than a milk jug. In fact, it's the smallest working neutrino detector in the world.

But COHERENT and a sister experiment at ORNL, PROSPECT, are showing that neutrino experiments don't have to be enormous to make big discoveries. These two modest experiments supported by DOE's Office of Science are poised to fill some major gaps in our understanding of this strange particle.

The Mysteries of the Neutrino

While neutrinos are some of the smallest particles in the universe, investigating them may reveal massive insights.

"Neutrinos tell us a tremendous amount about how the universe is created and held together," said Nathaniel Bowden, a scientist at DOE's Lawrence Livermore National Laboratory and co-spokesperson for PROSPECT. "There's no other way to answer a lot of the questions that we find ourselves having." Understanding how neutrinos interact may even help us understand why matter—and everything made out of it—exists at all.

But neutrinos haven't made answering these questions easy. There are three different types of neutrinos, each of which behaves differently. In addition, they change type as they travel. Some scientists have proposed a not-yet-seen particle called the sterile neutrino. Physicists theorize that if sterile neutrinos exist, they would interact with other particles even less than regular ones do. That would make them nearly impossible to detect.

But that's a big "if." A sterile neutrino would be the first particle not predicted by the Standard Model, physicists' summary of how the universe functions.

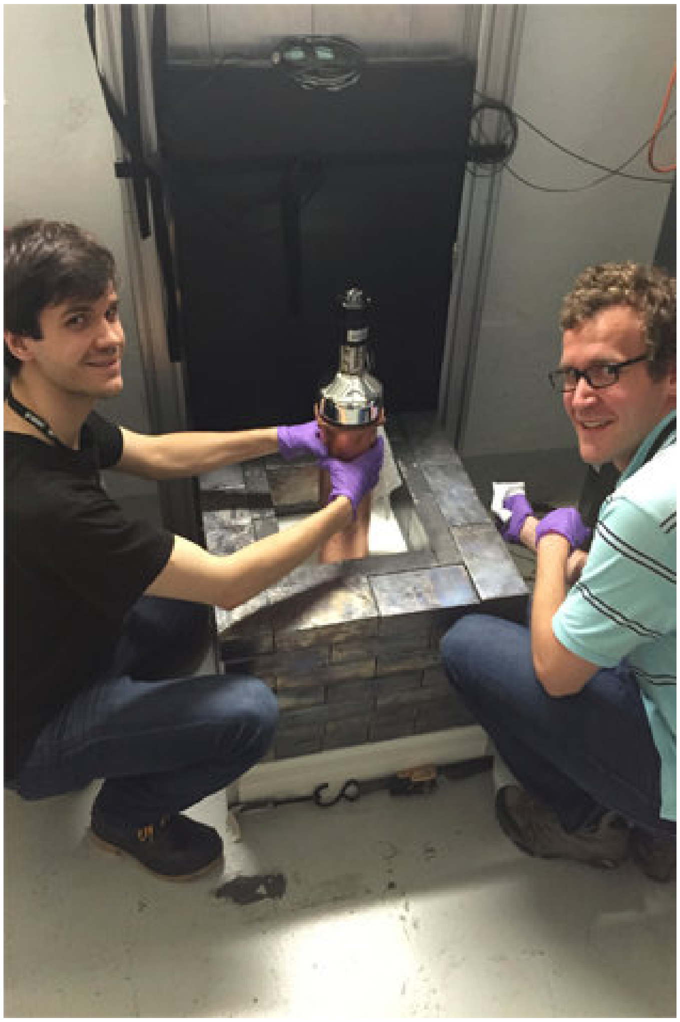
"Neutrinos may hold the clue to discovering particle physics beyond the Standard Model," said Karsten Heeger, a Yale University professor and co-spokesperson for PROSPECT.

Searching for a Coherent Answer with COHERENT

A team of scientists from ORNL, other DOE national laboratories, and universities designed the COHERENT experiment to identify a specific interaction between neutrinos and nuclei. While physicists had predicted this interaction more than 40 years ago, they had never detected it.

Most neutrinos only interact with individual protons and neutrons. But if a neutrino's energy is low enough, it should interact with an entire nucleus rather than its individual parts. Theorists proposed that when a low-energy neutrino approaches a nucleus, the two particles exchange an elementary particle called a Z boson. As the neutrino releases the Z boson, the neutrino bounces away. As the nucleus receives the Z boson, the nucleus recoils slightly. That interaction is called coherent elastic neutrino-nucleus scattering.

Because most nuclei are much bigger than individual protons or neutrons, scientists should see this type of interaction more frequently than interactions driven by higher energy neutrinos. By "seeing" the tiny recoil energy, COHERENT's gallon-sized detectors make it possible for scientists to study neutrino properties.



Bjorn Scholz (left) from the University of Chicago and Grayson Rich of the University of North Carolina at Chapel Hill and the Triangle Universities Nuclear Laboratory show off the world's smallest neutrino detector, which is part of the COHERENT experiment. Credit: US Department of Energy

"It's kind of cool that you could actually see an interaction of neutrinos with something you can hold in your hand," said Kate Scholberg, a Duke University professor and collaborator on COHERENT.

But none of this would be possible without ORNL's SNS. The neutrinos the SNS produces pass through concrete and gravel to reach ORNL's basement. They have just the right energy to induce this particular interaction. The SNS's pulsed beam also allows scientists to filter out background "noise" from other particles.

"There's quite a flux of neutrinos that was being wasted, at the SNS, so to speak. It is the perfect source for coherent scattering—the cat's pajamas," said Juan Collar, a University of Chicago professor and collaborator on COHERENT.

After running for 15 months, COHERENT caught neutrinos in the act of handing off Z bosons 134 times.

Looking over his graduate student's shoulder as he crunched the data, Collar was thrilled to see that the results came out exactly as expected. "When we finally looked at the processed, full dataset, we went 'wheeeeeee!'" he said.

Measuring this phenomenon – neutrino-nucleus elastic scattering – gives physicists a new and versatile tool to understand neutrinos.

"It's opened our window to look for the physics beyond the Standard Model," said Efremenko.

Using this interaction, scientists may be better able to understand how supernovae explode and produce neutrinos.

While these detectors are mainly used for fundamental research, their tiny size could also be useful for other applications. Nuclear reactors produce different types and amounts of neutrinos, depending on whether they produce energy or weapons-grade material. A detector as small as COHERENT's could make the effort to monitor nuclear facilities much easier.

Finding Precision with PROSPECT

While COHERENT looked for a specific phenomenon, the PROSPECT experiment will focus on making incredibly precise measurements of neutrinos from a nuclear reactor as they change type. Past nuclear reactor experiments have resulted in measurements that depart from theory. The PROSPECT team has designed an experiment that can explore any discrepancies, eliminate possible sources of error, or even discover the sterile neutrino.

Compared to previous neutrino reactor experiments, PROSPECT will be able to more accurately measure the number and type of neutrinos, the distance they travel from the reactor, and their energy. PROSPECT differs from other experiments in that its detector has multiple sections instead of one single chamber. This allows scientists to measure and compare various neutrino oscillation lengths – that is, how far from the reactor neutrinos are changing type.

If sterile neutrinos exist, this detector design may also enable scientists to observe regular neutrinos transitioning into sterile neutrinos. In theory, this new form of neutrinos should appear at a specific distance from the detector core.

The High Flux Isotope Reactor (HFIR), a DOE Office of Science user facility at ORNL, will provide PROSPECT with its neutrinos. Commercial nuclear reactors use a variety of uranium and plutonium fuels with different combinations of isotopes. This results in a broad spectrum of neutrino energies. That makes it difficult to pinpoint which isotopes are producing which neutrinos. As a research reactor, HFIR only uses one isotope of uranium: uranium-235. By measuring the antineutrinos from that single isotope, the PROSPECT team can better understand how all nuclear reactors produce neutrinos.

Scientists in the PROSPECT collaboration recently finished building a detector at Yale University's Wright Laboratory. While the active detector region is much bigger than COHERENT's milk-jug sized detector, it's still only four feet wide and weighs about five tons. Compared to detectors that weigh thousands of tons, this experiment too runs on the small side. Once PROSPECT is completed and in place, it will take data for three years.

While these experiments seem miniature in comparison to others, they could reveal answers about neutrinos that have been hiding from physicists for decades. It may just be a matter of scientists knowing where and how to look, even if that's down a seemingly ordinary storage hallway.

Provided by US Department of Energy

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