
ν_e
ν_τ
ν_μ

A neutrino appearance experiment:

NOνA

Many mysteries of the neutrino could be answered by a proposed additional detector for the Illinois-to-Minnesota neutrino beam. By Kendra Snyder

Deep in the woods of Minnesota, close to the Canadian border, particle physicists hope to construct the next neutrino experiment on a secluded piece of land, fit for studying a lightweight particle that was, itself, once ignored. "As a graduate student, I was taught that neutrinos had zero mass," says Fermilab particle physicist John Cooper. "We now know that's not true, and it makes me wonder what else there is to find out about them."

The proposed project is meant to reveal what no other neutrino experiment has found so far. The plan: build a detector 51 feet tall, 51 feet wide, and 429 feet long, longer than a football playing field; fill it with 24,000 tons of scintillator oil, delivered by a tanker truck three days a week for two years; and send neutrinos 810 km through the earth from Fermilab to the massive detector at close to the speed of light. The result: the NuMI Off-axis ν_e (electron neutrino) Appearance experiment (NOνA). "What we're trying to understand are the most fundamental things about these particles: ordering of the masses and how the weak interactions treat these particles," says Gary Feldman, a Harvard physicist and co-spokesman for the NOνA experiment. "A great deal of effort has gone into determining the analogous properties of quarks. Now it's time to do that with neutrinos."

There are three types of neutrinos in nature, found to morph from one form to another as they travel unimpeded through the universe. Scientists have observed two of these oscillations, and NOνA is seeking another, in which muon-type neutrinos switch to electron-type neutrinos. A crucial quantity related to this oscillation—known as the mixing angle θ_{13} (pronounced "theta-one-three")—has not yet been measured, but theoretical models predict

Physicists examine the disappearance and appearance of the three types of neutrinos to understand the phenomenon of neutrino oscillations. The NOνA experiment will count how many muon neutrinos (ν_μ) leaving Fermilab will appear as electron neutrinos (ν_e) in Minnesota.

Photos: Sandbox Studio

that it is nonzero. No existing experiment has the ability to measure θ_{13}, and with good experimental sensitivity for a large range of θ_{13} values, NOνA would team up with experiments around the world in providing the answer.

Once θ_{13} is measured, NOνA scientists would attempt to order the three known neutrinos from least to most massive, a hierarchy not yet known. Ultimately, experimenters hope to shed light on one of the most tantalizing of physics questions: What happened to the universe's antimatter? The big bang should have created equal amounts of matter and antimatter, yet today, there is only matter. Some scientists believe that this puzzling phenomenon is tied to the properties of neutrinos.

Switching identities

Neutrinos are neutral particles that switch among three flavors: electron, muon, and tau. Electron-type neutrinos from the sun change to muon- and tau-type neutrinos. Muon-type neutrinos produced by cosmic rays in the Earth's atmosphere oscillate to tau-type neutrinos. Some scientists believe there is at least one more type of neutrino oscillation: the switch of muon-type neutrinos to electron-type neutrinos, characterized by θ_{13}.

NOνA would look for that oscillation by using Fermilab's NuMI beamline, which sends neutrinos straight through the ground 735 km from Fermilab to the Soudan mine in northern Minnesota. There, half a mile underground, Fermilab's Main Injector Neutrino Oscillation Search detector (MINOS) takes data to verify atmospheric neutrino oscillations and attempts to make a low-sensitivity measurement of θ_{13}. But the NuMI beam doesn't stop there: its neutrinos continue beyond Soudan, exiting the Earth's surface, with some passing through the proposed NOνA site. Like MINOS, NOνA would be a two-detector experiment, with a small near detector on the Fermilab site. The NOνA far detector, however, would be positioned 12 km off the NuMI beam axis instead of directly on the beam.

MINOS studies the disappearance of muon neutrinos as they travel from Fermilab to Soudan, while NOνA would look for the appearance of electron neutrinos with a detector system much more sensitive than that of MINOS. Although the MINOS experiment might be able to detect a few electron neutrinos, the NOνA far detector would provide more neutrino events in the energy range in which the oscillation takes place and fewer background events than the MINOS experiment says Cooper, NOνA project manager and co-spokesman. "If you're far enough away and just the right direction off-axis, then you're sitting at just the right energy to observe an oscillation of a muon-type neutrino to an electron-type neutrino," he says.

A massive issue

By comparing the types of neutrinos at the NOνA near detector with the far detector, scientists can determine if a muon- to electron-neutrino oscillation takes place. If a sufficient signal for electron-type neutrino appearance is seen, NOνA scientists might be able to order the three neutrino masses. There are two possible neutrino mass hierarchies, called normal and inverted.

"One could assume that the electron neutrino has the lowest mass, but maybe that's not true," Cooper says. "You never know anything in this business until you measure it."

Understanding the mass ordering of neutrinos is a key to understanding physics at extremely high energies. The mass ordering can only be determined by electron neutrinos crossing through the earth and interacting with atoms in the ground (the "matter effect"), which is not seen with muon and tau neutrinos. The farther the electron neutrinos have to travel, the larger this matter effect becomes. If a muon to electron neutrino oscillation is seen, scientists would run a beam of antineutrinos, the antiparticles of neutrinos that also have a small mass and no charge. They would then compare the antineutrino events seen in the far detector to the neutrino events. If the normal mass ordering is right, NOνA scientists would expect to see an enhancement of neutrinos and a suppression of antineutrinos. The opposite would be true if the inverted mass ordering is correct.

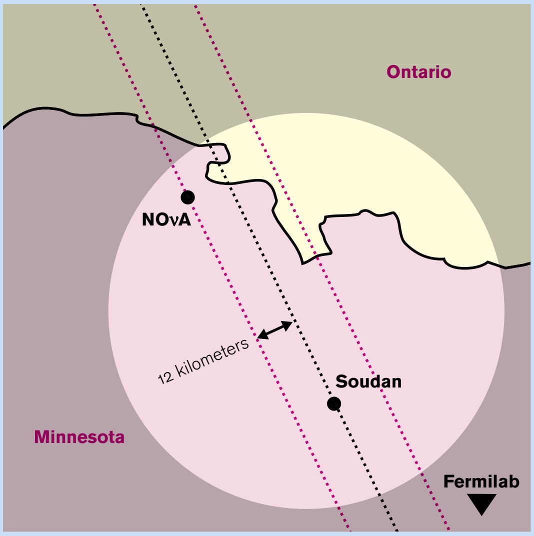
Antimatter disappearance

One ultimate question NOνA scientists hope to answer is why there is only matter in the universe, even though the big bang should have created an equal amount of antimatter. For the antimatter to have disappeared, creating this asymmetry, matter and antimatter must behave differently, says Fermilab theorist Boris Kayser. "Do neutrinos couple to particles of matter differently than they do to particles of antimatter?" Kayser asks. "And could it be that the difference is somehow behind the asymmetry we see in the universe today?"

Some scientists believe the light neutrinos we observe are naturally paired with neutrinos that are too heavy to be made in a particle physics laboratory, but were abundant after the big bang. In this theory, referred to as the "seesaw scenario," both the light and heavy neutrinos are identical to their antiparticles, Kayser says. But when the heavy neutrinos decayed in the early universe, they perhaps had a different probability for making matter than antimatter, a property called CP violation. Scientists can't look for that CP violation directly in today's laboratories because "there isn't enough 'oomph' in our accelerators," Kayser says. However, light neutrinos can be studied for this behavioral difference.

NuMI beamline

Detailed map



In order for the three-neutrino world to violate CP, all three mixing angles have to be nonzero, the last unknown being θ_{13}. "We need that number to be nonzero, please," Kayser says. "If it's zero and there are only three neutrinos, there's no CP violation in neutrino oscillation." If θ_{13} is nonzero, then experiments can determine the ordering of neutrino masses and scientists can begin to understand how neutrinos helped shape the universe as we know it.

Other searches

NOνA isn't alone in the search for θ_{13}. In Japan, the T2K experiment will study an off-axis neutrino beam, sent 295 km from the Japan Proton Accelerator Research Complex (JPARC) to the SuperKamiokande detector. Data collection is expected to start at the end of the decade. A third-generation experiment, increasing the JPARC intensity and building a new, more massive detector, is also under discussion. In Europe, scientists are discussing an experiment using a proposed CERN facility called the Superconducting Proton Linac (SPL). It would provide both a conventional neutrino beam, and a beam based on the decay of accelerated ions, over a 130 km baseline to a detector in the Fréjus tunnel between France and Italy.

However, none of these experiments would have a sufficiently long baseline to resolve the ordering of the neutrino mass states without NOνA data, Feldman says. Longer baselines equate to larger matter effects and better detection. "Only the long baseline from NOνA will give the answer," Feldman says. But because there are multiple unknown parameters in NOνA's search—including θ_{13}, the ordering of the mass states, and the parameters that measure CP violation—NOνA might only provide all the answers sought by combining its results with those from JPARC, CERN, or an experiment measuring neutrinos emitted by nuclear reactors. "All these experiments are difficult and they're difficult in different ways," Kayser says. "If you're doing something difficult, you want to try to go about it in several ways. You can use method number two to check that you were not fooled in method number one."

The path to approval

After a review in April 2005, Fermilab management approved the NOνA experiment. Now, the proposal is under discussion by two Department of Energy advisory panels. The Neutrino Scientific Assessment Group and the Particle Physics Project Prioritization Panel will decide if and how NOνA fits into the next decade of particle physics experiments. Then conceptual, technical, and budgetary plans must get DOE review and approval. If a final independent review is passed, the project will get the official go-ahead. Scientists hope for a project start in October 2007 with the full detector constructed by July 2012, ready to collect data for five years.

The NOνA collaboration includes more than 130 people from 30 institutions, but Cooper says it needs more people to handle what could be a revolutionary experiment: unlocking the secrets of the neutrinos. Says Kayser: "Neutrinos are a billion times more abundant than the elementary particles of which we're made. So clearly, if you want to understand the universe, you have to understand the neutrinos."