VIEWPOINT

Ghostly Neutrino Comes into Sharper Focus

The first results from the NOvA experiment set new constraints on charge-parity violation in neutrinos and on the ordering of neutrino masses.

by Joshua B. Spitz*

The neutrino may be tiny, at least according to the Italian meaning of its name ("little neutral one"), but it had an enormous impact across multiple aspects of our Universe. For one, the properties of the neutrino, including mass, influenced the formation of the large-scale structure of the Universe. In addition, if neutrinos behave differently than antineutrinos—that is, if they violate charge-parity symmetry (*CP*)—neutrinos may be partially responsible for the dominance of matter over antimatter. The NOvA neutrino experiment has now released its first measurement of muon neutrinos oscillating into electron neutrinos. The results pose constraints on two great mysteries in physics: the level of *CP* violation in neutrinos and the ordering of the neutrino masses.

Takaaki Kajita and Arthur McDonald were awarded the 2015 Physics Nobel Prize for finding that one type, or flavor, of neutrino can change into another type. This mixing implies that neutrinos have a small mass. This turns out to be a big deal, since neutrinos outnumber electrons, protons, and neutrons in today's Universe by a factor of $\sim 10^{10}$. Among other things, the nonzero mass of the neutrino influenced the formation of galaxies and galactic clusters that set the structure of the Universe; the leptogenesis mechanism, occurring just a tiny fraction of a second after the big bang, which is the likely cause of matter dominance in today's Universe; and the process by which heavy elements are produced in core-collapse supernovae. Neutrino mixing is also crucial for interpreting solar neutrino measurements, which provide a window on the fusion reactions in stars.

Now that we know neutrinos mix and have mass, what's next? Our current challenges are to fully elucidate neutrino mass (for instance, by determining how the neutrino obtains mass and what its value is) and to understand how the quantum-mechanical mixing happens. This information, in turn, can help us understand the neutrino's contribution to astrophysical and cosmological processes. While there is

*Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

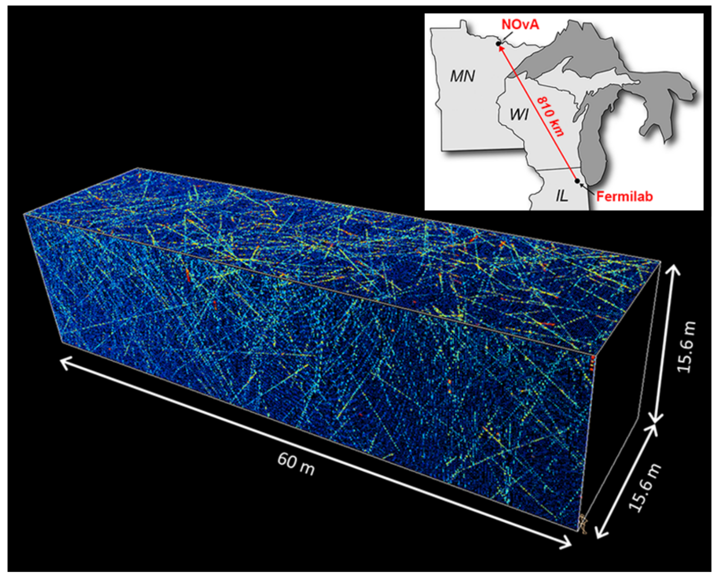

Figure 1: (Inset) Scheme of the NOvA beam line. A neutrino beam, generated at the Fermilab accelerator complex, propagates 810 km through the Earth to reach the 14-kiloton "far detector" in northern Minnesota. (Main) NOvA data recorded in the far detector volume for 5 milliseconds, showing thousands of cosmic-ray particle tracks. (NOvA)

much left to be understood, it is clear that the three flavors of neutrinos (electron, muon, and tau) mix among each other according to a set of rules. Given a neutrino path length and energy, these rules, and the parameters on which they depend, specify the probability for a neutrino of one flavor to change into another flavor. However, some of these parameters, such as the degree of *CP* violation, are poorly known.

The NOvA experiment explores neutrino mixing by investigating what happens to a beam of muon neutrinos after traveling a distance of 810 km (see Fig. 1, inset). This beam line—the longest of its kind to date—originates at the Fermilab accelerator complex in Batavia, Illinois. There, a "near detector" samples and characterizes the neutrino beam shortly after it's generated to determine the beam composition before the neutrinos mix. The beam then takes an 810-km journey through Earth to reach, after 2.7 milliseconds, the 14-kiloton NOvA "far detector" in Ash River, Minnesota. Such a long trip provides the neutrinos enough time to mix before the far detector (Fig. 1) samples the beam again.

NOvA's far detector observed six electron neutrinos originating from the initial beam of muon neutrinos, whereas only 0.99 ± 0.11 events would be expected in the absence of mixing [1]. This appearance of electron neutrinos (3.3σ above background) is indicative of muon neutrinos oscillating into electron neutrinos. This measurement is not the first of its kind, which uses long-baseline, accelerator-based neutrinos, and the results are not unexpected, based on recent observations that the mixing is large at this distance and energy scale [2–6]. However, the NOvA experiment provides a unique window on the process, mainly thanks to the design and size of the far detector, the intensity of the neutrino beam, and the length of the beam line.

By measuring how muon neutrinos change into electron neutrinos, NOvA is sensitive to the two main unknown aspects of neutrino mixing, namely, the mass ordering of the three neutrino states and whether neutrinos mix differently than antineutrinos. The first, which is referred to as the "neutrino mass hierarchy," is described as a binary number: the mass states are either ordered in a "normal" way (mass state 1, dominated by the electron flavor, is the lightest) or an "inverted" way (mass state 3, dominated by muon and tau flavors, is the lightest). The second, quantified as a parameter known as the neutrino *CP* violating phase (δ_{CP}), is a number between 0 and 2π.

Both the mass hierarchy and δ_{CP} affect neutrino oscillations and thus the NOvA signals. For example, the highest number of electron-neutrino events is expected for the case of a normal mass hierarchy and a value of δ_{CP} around $3\pi/2$. NOvA's measurement of the appearance of electron neutrinos, whose number is on the high end of what's expected in various mixing scenarios, allows the collaboration to exclude a range of possible values for δ_{CP} ($0.1\pi < \delta_{CP} < 0.5\pi$) at a confidence level of 90% in the case of an inverted hierarchy. It is worth noting that NOvA also performed an alternative signal-event identification analysis, using machine-learning techniques to select electron neutrinos, which can be difficult to identify unambiguously. This secondary analysis, which found a few more electron neutrinos (11 total), puts further constrains on δ_{CP}: it disfavors (at the 90% confidence level) all values of δ_{CP} in the case of an inverted hierarchy, and the $0.25\pi < \delta_{CP} < 0.95\pi$ range for a normal hierarchy. Both primary and secondary analyses indicate that a normal neutrino mass hierarchy is more likely than an inverted hierarchy.

These initial NOvA results are important for the eventual precise determination of δ_{CP}, which may come from the ultralarge DUNE and Hyper-Kamiokande experiments in the next decade [7, 8]. But given that the data used for the NOvA analysis were taken over the course of only 15 months, we can look forward to many more exciting results from this experiment, which is expected to take data for at least six years total.

Similarly to δ_{CP}, the sum of the neutrino masses is imprinted on the evolutionary history of the Universe. Neutrino mass has an impact on galactic structure and cosmic microwave background observables due to its effect on how matter gravitationally clumped together in the early Universe. Using telescope-based experiments with sensitivity to neutrino properties, astrophysicists are quickly closing in on a measurement of the sum of the masses, which, in combination with mixing results, can be used to infer the neutrino mass hierarchy (see review in Ref. [9]). Meanwhile, a combination of data from the T2K neutrino-mixing experiment in Japan and NOvA may conclusively establish the mass hierarchy in the near future. What an extraordinary thing, to be able to measure a property of the neutrino with two wildly different techniques, one using telescopes and the other using particle accelerators. These combined efforts are bringing us into a golden age of physics, in which we may finally understand the relationship between the smallest (particle) and the largest (cosmic) scales.

This research is published in Physical Review Letters.

REFERENCES

[1] P. Adamson *et al.* (NOvA Collaboration), "First Measurement of Electron Neutrino Appearance in NOvA," Phys. Rev. Lett. **116**, No. 116, 151806 (2016).
[2] P. Adamson *et al.* (MINOS Collaboration), "Electron Neutrino and Antineutrino Appearance in the Full MINOS Data Sample," Phys. Rev. Lett. **110**, 171801 (2013).
[3] K. Abe *et al.* (T2K Collaboration), "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam," Phys. Rev. Lett. **112**, 061802 (2014).
[4] Y. Abe *et al.* (Double Chooz Collaboration), "Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment," Phys. Rev. Lett. **108**, 131801 (2012).
[5] F. P. An *et al.* (Daya Bay Collaboration), "Observation of Electron-Antineutrino Disappearance at Daya Bay," Phys. Rev. Lett. **108**, 171803 (2012).
[6] J. K. Ahn *et al.* (RENO Collaboration), "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment," Phys. Rev. Lett. **108**, 191802 (2012).
[7] R. Acciarri *et al.*, "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF," arXiv:1512.06148.
[8] K. Abe *et al.*, "Letter of Intent: The Hyper-Kamiokande Experiment Detector Design and Physics Potential," arXiv:1109.3262.
[9] K. N. Abazajian *et al.*, "Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure," Astropart. Phys. **63**, 66 (2015).

10.1103/Physics.9.39

