Long-Baseline Neutrino Experiments March On

Long-baseline neutrino experiments are paving the way for the solution of two outstanding puzzles in neutrino physics—mass ordering and charge-parity violation.

By **Sara Bolognesi**

In 1998, researchers discovered that neutrinos can change their “flavor” as they travel. This behavior is only possible if neutrinos have a mass—contrary to the initial assumption of the standard model of particle physics. The discovery of this beyond-standard-model behavior, recognized by the 2015 Nobel Prize in Physics, drove intense efforts to characterize neutrino oscillations through increasingly accurate experiments. One such effort, the NOvA experiment at Fermilab, now reports the analysis of oscillation data collected between 2014 and 2020 [**1**], delivering some of the most accurate estimates to date of parameters describing neutrino oscillations and providing important hints on two important aspects of neutrino physics—the ordering of neutrino masses and the degree of charge-parity (CP) violation. The results bode well for the next generation of “long-baseline” experiments, which will dramatically boost our ability to probe elusive aspects of neutrino physics.

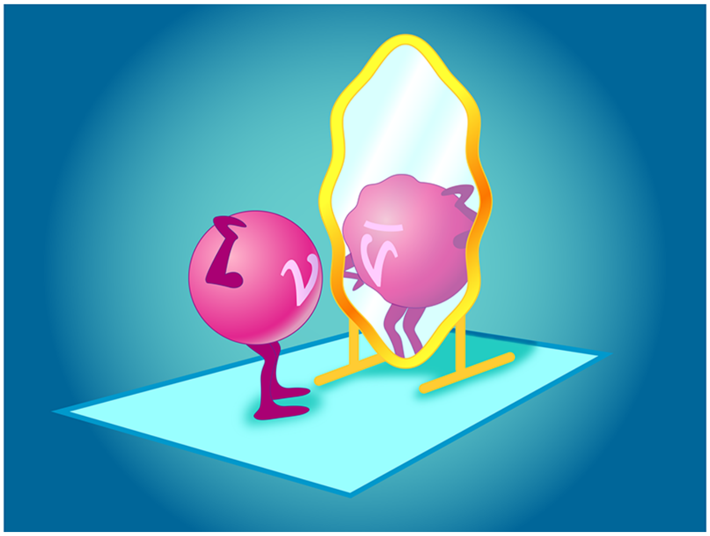

Figure 1: Neutrinos may behave differently from their “mirror” antiparticle counterparts. Experiments such as NOvA seek to spot these differences by comparing how neutrinos and antineutrinos change their flavor, or “oscillate,” over long distances.
Credit: APS/Carin Cain

When neutrinos of a given type, or flavor, travel over some distance, they can switch their flavor with a probability depending on distance and on neutrino energy. This oscillation can be explained by assuming that there are three neutrino mass eigenstates that mix to form three flavor eigenstates (electron, muon, and tau) among which oscillations occur. Such behavior is parametrized (that is, mathematically described by a limited set of measurable numbers) by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. As often occurs in physics, precision measurements of a phenomenological parametrization can deliver hints to new physics—which could mean developing a simpler model connected to a smaller set of parameters or even discovering a more fundamental theory, solely based on symmetries, that describes observations.

Today’s experiments aim to tackle, in particular, two crucial open questions. First, are neutrinos ordered in mass in a similar way (“normal ordering”) as their charged-lepton partners, the well-known electron, muon, and tau particles? A naive analogy would suggest that this is the case—but finding an “inverted ordering” would be an exciting result that could guide theoretical developments. Second, do neutrinos oscillate in the same way as their antiparticles (antineutrinos), that is, do they obey CP symmetry (Fig. **1**)? If not, we would establish, for the first time, CP violation by leptons (the particle sector that includes neutrinos, electrons, muons, and taus). CP violation is at the heart of one of physics' greatest puzzles—matter's dominance over antimatter in the Universe. Understanding CP violation in different particle sectors, including leptons, could help in solving this puzzle.

The discovery of neutrino oscillations was enabled by two natural sources of neutrinos: cosmic rays hitting Earth's atmosphere, and nuclear reactions in the Sun. Today, artificial neutrino sources, such as particle accelerators, allow researchers to better control the flavor and energy of the produced neutrinos and the distance, or "baseline," over which these particles travel before they are detected. Particle accelerators can work in neutrino-beam and antineutrino-beam modes, producing separate fluxes of neutrinos and antineutrinos, which is crucial for CP-violation searches. Presently, two accelerator experiments have long enough baselines to observe PMNS neutrino oscillations: T2K in Japan and NOvA in the US, with baselines of 295 and 810 km, respectively.

In 2020 the two collaborations announced results that indicated an intriguing, yet mild, tension [**2**, **3**]. Both experiments slightly favored normal ordering over inverted ordering, although NOvA, by virtue of its longer baseline, has a much more pronounced sensitivity to mass ordering. The T2K experiment suggested that neutrinos oscillate faster than antineutrinos—implying a large CP violation. The degree of CP violation extracted from NOvA's results, however, depended on mass ordering. For normal ordering, NOvA favored a small CP violation, whereas for inverted ordering, NOvA's results would be compatible with T2K's. Statistical fluctuations are the most economical explanation for these differences, but the tension is an opportunity for a deep investigation of the systematic uncertainties affecting these measurements. More exotic explanations for the tension, including "nonstandard" interactions of neutrinos, have been also proposed.

NOvA's new report [**1**] offers a detailed description of the results announced in 2020. With respect to the previous analysis published by NOvA in 2019 [**4**], the new one includes about 50% more data in neutrino-beam mode and the reanalysis of all data taken since 2014. The reanalysis is further optimized to exploit the fact that NOvA's near and far detectors are based on the same technology, using a procedure that partly cancels out systematic uncertainties. NOvA mostly produces muon neutrinos or antineutrinos and uses as main observables the number and energy of muon neutrinos and antineutrinos that survive the trip to the far detector and the number and energy of electron neutrinos that appear at the far detector. From these measured observables, the analysis extracts estimates of oscillation parameters, of mass ordering, and of the degree of CP violation.

Since the 2020 announcement, a number of researchers have already performed "joint fits" to the sets of data coming from NOvA, T2K, and other experiments (including those using neutrinos produced by nuclear reactors, by the Sun, and by cosmic rays) [**5**–**7**]. These joint fits favor normal ordering, with a degree of CP violation lying between NOvA's and T2K's. The preference for normal ordering is highly influenced by data from Super-Kamiokande—an observatory in Japan that measures cosmic-ray-produced neutrinos—which is sensitive to mass ordering. When T2K and NOvA results are included in the fits, such preference diminishes because inverted ordering would release the tension between those experiments seen for normal ordering. Clearly, there is more work to be done. Those joint fits, however, cannot account for correlations of the systematic uncertainties between NOvA and T2K. Fortunately, the two experiments are cooperating to produce a new joint fit that will clarify the possible impact of such correlations when combining their measurements.

So, what does the future hold in store? A new generation of long-baseline experiments under construction, such as Hyper-Kamiokande in Japan and the Deep Underground Neutrino Experiment (DUNE) in the US, will boost the available statistics by more than a factor of 20. At that point, an unprecedented control over the systematic uncertainties will be needed. The most complex of those uncertainties—associated with the modeling of neutrino production and of neutrino-nucleus interactions—touch on deep nuclear-physics problems that require a close collaboration with the nuclear-physics community. The statistics boost is likely to allow researchers to make some easy progress: establishing the mass hierarchy and the degree of CP violation. But with the flurry of data becoming available in the longer term, we may need to look at neutrino oscillation with a more open mind, possibly relaxing some of the restrictive assumptions of the current paradigm, such as a unitary PMNS matrix and a minimal scenario involving only three neutrino flavors and only standard interactions.

To control systematic uncertainties and allow for a more model-independent interpretation of the data, the combination of complementary experiments with different baselines and neutrino energies will be crucial. T2K and NOvA are showing how powerful these synergies can be. A guiding example for neutrino searches may come from the most celebrated success of particle physics—the discovery of the Higgs boson. Such success was built on multiple generations of experiments that constantly improved their performance and refined the fundamental understanding of the electroweak sector, as well as on the combination of the two major Higgs-searching experiments—ATLAS and CMS.

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