# Neutrino Mystery Endures

New neutrino-oscillation data show no sign of an anomalous signal seen in previous studies, but the analyses can’t yet fully rule out its presence.

By **Elizabeth Worcester**

There are three known flavors of the elementary particle known as a neutrino: $\nu_e$, $\nu_\mu$, and $\nu_\tau$. But physicists think that there could be more. This possibility has been suggested by the results of experiments looking at neutrino oscillation—a quantum-mechanical phenomenon that involves a change in the flavor of a particle as it travels. This behavior was first seen in the 1960s when scientists measured fewer neutrinos from the sun than they expected, but it took decades of experimental work to prove conclusively that these “missing” neutrinos had changed flavor on their journey to Earth. Today, neutrino-oscillation experiments can measure the “disappearance” and/or “appearance” of neutrinos as they switch flavors. In 2021, the MiniBooNE Collaboration reconfirmed earlier observations of an anomalous signal that could be incompatible with our understanding of the oscillation of the three known neutrino flavors [**1**]. The MicroBooNE Collaboration has now further explored this exciting possibility [**2–6**]. They find no such anomalous signal, but they can’t yet rule out the possiblilty that new neutrinos might be out there.

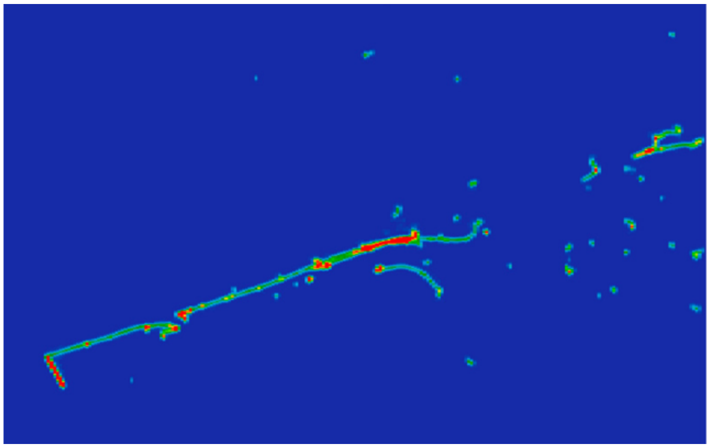

**Figure 1:** When an electron neutrino ($\nu_e$) interacts with the MicroBooNE detector, it produces an electron and a proton whose paths the detector precisely tracks. The colors represent the amount of energy deposited in the detector, with red representing higher-energy deposits.
**Credit: MicroBooNE**

The flavor states have no definite mass. Rather, each is described by a linear combination of the three neutrino mass states. As a neutrino propagates, the phases of its mass states change, altering the probability of detecting it in one flavor or another. This probability depends on the distance the neutrino has traveled, the energy of the neutrino, the differences in mass between the neutrino mass states, and the mixing angles that characterize the linear combinations of states. In a given experiment, the distance and energy range are set, and one can calculate the oscillation probability using measured values for the neutrino mass differences and mixing angles. For the MiniBooNE experiment, such calculations are clear: if the picture of three-neutrino oscillation is complete, the $\nu_\mu$’s produced at the start of the beamline should not oscillate into $\nu_e$’s. But the MiniBooNE detector picked up a $\nu_e$-like signal that suggests exactly that switch (see **Viewpoint: The Plot Thickens for the Fourth Neutrino**). The MicroBooNE Collaboration has now performed three analyses of their data to try to determine the nature of the signal MiniBooNE detected [**2–5**].

The MicroBooNE and MiniBooNE experiments are located along the same neutrino beamline at Fermilab in Illinois. Neutrinos themselves leave no signals in particle detectors. Rather, scientists measure their properties by observing the groups of particles, collectively called final states, that are produced on the rare occasions that a neutrino interacts with the matter in a detector. For MiniBooNE, which uses a so-called Cherenkov detector, charged particles from the final state produce rings of light, which can be analyzed to learn about the particles that made them. In contrast, for MicroBooNE, which uses a liquid-argon time-projection chamber (LArTPC) detector, the final state particles leave behind trails, which are captured as high-resolution images of the particle trajectories (Fig. **1**). The imaging capability of LArTPC detectors makes them particularly adept at distinguishing $\nu_e$ interactions from other events that may appear similar. This capability means that MicroBooNE is well equipped to study the nature of the anomalous MiniBooNE signal.

The MicroBooNE Collaboration used a variety of techniques to interpret their data, including deep learning, tomography, and multialgorithmic pattern recognition. Their three analyses all looked at the same dataset, but each was designed to focus on a different final state. The analyses determined the flavors of the incoming neutrinos as well as their interaction topology, interaction kinematics, and energy. The analyses were performed blind, meaning that the group doing that work only studied the experimental signal after they had finalized the analysis procedures using simulated and other experimental data.

Based on their analyses, the MicroBooNE Collaboration reports that their $\nu_e$-like signal is consistent with that predicted by the three-neutrino model. This result thus disfavors the hypothesis that the anomalous signal found in the MiniBooNE data is indeed fully explained by a $\nu_e$ excess.

In another study, Carlos Argüelles of Harvard University and colleagues analyzed the results reported by MiniBooNE and MicroBooNE, comparing the MicroBooNE $\nu_e$-like signal to the predictions of various models that are compatible with the MiniBooNE data [**6**]. The team finds that experimental uncertainties in the MiniBooNE analysis allow for significant variation in the corresponding $\nu_e$-like signal expected for MicroBooNE. Thus, they say, the MicroBooNE result cannot fully rule out a $\nu_e$-excess interpretation of the MiniBooNE data in a model-independent way. Argüelles and colleagues also fit the MicroBooNE results to a simple model that assumes the existence of a sterile neutrino—a hypothetical neutrino that interacts with matter only via gravity. In this fit, the team finds that some values of the model parameters that work with the MiniBooNE data are not fully ruled out by the MicroBooNE data. The implication is that sterile neutrinos could still potentially explain the anomaly, a conclusion consistent with what the MicroBooNE Collaboration found.

The MicroBooNE Collaboration's result represents an important step forward for the field, both in terms of the LArTPC analysis techniques used to do precision science and in the progress made toward understanding this long-standing anomaly. Much of the future neutrino program in the United States is based on LArTPC technology, so the techniques developed by MicroBooNE provide an excellent foundation. It will be very exciting to see more results from this experiment as well as from two new LArTPC experiments in the same beamline as MicroBooNE: ICARUS and the Short-Baseline Near Detector (SBND). These experiments—both of which I am involved in—will work together to perform a multidetector analysis, increasing the amount of data available and reducing the experimental uncertainties relative to the current results. The ICARUS Collaboration has just started to collect data and SBND is currently being installed. I am hopeful that these experiments will shed further light on—or even solve—this enduring neutrino mystery.

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## REFERENCES

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