New result contradicts troubling old evidence of neutrino oscillation at small distances

A decade ago, the findings of an accelerator experiment at Los Alamos seemed to require the existence of sterile neutrinos immune to the weak nuclear force.

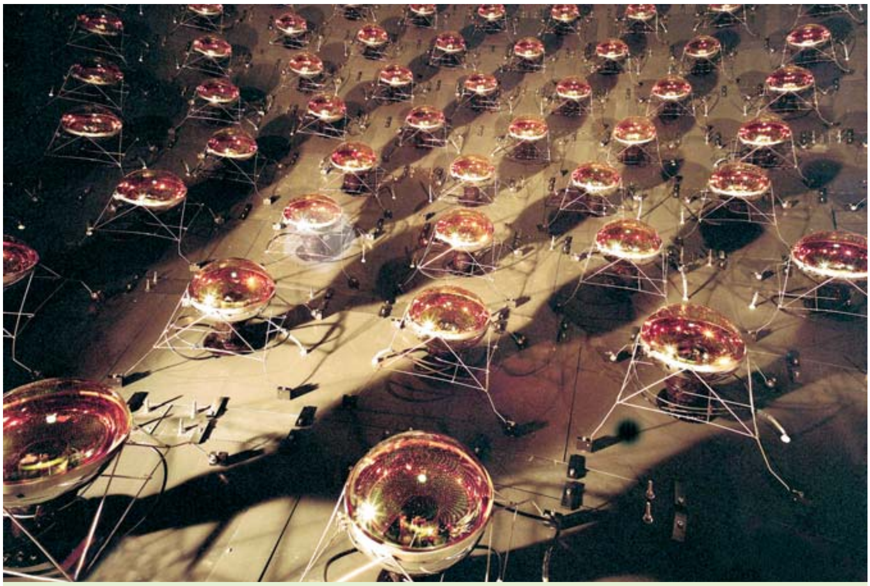
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Figure 1. The MiniBooNE neutrino detector at Fermilab is a 12-meter-diameter spherical vessel filled with mineral oil. Seen here is part of the array of 1280 fast 12-inch photomultiplier tubes on its inner wall. A beam of muon neutrinos traverses the detector. Neutrino collisions in the oil produce charged particles whose Cherenkov light is registered by the phototubes.

To a packed auditorium at Fermilab on 11 April, the MiniBooNE collaboration presented the much-anticipated first results of a neutrino-oscillation experiment that began taking data five years ago.[1] The MiniBooNE experiment at Fermilab's Tevatron was designed to confirm—or lay to rest—the most discordant and disputed note in an otherwise impressively harmonious extension of particle theory's standard model. That extension is the simplest adaptation of the standard model to the undisputed existence of neutrino states with different nonzero masses.

The discordant note had first been struck in 1995 by an experiment at Los Alamos National Laboratory (see PHYSICS TODAY, August 1995, page 20). The Liquid Scintillator Neutrino Detector (LSND) group at Los Alamos, using a neutrino beam produced by 800-MeV protons from the lab's LAMPF accelerator, reported the observation of neutrino oscillation on a length scale of only 30 meters. All other observations of the oscillating metamorphosis of neutrino flavors involved distance scales ranging from 100 to 10^8 kilometers.

The standard model can accommodate the three mass eigenstates revealed by those long-distance-scale experiments. But three is its limit for neutrinos that participate in the ordinary weak interactions. The LSND result, if true, would require the existence of one more neutrino state, which would have to be "sterile," that is, immune to all the known forces except gravity.

By 1997, after two more years of data taking, the LSND result was statistically robust.[2] It had to be taken seriously. Since then, the specter of sterile neutrinos has imposed an intrusive and ungainly caveat on the otherwise elegant evolution of the standard model's neutrino sector.

MiniBooNE

Unlike the large-scale observations of flavor oscillation of neutrinos from the Sun and from cosmic-ray showers, the LSND result had not been independently confirmed by other experiments. That's why the MiniBooNE collaboration was formed in 1998 to build a detector facility that would be both different and similar enough to LSND to settle the issue once and for all.

And that's almost what happened. "Our 11 April report closed one door," says MiniBooNE co-spokesman William Louis of Los Alamos, who had also been a leader of LSND. "But in doing so, it may have opened another." To great relief among the theorists, Louis and co-spokesman Janet Conrad of Columbia University reported that the MiniBooNE data, with much higher statistics than LSND, ruled out with 98% confidence the neutrino-oscillation parameters reported by the Los Alamos group a decade ago.

Louis's tentatively opened door refers to an unanticipated spectral anomaly in MiniBooNE data not directly related to the claimed LSND oscillation effect or its negation. "It may be just a prosaic problem with our analysis," says Conrad, "or it could be a harbinger of important new physics."

The drama was heightened by MiniBooNE's "blind analysis" of its data. To avoid unconscious bias, the group had estimated backgrounds and optimized all of its data-selection criteria without knowing how they would affect the final result. The experimenters got to "open the box" and look at what their data did to the LSND claim only three weeks before going public. That's when they discovered the spectral anomaly. "So we've had very little time yet to try and understand it," says Conrad. But eager theorists are already jumping in with exotic conjectures.

Flavor oscillation

MiniBooNE's neutrino beam comes from the decay of π^+ mesons focused into a beam after being produced by 8-GeV protons hitting a metal target. The

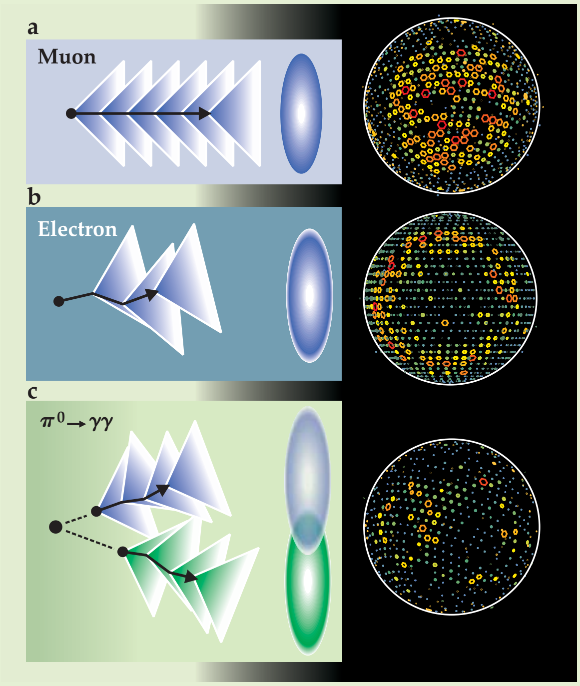

Figure 2. Phototube hit pattern in MiniBooNE's oil Cherenkov detector identifies an energetic charged particle produced in a neutrino collision in the oil. **(a)** Cones of Cherenkov light from a muon, with a long, straight trajectory, produce a filled circle of phototube hits on the detector's downstream wall. **(b)** A typical electron has a shorter, more crooked trajectory, yielding a ragged open circle of phototube hits. **(c)** A pair of gammas from the decay of a π^0 produces two electron-like circles. Colors on the phototube displays indicate the number of Cherenkov photons exciting a tube. Red and green signify, respectively, the most and fewest photons. (Adapted from ref. 1.)

protons are from the booster accelerator that feeds the Tevatron's main injector, and the neutrino detector is 500 meters downstream of the target. ("BooNE" is short for booster neutrino experiment, and the diminutive reflects a plan for possible expansion of the facility if something interesting warrants it.)

Neutrinos are created by weak interactions in three flavors (ν_e , ν_μ , and ν_τ) associated with the three varieties of charged leptons: the electron, the heavier muon, and the much heavier tau. The flavor states are different superpositions of the three neutrino mass eigenstates.

The only neutrino variety produced in π^+ decay is ν_μ. But neutrino oscillation of the kind reported by LSND means that, at a distance L downstream of its creation, a ν_μ of energy E has a probability

$$P = A \sin^2(L\Delta m^2/4\hbar cE) \qquad (1)$$

of having morphed into a ν_e. The parameter Δm^2 is the difference between the squared masses of the two mass eigenstates involved. (There's an implicit approximation that oscillation in any one observational regime involves only two of the three mass states.) And the amplitude A, which can range from 0 to 1, is a measure of the misalignment between the mass states and the flavor states in Hilbert space.

Experimenters seek to measure those two neutrino-oscillation parameters by looking downstream for neutrino interactions that signal the emergence of electron neutrinos in the ν_μ beam. The LSND experiment had yielded a very small A of about 4×10^{-3}, and a disturbingly large Δm^2 of order 1 eV^2.

Why disturbingly large? Solar-neutrino observations convincingly describe the disappearance of electron neutrinos from the Sun with a Δm^2_{sol} of about 10^{-4} eV^2 (see PHYSICS TODAY, July 2002, page 13). And the disappearance of muon neutrinos from cosmic-ray showers in the atmosphere implies a Δm^2_{atm} of about 5×10^{-3} eV^2. If, as the standard model asserts, there can be only three mass states of ordinary neutrinos, these two mass-squared differences constrain the third: It can't exceed $\Delta m^2_{\text{atm}} + \Delta m^2_{\text{sol}}$ unless it involves a pathological fourth neutrino species.

The search

Because the A in question is so small, testing the LSND result at MiniBooNE means ferreting out the interactions of at most a few hundred oscillation-produced electron neutrinos hidden within a much larger background of interlopers and impostors. A ν_e distinguishes itself from a ν_μ by creating an electron instead of a muon on the rare occasions when it interacts with a nucleus in the detector.

The MiniBooNE detector is a 12-meter-diameter sphere filled with mineral oil. Shielding downstream of the pion-decay region lets almost nothing but neutrinos through to the detector. Some 1300 photomultiplier tubes facing inward from the periphery of the oil register Cherenkov light from the tracks of charged particles produced by neutrinos hitting nuclei in the oil (see figure 1). Another 240 veto photomultipliers facing outward monitor the periphery for cosmic rays or other charged interlopers.

Beam neutrinos enter the detector with a very broad distribution of energies peaking at about 700 MeV. That's more than 10 times the neutrino-energy scale of the LSND experiment with its much less energetic beam protons. But equation 1 asserts that the energy dependence of neutrino oscillation scales like L/E. So MiniBooNE's correspondingly greater distance from proton target to detector lets it explore the same range of oscillation parameters that LSND covered.

But the differences between the two experiments have an important purpose. Beyond seeking much higher statistics, the MiniBooNE collaboration introduced significant differences to avoid unknown systematic errors that might have led LSND astray. LSND had a smaller oil Cherenkov detector similar to MiniBooNE's. But instead of directing a ν_μ beam into it, LSND had in fact used a beam of muon antineutrinos ($\bar{\nu}_\mu$) from the decay of positive muons. That shouldn't affect the final outcome if one makes the usual assumption—implicit in the two-parameter phenomenology—that flavor oscillation is the same for neutrinos and their antiparticles. Of course a 50-MeV $\bar{\nu}$ and a 500-MeV ν of the same flavor interact quite differently with nuclei in the oil. And it's those interactions that are supposed to reveal instances of flavor metamorphosis.

In almost four years of running, MiniBooNE's ν_μ beam created millions of collisions in the detector with a telltale emerging muon signaling that the neutrino was still a ν_μ when it collided. The search was for a tiny fraction of collisions that might instead have produced an electron as a result of flavor oscillation. In particular, MiniBooNE was looking for quasi-elastic collisions:

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e} + \mathrm{p}\,, \qquad (2)$$

a reaction for which one can estimate the incident neutrino's energy E quite well just by measuring the electron's energy and direction. The low-energy

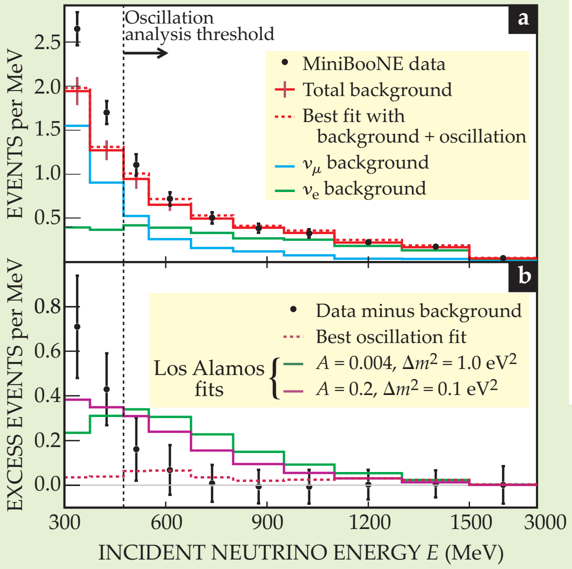

Figure 3. (a) MiniBooNE's observed distribution of quasi-elastic ν_e collisions as a function of the neutrino's energy, plotted with expected backgrounds from masquerading ν_μ collisions and from real ν_e contamination in the neutrino beam. Data for energy E above the indicated analysis threshold were used to determine the parameters of a model that allows neutrino oscillation on top of background. **(b)** The background-subtracted distribution, compared with predictions from two alternative neutrino-oscillation fits to the old Los Alamos results under scrutiny. They fit neither the data above the analysis threshold nor the unexpected excess below it. The best MiniBooNE oscillation parameters, incompatible with the Los Alamos results, do fit the data above the analysis threshold. But those data are adequately described by background alone. And none of the neutrino-oscillation fits explain the surprising low-energy excess. (Adapted from ref. 1.)

recoil proton is generally not seen.

Electrons and muons engender different patterns of Cherenkov light cones at the photomultiplier array when they plow through the oil at hundreds of MeV (see figure 2). Muons typically have long, straight trajectories that activate a neat filled circle of phototubes on the detector's far wall. Electrons have shorter trajectories with many slight changes of direction. The result is a ragged open circle of phototube hits. An energetic gamma produces a phototube hit pattern much like that of an electron of the same energy. But most such gammas come in pairs from the prompt decay of a π^0 created in the collision. So they usually give themselves away as a pair of rings. For good measure, one can often reconstruct from the rings a two-gamma center-of-mass energy roughly equal to the π^0 mass.

Most collision events that produce a muon could be discarded out of hand, either because the muon's eventual decay generated a second, late Cherenkov light pattern or because the muon exited the detector before decaying. The team also discarded all events with evidence that pions, neutral or charged, were produced along with an electron or muon. But all those cuts still left tens of thousands of events whose spatial and temporal patterns of phototube hits had to be analyzed by an elaborate computer model that decided how well each resembled reaction 2.

Opening the box

Fewer than a thousand events survived that particle-identification analysis with incident-neutrino energy exceeding 300 MeV, below which the high probability of misidentification renders the data of little value. Figure 3a shows the observed energy distribution of those events. Also shown is the expected background of spurious events. That background, which is more than twice the actual neutrino-oscillation signal one would expect from the LSND parameters, has two main sources: MiniBooNE's ν_μ beam has a small ν_e contamination from decays of muons and kaons produced by the proton beam. And the rest of the estimated background is mostly ν_μ collisions masquerading as ν_e events.

In keeping with its blind analysis, the collaboration did not allow itself to know the distribution of events in figure 3a before deciding that the optimum energy range for fitting neutrino-oscillation parameters plus background to the data would be 475–1250 MeV. Shown in figure 3a, the best oscillation-plus-background fit adds almost nothing to the estimated background alone, which by itself fits the data quite adequately above 475 MeV. In any case, the oscillation fit yields a Δm^2 of 4 eV^2, quite inconsistent with the old LSND result.

It's the excess of observed events below 475 MeV that surprised the experimenters when they finally opened the box in March. That's the new door Louis was talking about. No values of the two neutrino-oscillation parameters can explain it. And it can't be dismissed as a purely statistical fluke.

Figure 3b compares the background-subtracted data with neutrino-oscillation predictions from two different LSND fits. Neither one fits the MiniBooNE data either above or below 475 MeV. The collaboration's joint analysis of the MiniBooNE and LSND data concludes with 98% confidence that neutrino oscillation describable by just the two conventional oscillation parameters cannot explain the LSND results.

If one then concludes that the LSND result was simply wrong and that MiniBooNE's low-energy excess of ν_e events is just an underestimate of low-energy backgrounds or something equally pedestrian that will soon be put right, the story is essentially over and sterile neutrinos were a bad dream. But the results might be hinting at deep reasons why the expected L/E scaling sometimes fails, or why neutrinos and antineutrinos are not simply mirror-image twins. Neutrino experiments are actively looking for such ν–$\bar{\nu}$ asymmetry as a possible explanation for the cosmic predominance of matter over antimatter. MiniBooNE is in fact now running with a $\bar{\nu}_\mu$ beam.

Some theorists aren't giving up yet on sterile neutrinos. For example, Thomas Weiler (Vanderbilt University) and coworkers speculate that the differences between the LSND and MiniBooNE manifest a departure from L/E scaling precisely because a sterile neutrino is involved. Unconstrained by forces other than gravity, it could take shortcuts through extra spacetime dimensions. Appearing thus to outrun ordinary flavored neutrinos, the sterile neutrino would generate phase differences that break the scaling by introducing a resonant energy into neutrino oscillation.[3] And if that resonance is near 300 MeV, says Weiler, it might explain MiniBooNE's low-energy excess as well as why LSND saw neutrino oscillation and MiniBooNE didn't.

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References

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