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Flavor oscillation may be different in neutrinos and antineutrinos

An unanticipated violation of matter–antimatter symmetry could reconcile conflicting experimental evidence about the possible existence of sterile neutrinos.

In 1995 William Louis and colleagues at Los Alamos National Laboratory reported the first evidence of neutrino flavor oscillation in an accelerator experiment. The report was disquieting, and became more so over the next three years as its statistical significance was bolstered by more data from the LANL experiment.

Why the disquiet? After all, neutrino oscillation, the metamorphosis of neutrino flavors with a probability that oscillates with travel distance L like $\sin^2(L/\lambda)$, was already well attested for neutrinos from the Sun and from cosmic-ray showers in the atmosphere. The characteristic oscillation length λ is given by $4\hbar E/c^3\Delta m^2$, where E is the neutrino's energy and Δm^2 is the difference between the squared masses of the two neutrino mass eigenstates involved.

The prevailing model of neutrino oscillation assumes that there are three different neutrino mass eigenstates in nature and that they are different linear superpositions of the three flavor eigenstates ν_e, ν_μ, and ν_τ, associated respectively with the three charged leptons: the electron, the muon, and the much heavier tau. The standard oscillation phenomenology presumes that, to adequate approximation, only two of the three neutrino mass states are involved in any one observational oscillation regime.

The LANL data, seeming to reveal the metamorphosis $\nu_\mu \rightarrow \nu_e$ over distances of less than 100 meters in a low-energy accelerator beam, were well fitted by Δm^2 of order 1 eV^2. That's several hundred times bigger than the Δm^2 measured for atmospheric neutrino oscillation and ten thousand times bigger than what's found for solar neutrinos. But if only three mass eigenstates exist, no one Δm^2 can exceed the sum of the other two.

By 1995 electron–positron collider experiments had already excluded the existence of more than three neutrino flavors participating in the weak interactions. So the LANL data seemed to require an additional "sterile" neutrino flavor, impervious to the weak interactions. That prospect was unappealing; it would have cluttered the elegant prevailing theory.

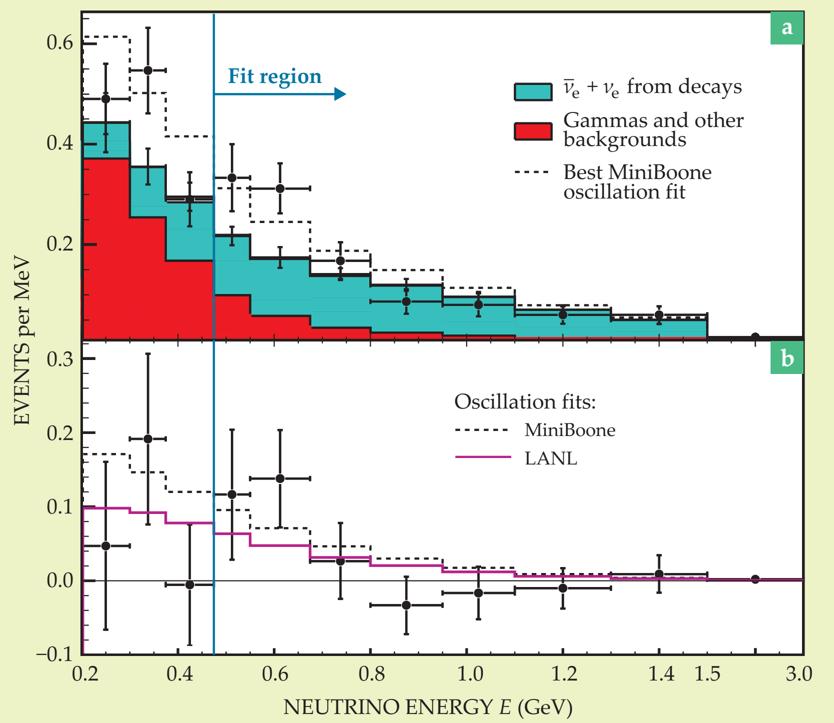

Figure 1. Energy distribution of electron antineutrinos whose collisions in Fermilab's MiniBoone detector appear to have created positrons. Such an event might signal the flavor oscillation of a muon antineutrino in the incident beam. **(a)** More likely, any one event is background due to electron-neutrino (and -antineutrino) contamination in the beam or to a gamma produced in the detector. Estimated backgrounds are shown together with the best oscillation fit to the excess over background. The fit ignores events with E below 475 MeV. **(b)** The background-subtracted E distribution and fit are shown together with a scaled fit to data from the Los Alamos National Laboratory experiment that first reported this kind of flavor oscillation. (Adapted from ref. 1.)

So experimenters at Fermilab responded by building the MiniBoone neutrino beam and detector, a facility explicitly designed to confirm the LANL result or lay it to rest. And indeed in 2007, with three years of data in hand, the MiniBoone collaboration announced that its results were incompatible with LANL's claim (see PHYSICS TODAY, June 2007, page 18). The neutrino-physics community breathed a sigh of relief.

Premature obituary

It now turns out that the sterile neutrino's obituary was premature. In the prevailing model, flavor oscillation is the same for neutrinos ν and antineutrinos $\bar{\nu}$. So whereas the LANL experiment had been done with a $\bar{\nu}_\mu$ beam, the MiniBoone collaboration used a ν_μ beam. They did that because, even though the fundamental physics was presumed to be the same, a ν_μ beam would permit significantly faster accumulation of data. But just to be sure, in 2006 they started taking data with a $\bar{\nu}_\mu$ beam. And lo and behold, their newly reported $\bar{\nu}_\mu$-beam result resembles the LANL result that started all the fuss.[1]

The new result is not yet statistically robust, but it already raises the stakes. The issue is no longer just whether sterile neutrinos exist. If all three experimental results are essentially correct, we now have the first evidence of *CP*-symmetry violation attributable to neutrino interactions. (The symmetry operators *C* and *P* are, respectively, particle–antiparticle exchange and parity.) The only *CP* violation previously observed in the laboratory occurs in quark decays, and that's too feeble an effect to explain the matter–antimatter imbalance of the cosmos. (See the article by Helen Quinn in PHYSICS TODAY, February 2003, page 30.)

The MiniBoone experiment is essentially a beam of ν_μ (or $\bar{\nu}_\mu$) with a broad distribution of energies around 500 MeV, passing through a 12-meter-diameter spherical detector filled with mineral oil and lined with photomultiplier tubes. The detector sits about 500 meters downstream of where the beam is formed by the decay of charged pions created by protons bombarding a metal target. The neutrino energies and travel distance are both about 15 times greater than those of the LANL experiment. But *L* and *E* enter the oscillation phenomenology only as the ratio *L*/*E*, and the MiniBoone parameters were chosen accordingly to provide maximum sensitivity to the LANL claim in an experiment with very different potential sources of error.

The bombarded target emits pions in profusion. The decay of a π^+ or a π^- creates, respectively, a ν_μ or a $\bar{\nu}_\mu$. So one can switch from a predominantly ν_μ beam to a predominantly $\bar{\nu}_\mu$ beam, albeit with lesser flux, by reversing the polarity of the magnetic "horn" that focuses pions of the desired charge onto the beam axis. Other magnets and shielding downstream of the pion-decay region clear the beam of hadrons, charged leptons, and gammas.

The signal that indicates the sought-after metamorphosis $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ would be the appearance in the detector of more $\bar{\nu}_e$ interactions than could be attributed to impostors or beam contaminants. A neutrino rarely interacts with a nucleon it's traversing. But when it does and turns into a charged lepton, it reveals its flavor by the kind of lepton it becomes. The phototube array distinguishes between muons and positrons or electrons by the Cherenkov light they generate in the oil: The heavier muons have straighter tracks in the oil and therefore project cleaner circles of Cherenkov light onto the detector's wall.

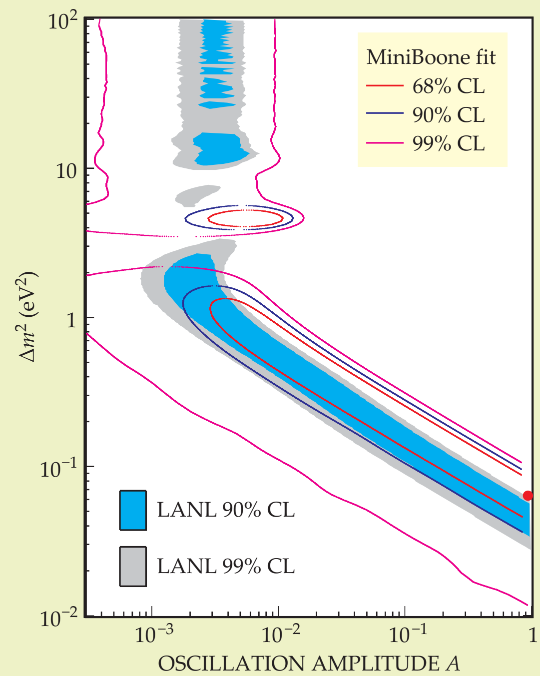

Figure 2. Neutrino-oscillation parameters favored by the MiniBoone and Los Alamos antineutrino-beam experiments are indicated by confidence-level contours in the parameter space of the oscillation amplitude *A* and the mass-squared difference Δm^2 between the two participating neutrino states. The best MiniBoone fit (red dot near maximum *A*) is ruled out by null results from reactor experiments that exclude *A* bigger than 0.1. (Adapted from ref. 1.)

The best-fit oscillation parameters from the LANL experiment predict that in the MiniBoone antineutrino beam, only one $\bar{\nu}_\mu$ in about 400 will have turned into a $\bar{\nu}_e$ by the time it enters the detector. The positrons created by those few changelings would be greatly outnumbered by impostors and positrons from various sources of background. So one wants to run the experiment long enough to reduce statistical uncertainties to the point where excesses over estimated background signals could be convincing.

The new result

The new MiniBoone result is based on three years of running in the antineutrino mode. But it is still statistically weaker than the earlier neutrino-mode null result. Figure 1a shows the number of positron-like interactions recorded by the detector as a function of the incident neutrino's energy *E*. That energy is calculated from the phototube array's measurement of the emerging charged lepton's energy and direction, on the assumption that the reaction was

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

Figure 1a also shows the estimated contributions from various backgrounds such as the creation of gammas by interactions in the detector and the contamination of the beam with electron neutrinos from the decays of kaons and muons. Because the backgrounds are worst for *E* less than 475 MeV, the collaboration ignored events below that cutoff in determining the best oscillation fit to the data. It's the same cutoff that the group had "blindly" chosen—from calibration data only—to avoid event-selection bias in its 2007 analysis of the neutrino-mode data.

In figure 1b, the observed energy distribution and the fit are shown with the estimated background subtracted off. Above 475 MeV, the observed excess is only about 25 events. But fitting the data with a background-only hypothesis is excluded at the 99.5% confidence level. That by itself signifies a neutrino-oscillation signal only 2.7 standard deviations (σ) above background. But as shown in figure 1b, the distribution of excess events is reasonably well described by an appropriately scaled fit to the LANL data, for which a more robust 3.8-σ oscillation signal had been claimed.

Any particular neutrino-oscillation fit is characterized by two parameters: Δm^2, which determines the oscillation length λ, and *A*, the amplitude of the probability oscillation. The latter, which can range from 0 to 1, is a measure of the misalignment in Hilbert space between the flavor and mass basis states.

Figure 2 shows the regions of the parameter space favored by the LANL and MiniBoone antineutrino data. The two experiments are clearly in substantial agreement. The single best fit to the MiniBoone data has *A* nearly maximal. But the likelihood distribution is fairly flat over a large parameter range, and *A* bigger than 10% seems to be excluded by limits from experiments at reactors.

Violating *CP* symmetry

Taken seriously and together, the MiniBoone antineutrino result and its LANL antecedent appear to reveal a new Δm^2 much larger than the sum of those that fit the solar and atmospheric oscillation data. That inequality would require a fourth neutrino mass eigenstate, predominantly sterile in flavor, and presumably much heavier than the other three.

But given the absence of any oscillation signal in the earlier neutrino-mode MiniBoone data, a single sterile neutrino state probably won't do. Incorporating that kind of *CP* violation into the standard model of particle theory requires interference between the couplings of *two* different sterile mass eigenstates to the known neutrinos.

Therefore MiniBoone team member Georgia Karagiorgi (MIT) and coworkers have tried to fit all three accelerator results plus limits from other relevant experiments with a very general model with two sterile mass states.[2] "We did succeed in fitting the neutrino and antineutrino data separately," says Karagiorgi. "But the two fits weren't mutually compatible."

"The failure to get a global fit with so general a model is instructive," says Fermilab theorist Boris Kayser. "It suggests that if the data faithfully reflect nature, they may be hinting at new interactions beyond the standard model." And indeed, theorists Evgeny Akhmedov and Thomas Schwetz at the Max Planck Institute for Nuclear Physics in Heidelberg have now reported a global fit with just one sterile neutrino state plus non-standard-model interactions.[3]

The MiniBoone team is continuing to run in antineutrino mode, hoping at least to double its event tally before Fermilab's accelerator complex is scheduled to shut down in March 2012 for major reconfiguration.

Bertram Schwarzschild

References

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Isotope ratios hint at a piece of pristine Earth

Could any material on Earth have remained isolated and undisturbed for 4.5 billion years? And if it did, how could we tell?

A few humans have been from the Earth to the Moon, and many more have been around the world in 80 days or fewer. But no one has yet made a journey to the center of the Earth. Our experience with the planet on which we live is almost entirely confined to the material and information that makes its way to the surface.

For that reason and others, precise measurements of Earth's overall composition are difficult or impossible. The continental crust, the most familiar part of Earth for most of us, is not a representative sample: Its composition is not even the same as that of the crust beneath the oceans. The difference is attributed to the effects of partial melting of the silicate mantle that lies beneath the crust. Certain incompatible elements—so called because they strain the crystal lattices of the solid mantle—were preferentially pushed out of the solid and into the melt. The continents formed from the melt; the oceanic crust formed, and is constantly regenerated, from the material left behind in the upper mantle, depleted in the incompatible elements. Since then, volcanism, tectonic-plate movements, and thermal convection have all served to transport material within and across the crust and mantle, slowly stirring the silicate portion of Earth like a batch of cookie dough.

Geochemists have long assumed, quite reasonably, that Earth as a whole has the same composition as the rest of the solar system, best represented by certain meteorites called chondrites. The chondrites never underwent the large-scale differentiation that Earth did, so it's easy to measure their compositions. Their isotopic compositions, in particular, yield important clues about long-gone radioactive elements and their abundances on Earth.

In 2005, however, Richard Carlson and his postdoc Maud Boyet made a surprising discovery[1] (see also PHYSICS TODAY, September 2005, page 19). Compared to the chondrites, every terrestrial sample they looked at was anomalously rich in neodymium-142, the decay product of relatively short-lived samarium-146. It follows that either Earth formed with significantly more Sm and less Nd than the rest of the solar system or it contains a hidden Sm-poor, Nd-rich reservoir that's never been observed.

Now, partially based on that discovery, Matthew Jackson—another of Carlson's postdocs, now at Boston Univer-

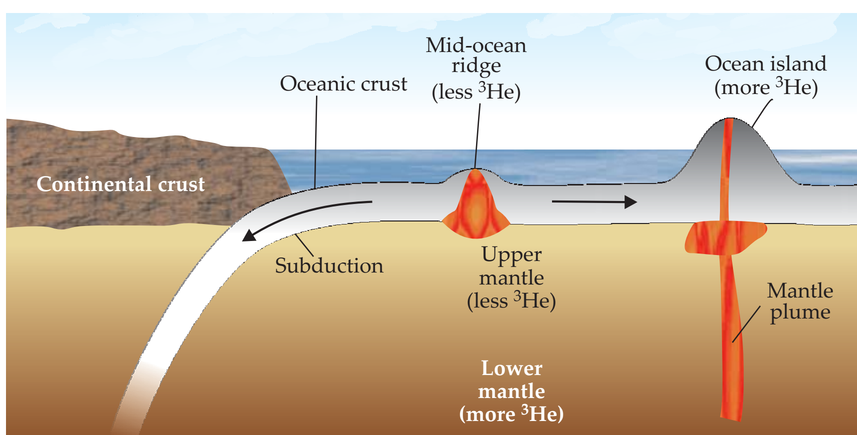

Figure 1. As oceanic crustal plates pull apart at the mid-ocean ridges, upper-mantle material melts and wells up to create new crust. The old crust subducts, or sinks beneath a neighboring plate back into the mantle. Ocean islands, in contrast to the ridges, form from molten plumes originating deep within the mantle. In each process, the molten mantle gives up some of its helium, including primordial ^{3}He that is never replaced. The upper mantle is thought to be more processed and more degassed than the lower mantle, so the mid-ocean ridges contain less ^{3}He than the ocean islands.