Reactor experiment reveals neutrino oscillation's third mixing angle

A nonzero value for this elusive parameter offers a possible explanation for the cosmic shortage of antimatter.

A major neutrino experiment set amidst six nuclear reactors on Daya Bay near Hong Kong has revealed a long-sought result. Having measured very small deficits of electron antineutrinos ($\overline{\nu}_e$) at various short distances from the reactors that create them, the international Daya Bay collaboration reports that θ_{13}, last of the three mixing angles that characterize neutrino oscillation, is definitely not zero.[1] In fact, it turns out to be big enough for experimenters now to begin investigating the role of neutrinos in creating the manifest matter–antimatter asymmetry of the cosmos.

The survival of so little antimatter from the Big Bang requires that some fundamental interactions violate *CP* symmetry—invariance under the combined operations of mirror inversion (*P*) and charge conjugation (*C*), the replacement of particles by their antiparticles. It's long been known that the weak interactions of quarks exhibit some *CP* violation. But that violation is too small to explain the cosmological asymmetry.

Hence the fervent interest in θ_{13}. If not the quarks, then perhaps neutrinos might violate *CP* strongly enough to do the trick. But within the purview of the standard theory of particle physics, any neutrino *CP* violation requires that all three mixing angles be nonzero. Earlier searches, having found no clear signal of a nonzero θ_{13}, concluded that it is at best significantly smaller than the other two mixing angles.

Mixing and oscillation

A neutrino is created or detected in one of three flavors, associated with the three charged leptons: electrons, muons, and taus. The three flavor eigenstates are different superpositions of the three neutrino-mass eigenstates. Because of quantum interference between mass states, a neutrino created with one flavor undergoes oscillatory flavor metamorphosis as it travels. Neutrino oscillation over large distances is well attested for MeV electron neutrinos created in the Sun and GeV muon neutrinos (ν_μ) created high in the atmosphere by cosmic rays. Those observations require that there must be three *different* neutrino masses: m_1, m_2, and m_3.

The misalignment between the flavor and mass basis states is parameterized by the three independent mixing angles θ_{12}, θ_{23}, and θ_{13}. To good approximation, neutrino oscillation in any one observational regime of distance and neutrino energy is characterized by just one θ_{ij} and the corresponding $\Delta m^2_{ji} \equiv |m_j^2 - m_i^2|$. For example, the probability that a ν_μ of energy E, created in the upper atmosphere, has a different flavor after a journey of distance L is

$$P_{\text{atmos}} = \sin^2 2\theta_{23} \sin^2(L/\lambda_{23}),$$

where the energy-dependent oscillation length λ_{23} is given by $4\hbar cE/\Delta m^2_{32}$.

From the atmospheric neutrino observations, θ_{23} is known to be close to 45° and Δm^2_{32} is 2.4×10^{-3} eV^2. The solar-neutrino data yield about 33° for θ_{12} and 8×10^{-5} eV^2 for Δm^2_{21}. It follows immediately that Δm^2_{31} (by definition equal to $\Delta m^2_{32} + \Delta m^2_{21}$) is close to Δm^2_{32}. So it was already clear before the Daya Bay experiment and Double Chooz, its smaller predecessor in France, that any θ_{13} oscillation of reactor antineutrinos, with typical energies of a few MeV, would have oscillation lengths λ_{13} of only a few kilometers.

The question facing the Daya Bay team was whether the oscillation amplitude $\sin^2 2\theta_{13}$ for the disappearance of reactor antineutrinos over such distances would be big enough to detect. Recent data from Double Chooz had hinted at a nonzero θ_{13} and set an upper limit of 0.16 on $\sin^2 2\theta_{13}$, which is what such experiments measure directly.[2] The Daya Bay $\overline{\nu}_e$ detector array was designed to measure a $\sin^2 2\theta_{13}$ as small as 0.01 in three years of data taking.

Happily, $\sin^2 2\theta_{13}$ turns out to be an order of magnitude bigger than Daya Bay's sensitivity limit. So with just two months of analyzed data in hand, Daya Bay spokesman Yifang Wang (Beijing Institute of High Energy Physics) was able to report in March to a worldwide webcast audience that $\sin^2 2\theta_{13} = 0.092 \pm 0.017$, corresponding to a θ_{13} of about 9°. That's an unexpectedly prompt 5.2-standard-deviation exclusion of the possibility that there are only two nonzero neutrino mixing angles.

Daya Bay

The Daya Bay experiment, primarily a China–US collaboration, extends over a triangular area roughly 2 km on a side. Six power reactors are arrayed in two clusters near two of the triangle's vertices. Near the third vertex is the "far" experimental hall. As shown in figure 1, it houses three of the experiment's six detectors, separated from the reactors by distances (1.5–1.9 km) at which one would expect to find roughly maximal disappearance. The other detectors occupy two "near" halls, each monitoring its cluster of reactors at distances of about 0.5 km. The halls are deep underground to reduce penetration by cosmic-ray muons. But because neutrinos essentially ignore material barriers, every detector sees unimpeded flux from all six reactors.

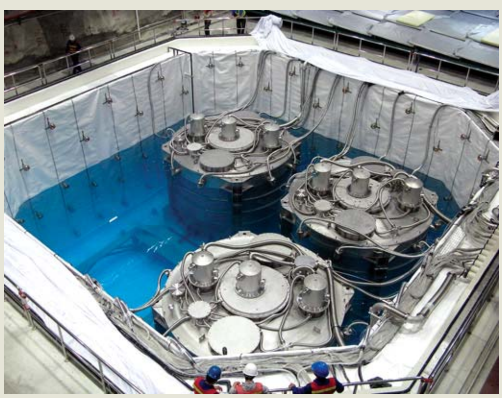

Figure 1. Three electron antineutrino detectors in the far hall of the Daya Bay experiment sit in a water-Cherenkov bath that unmasks cosmic-ray interlopers. The hall, several hundred meters underground, is about 2 km from an array of six power reactors. Each detector measures the $\overline{\nu}_e$ flux from the reactors by recording light flashes due to $\overline{\nu}_e$ collisions in its 20 tons of liquid scintillator.

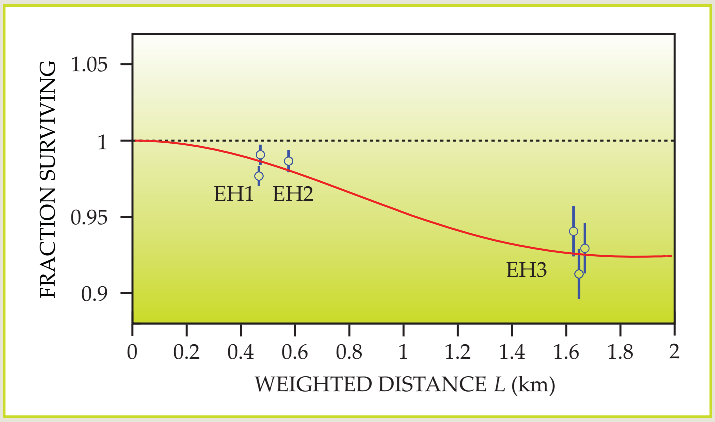

Figure 2. Observed fraction of the $\overline{\nu}_e$ flux expected at each detector in the absence of neutrino oscillation is plotted against the effective mean distance of each experimental hall (EH) from the six reactors that produce the antineutrinos. The curve shows the prediction from the best neutrino-oscillation fit to the flux-shortfall data. (Adapted from ref. 1.)

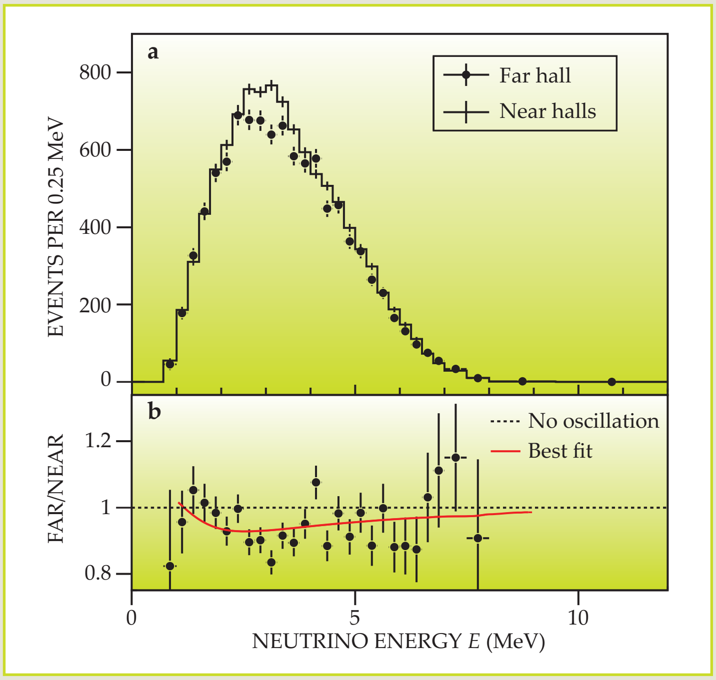

Figure 3. Distortion of the energy spectrum by neutrino oscillation. **(a)** The $\overline{\nu}_e$ energy distribution observed in the far experimental hall (EH3 in figure 2) is compared with what's expected, assuming no neutrino oscillation, from the spectra measured in the near halls (EH1 and 2). The shortfall is concentrated near 3 MeV. **(b)** The ratio of the far-hall observations to those no-oscillation expectations agrees well with the best oscillation fit to all the Daya Bay data. (Adapted from ref. 1.)

On those distance scales, the probability that flavor oscillation will render a $\overline{\nu}_e$ invisible at a distance L from the reactor that created it is

$$P_{\text{react}} = \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{31} L / 4\hbar c E),$$

where θ_{13} was the only unknown, to be determined by shortfalls in the near and far detectors. The energy spectrum of antineutrinos emerging from the reactors peaks near 3 MeV.

At the heart of each detector is 20 tons of gadolinium-doped liquid scintillator monitored by several hundred photomultiplier tubes. Electron antineutrinos from the reactors are detected by their inverse-beta-decay reactions

$$\overline{\nu}_e + \text{p} \rightarrow \text{e}^+ + \text{n}$$

with hydrogen nuclei in the scintillator. The scintillation light generated by the emerging positron provides an approximate measure of the incident antineutrino's energy.

Of course, radioactive and cosmic-ray interlopers produce spurious scintillation signals in spite of elaborate shielding measures. That's why the scintillator is laced with Gd, which has an enormous capture cross section for neutrons. That capture and its subsequent nuclear-decay cascade produce a characteristic 8-MeV scintillation about 30 μs after the positron signal. So, to minimize backgrounds, the experimenters require a candidate $\overline{\nu}_e$ event to exhibit both a prompt e^+ signal and a delayed signal consistent with n capture by a Gd nucleus.

Disappearance and appearance

The best fit for $\sin^2 2\theta_{13}$ was determined from the $\overline{\nu}_e$ shortfalls—relative to expectations in the absence of oscillation—observed by each of the six detectors in 55 days of data taking last winter. Figure 2 summarizes those shortfalls and compares them with what the best oscillation fit predicts at their various distances from the reactors. The weighted mean distances in the plot take account of different reactor power levels and the trivial inverse-square falloff of flux with distance.

Figure 3a compares the $\overline{\nu}_e$ energy spectrum observed in the far hall with what's expected, assuming no oscillation, from the near-hall observations. As the theory predicts, the observed shortfall is energy dependent; it's greatest near 3 MeV. Figure 3b shows that the observed spectral distortion is well described by the best oscillation fit.

The uncertainty on the $\sin^2 2\theta_{13}$ measurement is, for now, dominated by limited statistics. "With two more detectors on the way and three more years of running, the error could come down to 4%," says Steven Kettell (Brookhaven National Laboratory), chief scientist for the experiment's US contingent. Knowing θ_{13} with precision is important for fundamental particle physics as well as for cosmology.

A nonzero θ_{13} is necessary—but not sufficient—for *CP* violation in neutrino interactions. Because there are three nonzero mixing angles, the unitary matrix that describes all the oscillations has an extra degree of freedom: an independent phase factor $e^{i\delta}$ that dictates the degree of *CP* violation. The situation is quite similar to quark-flavor mixing, in which three mixing angles plus one complex phase account for all the *CP* violation thus far observed (see PHYSICS TODAY, December 2008, page 16).

Standard theory can't predict δ. It might be zero, in which case all neutrino *CP*-violation bets are off. But it can be measured—now that all three mixing angles are known—by accelerator experiments designed to monitor the appearance, over long distances, of other flavors in GeV ν_μ beams from accelerators that create their parent pions in sufficient profusion. Such a one is the proposed Long-Baseline Neutrino Experiment (LBNE). The plan is to direct an intense ν_μ beam from Fermilab at a detector inside the DUSEL underground laboratory in South Dakota. But LBNE has funding problems, and its future is in question (see page 30 of this issue).

The path from establishing neutrino *CP* violation to explaining the cosmic antimatter shortage is not straightforward. Cosmologists generally favor the idea that the *CP*-violating neutrinos actually responsible for the disappearance of antimatter after the Big Bang were not the light ones we know—all of them lighter than 1 eV. (For comparison the electron's mass is 0.5 MeV.) Rather, they were short-lived, ultramassive neutrinos, impervious to the standard weak interactions, proposed by a number of theorists around 1980 to explain why neutrinos are so much lighter than the charged leptons and quarks.

The putative heavy neutrinos in that widely credited "seesaw model" have masses something like 10^{10} GeV, so that the quark and charged-lepton masses would approximate the geometric mean of the light and heavy neutrinos. The lighter the one, the heavier the other; hence the seesaw metaphor. The immediate relevance of the Daya Bay result for cosmology, then, is that the degree of *CP* violation by the heavy seesaw neutrinos should be comparable to that of the neutrinos we know.

As we go to press, the South Korean RENO collaboration reports that its reactor experiment has confirmed Daya Bay's $\sin^2 2\theta_{13}$ measurement.[3]

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References

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2. Y. Abe et al. (Double Chooz collaboration), *Phys. Rev. Lett.* **108**, 131801 (2012).
3. J. K. Ahn et al. (RENO collaboration), http://arxiv.org/abs/1204.0626.

Custom shapes from swell gels

A new lithographic method patterns UV-sensitive, water-absorbing polymers to produce complex, self-folding shapes.

The curves and folds of a flower, the wrinkling of our skin, and the wavy edge of torn plastic are among the countless examples of patterns that emerge from the physics of thin elastic sheets. As cells grow nonuniformly in a petal, say, or as ripped plastic deforms along its edge, stresses build up. To accommodate the deformation and relieve the stress, the material has to either compress internally or bend. Both distortions cost energy, but which one Nature chooses depends directly on thickness: The thinner the sheet, the cheaper it is to buckle out of the plane.

For the past decade, researchers have been striving to translate that competition between compression and bending into practical strategies for controlling the shape of a thin film embedded in our three-dimensional world. The mechanism by which in-plane stresses actually break a sheet's local symmetry is subtle, mathematically formidable, and not entirely understood. But fortunately, one can turn to differential geometry, which has long been deeply entwined with the theory of elasticity, to engineer structures (see the article by Michael Marder, Robert Deegan, and Eran Sharon in PHYSICS TODAY, February 2007, page 33). According to Carl Friedrich Gauss's famous theorema egregium ("remarkable theorem"), the metric tensor of a surface—that is, the collection of distances between points in a coordinate system—is all that's needed to locally determine the surface's curvature.

In 2007 Eran Sharon realized the theorem could be used as a shape-selecting principle, provided one could inscribe the required lateral stresses on a flat sheet to generate a new target metric. In response to those stresses, the sheet would ideally settle into an equilibrium configuration that, properly buckled, minimizes the elastic energy and realizes the new metric. As proof of principle, he and colleagues from the Hebrew University of Jerusalem demonstrated the idea, at least for axially symmetric shapes, using disks of temperature-sensitive polymer gels.[1]

Now, University of Massachusetts Amherst researchers led by polymer scientist Ryan Hayward and physicist Christian Santangelo have generalized the idea into a lithographic method that can produce, at least in principle, a nearly arbitrary 3D shape.[2] What's more, it's inexpensive, easily reproducible, and potentially scalable—from areas under a square millimeter, as tested in the first implementations, to, says Hayward, areas of several square centimeters.

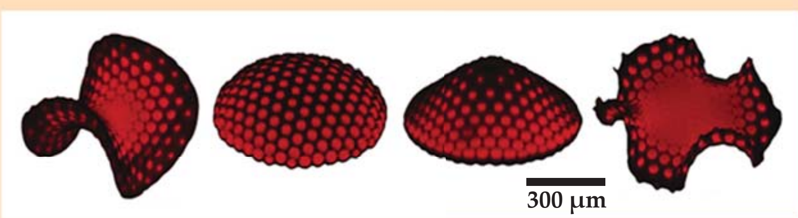

Figure 1. Originally flat sheets of polymer gel adopt a Gaussian curvature that is either positive (as with the dome and cap in the middle) or negative (as with the saddle and ruffled edges of the Enneper surface on the ends), depending on how they are patterned with UV light. The larger the red dots, the greater the UV exposure and the smaller the swelling. (Adapted from ref. 2.)

Designed response

The method starts with a thin (typically 10-μm) film of hydrogel, a cross-linked network of polymer chains. When cooled in a water bath to about 22 °C, the gel swells by absorbing water until the osmotic pressure balances the pressure exerted by the polymer chains. The