

Viewpoint

Rethinking the Neutrino

Janet Conrad

Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139, USA

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*The Daya Bay Collaboration in China has discovered an unexpectedly large neutrino oscillation.*Subject Areas: **Particles and Fields**

A Viewpoint on:

Observation of Electron-Antineutrino Disappearance at Daya Bay

F. P. An et al.

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To some, this may be the year of the dragon, but in neutrino physics, this is the year of θ_{13} . Only one year ago, this supposedly “tiny” mixing angle, which describes how neutrinos oscillate from one mass state to another, was undetected, but the last twelve months have seen a flurry of results from experiments in Asia and Europe, culminating in the result from the Daya Bay Collaboration, now being reported in *Physical Review Letters*, that shows that θ_{13} is not small after all [1]. A not-so-tiny mixing angle forces us to rethink theory, calling for new explanations for why quarks and leptons are so different. It also opens the door to new experiments, potentially allowing the discovery of *CP* violation—a difference between neutrinos and antineutrinos that may be related to the matter asymmetry of the early universe.

Neutrino oscillations are a simple idea that can be derived in any intermediate level quantum mechanics class. In the weak interaction, neutrinos are produced and detected in “flavor” eigenstates—electron (e), muon (μ), and tau (τ). However, the Hamiltonian depends on energy, which in turn depends on mass. In a simple two-neutrino model, with just the muon and electron flavors, the mass eigenstates (ν_1 and ν_2) can be rotated with respect to the flavor eigenstates,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}. \quad (1)$$

Mixing between flavor and mass states sounds strange, but quarks do it. Why shouldn't neutrinos do it too?

A result of this mixing is that the neutrino born via the weak interaction in one flavor state will evolve with time to have some probability of interacting as the other flavor. The probability of this oscillation is equal to $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$, in the (admittedly strange, but useful) units of L (in meters, m), E (in mega-electron-volts, MeV), and $\Delta m^2 = m_2^2 - m_1^2$ (in eV^2). This formula depends on two fundamental parameters: the mixing angle, θ , which sets the amplitude for the oscil-

lation probability, and the squared mass splitting, Δm^2 , which affects the wavelength of the oscillation. It also depends on two experimental parameters: L , the distance the neutrinos have traveled from source to detector, and E , the energy of the neutrino. While Eq. (1) is a simplified two-neutrino picture, expanding to the three known flavors, ν_e , ν_μ , and ν_τ , it follows a similar line of thought; in this case the two-dimensional rotation matrix with one angle, θ , becomes a three-dimensional matrix with three Euler angles: θ_{12} , θ_{23} , and θ_{13} .

The story of neutrino oscillations measurements begins with an article by Davis on a search for solar neutrinos that appeared in *Physical Review Letters* in 1964 [2] (also a year of the dragon!). But despite Davis' subsequent discovery of a very obvious signature, it took a long time for physicists to understand and correctly interpret the data as a problem with the underlying particle physics. In the standard model, neutrinos are massless. This assumption is necessary to explain parity violation, a 100% asymmetry in the spin dependence of beta decay. But if neutrinos have zero mass, $\Delta m^2 = 0$ in Eq. (1), the oscillation probability goes to zero, so oscillations cannot occur. The standard model was so successful in all other aspects of particle physics that it took years and many careful follow-up experiments for physicists to accept the experimental reality: neutrinos have mass and do oscillate.

As we have continued to study oscillations, we have learned that neutrinos are not like the other particles in many ways. For one thing, the mass splittings are very small compared to those of their charged particle partners. For another, two of the mixing “Euler” angles, θ_{12} and θ_{23} are very large—exactly the opposite of the mixing matrix seen in quarks. But the last mixing angle, θ_{13} , remained elusive, despite a dedicated search by two experiments: Palo Verde, in Arizona [3], and Chooz, in France [4]. Many people assumed that the θ_{13} was very tiny, partially inspired by the phenomenology of

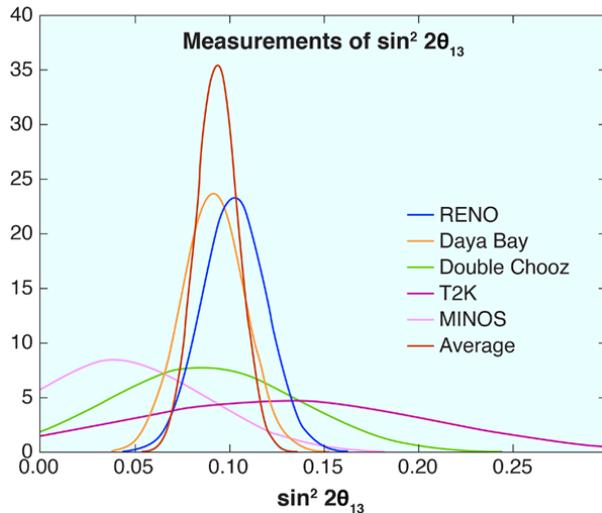


FIG. 1: Measured values of $\sin^2 2\theta_{13}$. Several experimental collaborations around the world have measured the mixing angle θ_{13} , which describes the probability that an electron neutrino will oscillate from one mass state to another, and found it to be much larger than expected. The normalized Gaussians shown here are centered on the measurements of $\sin^2 2\theta_{13}$, where the widths of the curves indicate the uncertainty of the measurement. (APS/Carin Cain)

so-called tri-bi-maximal mixing [5]. In its purest form, this idea, put forward in 2002 to explain the pattern of mixing angles, requires $\theta_{13} = 0$. Various other theories gave order of magnitude predictions from 1×10^{-5} to 1×10^{-2} . Experimentalists responded by designing for small $\sin^2 2\theta_{13}$ values. The present-generation experiments were designed to reach $\sin^2 2\theta_{13} = 0.01$, but the Neutrino-Facility-of-Our-Dreams could potentially reach 1×10^{-4} .

Suddenly, this view has changed. The first challenges to expectation have come from accelerator-based “appearance” experiments, which look for interactions of a new flavor (ν_e) in a sea of interactions of the original flavor (ν_μ). While this sounds like a search for a needle in a haystack, in a well-designed experiment, like T2K in Japan (see 18 July 2011 Viewpoint) [6] and MINOS [7] at Fermilab in Illinois, the needle sticks out. Nevertheless, these experiments had low statistics and confusing results. The errors were relatively large and the results were still consistent with $\theta_{13} = 0$. But the central values were not tiny (see Fig. 1)—a first clue that θ_{13} was going to be larger than expected. Appearance experiments are problematic because, in the case of three neutrinos, they are sensitive to unknown parameters beyond θ_{13} , including the ordering of the mass states (called “the mass hierarchy”) and the CP -violating parameter. On the other hand, disappearance experiments have a much simpler oscillation formula, which reduces to $P_{\text{disapp}} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$.

Daya Bay, which is located in China, is illustrative of the new generation of disappearance experiments. This

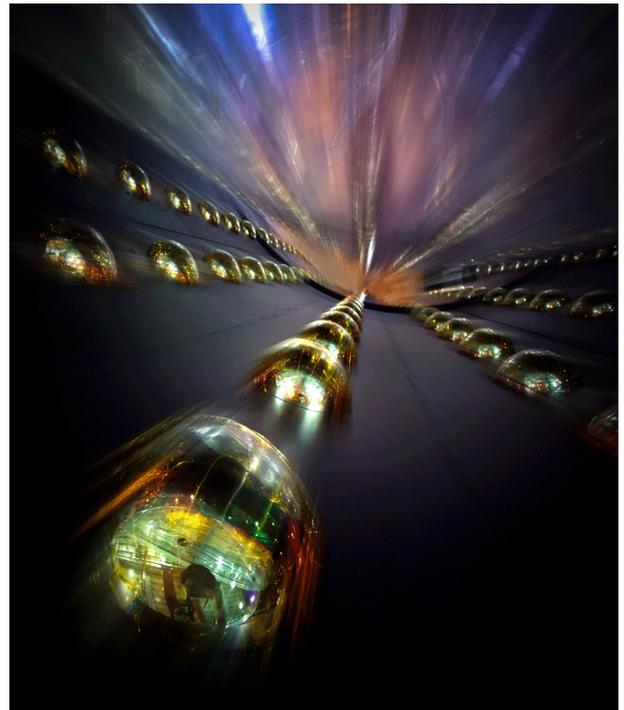


FIG. 2: The interior of one of the six antineutrino detectors at Daya Bay. (Roy Kaltschmidt, Lawrence Berkeley National Laboratory)

experiment is housed at one of the new ultrapowerful reactor complexes that are coming online worldwide. Reactors are copious sources of antielectron neutrinos ($\bar{\nu}_e$), for free! The idea is to search for antineutrino disappearance as a function of distance, so experiments have multiple detectors. Daya Bay uses six (Fig. 2). These can be placed at varying distances (L) from the reactor source to trace the oscillation wave. The antineutrinos interact with free protons in the scintillator oil of the detector via an “inverse beta-decay” process that produces a positron and a neutron: $\bar{\nu}_e + p \rightarrow e^+ + n$. This interaction has a cross section known to high precision; the energy of the antineutrino can be fully reconstructed, and the positron followed by a subsequent neutron capture produces a coincidence signal that separates the signal from background. The development of long-lifetime gadolinium-doped scintillator was a crucial breakthrough in detecting θ_{13} , since this improves the neutron capture time by more than an order of magnitude.

In fact, the first reactor experiment to present a result was Double Chooz, in France [8]. The central value was again relatively large (Fig. 1), and at that point, it began to sink in: θ_{13} must be big. Within five months, Double Chooz’s experiment was followed by the Daya Bay result, $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$ [1]. In particle physics, a statistical significance of 5σ is needed to claim a discovery, and Daya Bay’s measurement was conclusive: θ_{13} is nonzero. The central value of their measurement was large and in excellent agreement with

Double Chooz. Hot on Daya Bay's heels was the result from the RENO experiment [9] in Korea, which yet again agreed with $\sin^2 2\theta_{13} \sim 0.1$.

What does large θ_{13} mean? It means that the neutrino community is suddenly busy organizing workshops to re-think the next steps. With a well-measured value of θ_{13} we can pursue the mass hierarchy and the CP -violation parameter in appearance experiments that should come online soon. We shall see if measurements of these new parameters also defy expectations.

In one year, we went from knowing nothing, to having a full picture of this mixing angle. We found the θ_{13} dragon, and it roared!

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About the Author

Janet Conrad



Janet Conrad graduated with a B.A. from Swarthmore College, received her M.Sc. from Oxford University and her Ph.D. from Harvard University. She was a postdoctoral researcher and then faculty with Columbia University. She then moved to the Massachusetts Institute of Technology. She has worked in the field of neutrino studies for 20 years, and was co-spokesperson of the MiniBooNE experiment. She is the recipient of the Maria Goeppert-Mayer Award of the American Physical Society. She is also a Sloan Fellow and a Guggenheim Fellow.