

Review of Neutrino Mixing and Results from Daya Bay

L Whitehead

University of Houston, Houston, TX USA
For the Daya Bay Collaboration

E-mail: lawhitehead@uh.edu

Abstract. Experimental observations have established that neutrinos undergo flavor oscillations as they propagate due to quantum mechanical mixing between the mass states and flavor states. The Daya Bay reactor neutrino experiment has observed the disappearance of electron-type antineutrinos from nuclear reactor cores at the Daya Bay nuclear power complex located in China. This observation allowed Daya Bay to make a measurement of the last neutrino mixing angle, which was previously only known to be small in comparison to the other neutrino mixing angles. An overview of the current status of neutrino oscillation measurements will be presented, followed by the most recent results from Daya Bay and prospects for JUNO, a future neutrino experiment in China.

1. Neutrino Oscillations

Neutrino mixing between the three flavor states (ν_e, ν_μ, ν_τ) and the mass states (ν_1, ν_2, ν_3) can be described by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and one phase parameter, δ . Due to this mixing, neutrinos undergo flavor oscillations in which a neutrino created in one flavor state can be observed at a later time in a different flavor state. The probability for flavor oscillations depends on the mixing parameters above and the differences in the squared masses of the neutrinos, Δm_{21}^2 and Δm_{31}^2 , where $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and $\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$. All three mixing angles have been measured, as well as the magnitudes of both the mass splittings. The measured values of these parameters are summarized in Table 1. Both the phase parameter δ and the mass hierarchy (the sign of the larger mass splitting Δm_{31}^2) are unknown at this time. The octant of θ_{23} is also an open question, because the current measured values allow for both $\sin^2 \theta_{23} < 0.5$ and $\sin^2 \theta_{23} > 0.5$ within the experimental uncertainties.

Prior to 2012, neutrino experiments had only been able to set limits on the mixing angle θ_{13} . Long-baseline accelerator neutrino experiments can measure θ_{13} by observing muon neutrino to electron neutrino transitions. The T2K experiment has recently confirmed electron neutrino appearance in a muon neutrino beam with a significance of 7.3σ [1]. However, the muon neutrino to electron neutrino transition probability also depends on δ and the sign of Δm_{31}^2 , both of which are unknown. Another way to measure θ_{13} is to search for the disappearance of electron antineutrinos from a reactor. The electron antineutrino survival probability in this channel is

$$P_{ee} = 1 - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2 \Delta_{21} - \sin^2(2\theta_{13})(\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}), \quad (1)$$

where $\Delta_{ij} = 1.267\Delta m_{ij}^2 \frac{L(m)}{E(\text{MeV})}$. At short baselines of around 1 km, the $\sin^2(2\theta_{13})$ term is dominant. Due to the ability to accumulate large statistics in a relatively short amount of time and the lack of dependence on δ or the mass hierarchy in this channel, a short-baseline reactor experiment is ideal for measuring θ_{13} .

Table 1. Summary of measured values

| Measured Value | Description |
|---|-----------------------------------|
| $\tan^2 \theta_{12} = 0.44 \pm 7\%$ | Combined solar and KamLAND[2] |
| $\sin^2(2\theta_{13}) = 0.084 \pm 6\%$ | Daya Bay |
| $\sin^2 \theta_{23} = 0.51 \pm 11\%$ | T2K[3] |
| $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2 \pm 3\%$ | Combined solar and KamLAND[2] |
| $ \Delta m_{31}^2 \approx \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \pm 4\%$ | MINOS/MINOS+[4], T2K[3], Daya Bay |

2. The Daya Bay Experiment

Daya Bay measures the antineutrino spectrum from six reactor cores located at the Daya Bay nuclear power complex in China. The Daya Bay detectors are located underground in experimental halls (EHs) built beneath mountains that provide shielding from cosmic ray background. There are two near sites (EH1 and EH2) close to the reactor cores and one far site (EH3) at a distance of ~ 2 km from the cores. Multiple functionally-identical antineutrino detectors (ADs) are placed at each site. The relative near-far measurement between nearly identical ADs allows for the cancellation of detector-related systematic uncertainties. The ADs use ~ 20 tons of gadolinium-loaded liquid scintillator as a target. Surrounding the target region is ~ 20 tons of undoped liquid scintillator to detect gammas that escape the target volume. The outer region of each AD contains ~ 40 tons of mineral oil to shield the inner volumes. The ADs are instrumented with 8-inch photomultiplier tubes (PMTs) mounted on the wall of the containment vessel in the mineral oil region. Antineutrinos are detected via the inverse beta decay (IBD) interaction, $\bar{\nu}_e p \rightarrow e^+ n$. The signal is a coincidence between the prompt energy due to the positron and the delayed energy (~ 8 MeV) due to the neutron capture on gadolinium. The neutron capture time on gadolinium is approximately $30 \mu\text{s}$. A muon system is employed to shield against natural radioactivity and fast neutrons and to tag cosmic muons that produce background in the ADs. The muon veto system consists of an active water shield and resistive plate chambers (RPCs). The ADs are placed inside the water pool such that there is at least 2.5 m of water shielding in every direction. The water pool is instrumented with 8-inch PMTs to detect the Cherenkov light emitted by muons passing through the water. The pool is divided into inner and outer regions separated by reflective Tyvek sheets. The RPC modules are installed on top of the pool.

Two ADs were installed in EH1 and took data for 90 days beginning in August 2011. This data set was used for a side-by-side comparison of ADs that established the residual uncorrelated detector uncertainty [5]. During this period, one AD was installed in EH2 and two ADs were installed in the EH3. Beginning in December 2011, data was taken in this 6-AD configuration for a total of 217 days. The first observation of electron antineutrino disappearance at Daya Bay was based on 55 days of data and measured a non-zero value of θ_{13} with a significance of 5.2σ [6]. An updated measurement was published based on 139 days of data [7]. The first spectral measurement by Daya Bay was based on the entire 217 days of data in the 6-AD configuration [8]. In the summer of 2012, the two final ADs were installed and a series of special

calibrations were performed. Daya Bay has been taking data with all 8 ADs (two at each near site and four at the far site) since October 2012. The results presented in the next section are based on 621 days of data-taking, including the entire 6-AD period.

3. Recent Results from Daya Bay

IBD interactions are selected by first rejecting events caused by PMT light emission. Candidate events are selected by requiring the coincidence of a prompt signal with energy between 0.7 and 12 MeV and a delayed signal with energy between 6 and 12 MeV within a time window of 1-200 μ s. Candidate coincidences occurring within 0.6 ms of a water pool muon, 1 ms of an AD muon, and 1 s of an AD showering muon are rejected from the sample. A multiplicity cut is performed to ensure that only isolated candidate pairs are selected. In total, Daya Bay has observed more than one million IBD interactions.

The top panel of Figure 1 shows the measured spectrum at the far site compared to the expected spectrum based on the near site data both without oscillations and with the best fit oscillations included. The bottom panel shows the ratio of the measured to expected spectrum. The observed relative rate deficit and relative spectral distortion are highly consistent with the oscillation interpretation.

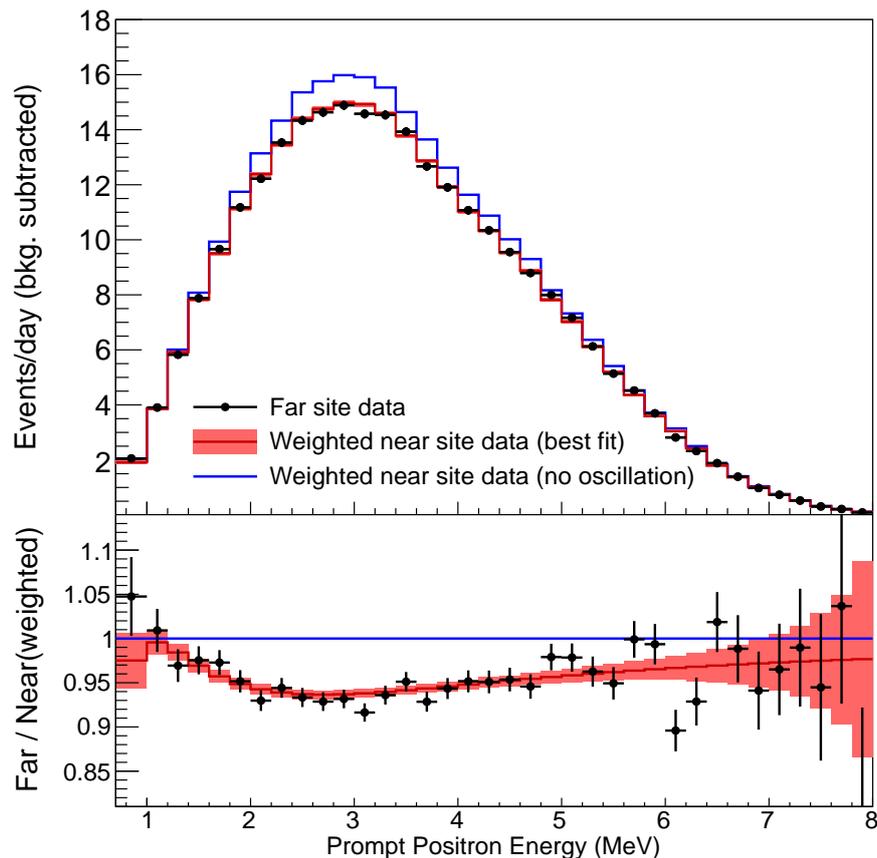


Figure 1. The top panel shows the measured spectrum at the far site compared to the expected spectrum based on the near site data both without oscillations and with the best fit oscillations included. The bottom panel shows the ratio of the measured to expected spectrum. The uncertainties are statistical only.

Because oscillations of reactor antineutrinos at a baseline near 1 km are mostly due to the Δ_{3i} terms in Equation 1 and $\Delta m_{21}^2 \ll |\Delta m_{31}^2| \approx |\Delta m_{32}^2|$, we define the effective mass-squared difference $\Delta_{ee} = \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}$ for the analysis. Figure 2 shows the 1σ , 2σ , and 3σ allowed regions for $\sin^2(2\theta_{13})$ and $|\Delta m_{ee}^2|$ based on the comparison of the rates and prompt energy spectra measured by the near site and far site ADs. The best fit values of $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$ and $|\Delta m_{ee}^2| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \text{ eV}^2$ are also indicated in the figure.

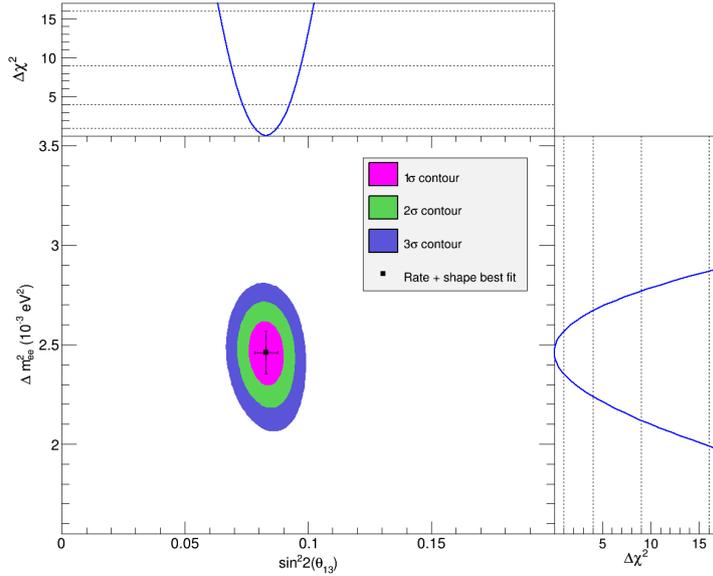


Figure 2. The 1σ , 2σ , and 3σ allowed regions for $\sin^2(2\theta_{13})$ and $|\Delta m_{ee}^2|$ based on the comparison of the rates and prompt energy spectra measured by the near site and far site ADs. The best fit values are indicated by the point. Also shown is the dependence of $\Delta\chi^2$ on each of the parameters.

Daya Bay has also recently announced an independent measurement of $\sin^2(2\theta_{13}) = 0.083 \pm 0.018$ by performing a rate-only analysis using neutron captures on hydrogen during the 217 days of the 6-AD data period [9]. A search for a light sterile neutrino has also been performed using data from the 6-AD period, placing stringent limits in the region of $10^{-3} \text{ eV}^2 < \Delta m_{41}^2 < 0.1 \text{ eV}^2$, a region which was largely unexplored [10].

4. JUNO

Because the reactor antineutrino disappearance probability depends on both Δm_{31}^2 and Δm_{32}^2 as shown in Equation 1, a Fourier transform of the L/E spectrum of reactor antineutrinos could reveal the mass hierarchy [11]. JUNO is a planned next-generation neutrino experiment that will seek to determine the mass hierarchy by a precision measurement of the reactor antineutrino spectrum at a baseline of 60 km. Unlike long-baseline accelerator neutrino experiments, JUNO's approach has the advantage of not depending on δ or θ_{23} . However, very good energy resolution is necessary to achieve the mass hierarchy determination. JUNO will be a 20-kt liquid scintillator detector with approximately 77% photocathode coverage to achieve an energy resolution of $3\%/\sqrt{E}$. JUNO will have a rich physics program in addition to the mass hierarchy measurement, including precision oscillation parameter measurements, supernova neutrinos, geoneutrinos, solar neutrinos, sterile neutrinos, atmospheric neutrinos, or other exotic searches. Civil construction is expected to begin in 2014, with data-taking scheduled for 2020 [12].

5. Summary

In summary, Daya Bay has measured $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$ and $|\Delta m_{ee}^2| = 2.44_{-0.11}^{+0.10} \times 10^{-3} \text{ eV}^2$ with 621 days of data. This is the most precise measurement of $\sin^2(2\theta_{13})$ to date, and the most precise measurement of $|\Delta m^2|$ in this channel, comparable in precision and consistent with the measurements from muon neutrino disappearance experiments. The precision of both parameters is expected to reach 3% with approximately 3 more years of data.

6. References

- [1] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **112**, 061802 (2014) [arXiv:1311.4750 [hep-ex]].
- [2] B. Aharmim *et al.* [SNO Collaboration], Phys. Rev. C **88**, 025501 (2013) [arXiv:1109.0763 [nucl-ex]].
- [3] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **112**, 181801 (2014) [arXiv:1403.1532 [hep-ex]].
- [4] A. Sousa, presented at the XXVI International Conference on Neutrino Physics and Astrophysics, Boston, MA USA, 2014.
- [5] F. P. An *et al.* [Daya Bay Collaboration], Nucl. Instrum. Meth. A **685**, 78 (2012) [arXiv:1202.6181 [physics.ins-det]].
- [6] F. P. An *et al.* [DAYA-BAY Collaboration], Phys. Rev. Lett. **108**, 171803 (2012) [arXiv:1203.1669 [hep-ex]].
- [7] F. P. An *et al.* [Daya Bay Collaboration], Chin. Phys. C **37**, 011001 (2013) [arXiv:1210.6327 [hep-ex]].
- [8] F. P. An *et al.* [Daya Bay Collaboration], Phys. Rev. Lett. **112**, 061801 (2014) [arXiv:1310.6732 [hep-ex]].
- [9] F. P. An *et al.* [Daya Bay Collaboration], arXiv:1406.6468 [hep-ex].
- [10] F. P. An *et al.* [DAYA-BAY Collaboration], arXiv:1407.7259 [hep-ex].
- [11] L. Zhan, Y. Wang, J. Cao and L. Wen, Phys. Rev. D **78**, 111103 (2008) [arXiv:0807.3203 [hep-ex]].
- [12] L. Wen, presented at the XXVI International Conference on Neutrino Physics and Astrophysics, Boston, MA USA, 2014.