Latest progress from the Daya Bay reactor neutrino experiment

Zhe Wang for the Daya Bay Collaboration
Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, China
Department of Engineering Physics, Tsinghua University, Beijing, China
E-mail: wangzhe-hep@mail.tsinghua.edu.cn

Abstract. Recently the Daya Bay reactor neutrino experiment has presented several new results about neutrino and reactor physics after acquiring a large data sample and after gaining a more sophisticated understanding of the experiment. In this talk I will introduce the latest progress made by the experiment including a three-flavor neutrino oscillation analysis using neutron capture on gadolinium, which gave $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \text{eV}^2$, an independent $\theta_{13}$ measurement using neutron capture on hydrogen, a search for a light sterile neutrino, and a measurement of the reactor antineutrino flux and spectrum.

1. Introduction
The basic theory of three-flavor neutrino mixing consists of three mixing angles, one Dirac phase, and two mass-squared differences. After the experimental confirmation of a non-zero $\theta_{13}$, measurements of the Dirac phase, $\delta_{CP}$, which is related to CP violation of leptonic sector, and the sign of $\Delta m^2_{32}$, are the next major goals in neutrino oscillation physics.

To reach the next milestone, the precision of $\theta_{13}$ is important and need to be improved. In [1], it was shown that with the improvement of the precision of $\theta_{13}$ from unknown to 1.5%, the maximum significance of determining $\delta_{CP}$ with several long baseline neutrino experiments will increase from 3 $\sigma$ to 4 $\sigma$. In the recent publication of the T2K experiment [2], the current value of $\theta_{13}$ indicates a positive $\Delta m^2_{32}$ and $\delta_{CP} = -\pi/2$ or $\pi/2$.

The Daya Bay reactor neutrino experiment is located next to six commercial nuclear reactors, each of which has a nominal thermal power of 2.9 GW. The experiment consists of two near halls and one far hall. The power-weighted baselines to the six power reactors are about 500 m and 1.7 km for the near and far halls, respectively. Each near hall has two antineutrino detectors (ADs) and the far hall has four ADs. All eight ADs have an identical three-zone design with 20 tons of gadolinium-loaded liquid scintillator in the innermost zone, 22 tons of liquid scintillator in the middle zone, and 37 tons of of mineral oil in the outermost zone. The reactor electron antineutrinos were detected by the inverse beta decay (IBD) interactions, where the neutron in the final state can be either captured on gadolinium (nGd) or on hydrogen (nH). The neutrino fluxes and energy spectra measured with the far site ADs were compared with the measurements at the near sites and/or reactor predictions. Deficits and distortions were observed.

Two sets of data of the Daya Bay experiments have been taken. The first set of data is 217 days taken from Dec. 2011 to Jul. 2012 with only six ADs installed and the second set of data
is from Oct. 2012 to Dec. 2013 with all eight ADs installed and running. More details of the Daya Bay Experiment can be found elsewhere [3].

In this talk, I will present the latest progress in the measurements of neutrino oscillation parameters with nGd and nH samples, the attempt to search for a light sterile neutrino, and the measurement of the reactor neutrino flux and spectrum.

2. Three-Flavor Neutrino Oscillation Analysis Using nGd

The understanding of the energy response of the antineutrino detectors was improved by studying 1) various constant-energy gamma sources, including $^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{241}$Am,$^{9}$Be and Pu-$^{13}$C which were deployed during special calibration periods, $^{68}$Ge, $^{60}$Co and $^{241}$Am,$^{13}$C, which were employed regularly, natural radioactivities inside the detector, $^{40}$K, $^{208}$Tl, and neutron capture on H, and 2) the $^{12}$B continuous beta decay spectrum from muon spallation products. The improvement led to a smaller energy non-linearity uncertainty and relative energy scale uncertainty.

The best oscillation analysis result is shown in Fig. 1. By analyzing the relative antineutrino fluxes and energy spectra between the near and far detectors, it was got that $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV$^2$ in the three-neutrino framework. The electron antineutrino survival probability as a function of the ratio of the effective propagation distance $L_{eff}$ over the average antineutrino energy $\langle E_{\nu} \rangle$ is shown in Fig. 2. More details about this result can be found in [4].

![Figure 1](image-url) 

**Figure 1.** Regions in the $|\Delta m^2_{ee}|$-$\sin^2 2\theta_{13}$ plane allowed at the 68.3%, 95.5% and 99.7% confidence levels by the near-far comparison of $\bar{\nu}_e$ rate and energy spectra. The best estimates were $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV$^2$ (black point). The adjoining panels show the dependence of $\Delta \chi^2$ on $\sin^2 2\theta_{13}$ (top) and $|\Delta m^2_{ee}|$ (right). The $|\Delta m^2_{ee}|$ allowed region (shaded band, 68.3% C.L.) was consistent with measurements of $|\Delta m^2_{32}|$ using muon disappearance by the MINOS [5] and T2K [6] experiments, converted to $|\Delta m^2_{ee}|$ assuming the normal (solid) and inverted (dashed) mass hierarchy. The plot is from [4].
Figure 2. Electron antineutrino survival probability versus effective propagation distance $L_{\text{eff}}$ divided by the average antineutrino energy $\langle E_{\nu} \rangle$. The data points represent the ratios of the observed antineutrino spectra to the expectation assuming no oscillation. The solid line represents the expectation using the best estimates of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$. The error bars are statistical only. $\langle E_{\nu} \rangle$ was calculated for each bin using the estimated detector response, and $L_{\text{eff}}$ was obtained by equating the actual flux to an effective antineutrino flux using a single baseline. The plot is from [4].

3. Independent $\theta_{13}$ Measurement using nH

A new measurement of the $\theta_{13}$ mixing angle has been obtained via the detection of inverse beta decays tagged by neutron capture on hydrogen. The antineutrino events for hydrogen capture are quite distinct from those for gadolinium capture with largely different systematic uncertainties, allowing a determination independent of the nGd result and an improvement on the precision of $\theta_{13}$ measurement. With the 217-day antineutrino data set obtained with only six antineutrino detectors, the neutrino event rate deficit observed at the far hall was interpreted as $\sin^2 2\theta_{13} = 0.083 \pm 0.018$ in the three-flavor oscillation model, which is statistical error dominant and has all main systematic uncertainties uncoupled with the nGd studies and gave a new independent measurement. Figure 3 shows a comparison of the prompt energy spectra of the IBD events of the far hall and the near halls weighted by the near-to-far baseline ratio, along with the ratio of the measured-to-predicted rates as a function of baseline. Clear evidence for electron antineutrino disappearance was observed. The expected Far/Near ratio based on the best-fit $\sin^2 2\theta_{13}$ value was compared to data and shown in Fig. 3 too. More analysis details can be found in the publication [7].

4. Search for a Light Sterile Neutrino

With the first 217 days of data, a search for light sterile neutrino mixing was performed [8]. The experiment has multiple baselines from the six antineutrino detectors to the six nuclear reactors, and this unique feature makes it possible to test for oscillations to a fourth (sterile) neutrino in the $10^{-3} \ eV^2 < |\Delta m^2_{41}| < 0.3 \ eV^2$ range. The study showed that the relative spectral distortion observed is consistent with the prediction of the three-flavor oscillation model. The excluded region for $\sin^2 2\theta_{14}$ and $|\Delta m^2_{31}|$ can be seen in Fig. 4, where the most of it had not been explored before.
Figure 3. The detected nH energy spectrum of the prompt events of the far hall ADs (blue) and near hall ADs (open circle) weighted according to baseline. The far-to-near ratio (solid dot) with best fit $\theta_{13}$ value is shown in the lower plot. In the inset is the ratio of the measured to the predicted rates in each AD vs. baseline. The plot is from [7].

Figure 4. Exclusion contours for the neutrino oscillation parameters $\sin^2 2\theta_{14}$ and $|\Delta m^2_{41}|$. Normal mass hierarchy is assumed for both $\Delta m^2_{31}$ and $\Delta m^2_{41}$. The red long-dashed curve represents the 95% C.L. exclusion contour with Feldman-Cousins method. The black solid curve represents the 95% CLs exclusion contour. The parameter space to the right side of the contours is excluded. For comparison, Bugey’s [9] 90% C.L. limits is also shown as the green dashed curve. The plot is from [8].
5. Measurement of the Reactor Antineutrino Flux and Spectrum

A new measurement of the neutrino flux and energy spectrum of electron antineutrinos from the six 2.9 GWth nuclear reactors was reported [10]. With the 217 days of data, the IBD yield was measured to be \((1.55 \pm 0.04) \times 10^{18} \text{ cm}^2/\text{GW}/\text{day}\) or \((5.92 \pm 0.14) \times 10^{43} \text{ cm}^2/\text{fission}\). The ratio of the measured flux to the prediction made with the Huber+Mueller (ILL+Vogel) fissile antineutrino model is \(0.946\pm0.022\) (\(0.991\pm0.023\)) and it agrees with results reported by previous short-baseline reactor antineutrino experiments, as seen in Fig. 5. At the energy region of 4-6 MeV, a bump was observed with a local significance of around 4\(\sigma\).

![Image of Figure 5](image-url)

**Figure 5.** The measured reactor \(\bar{\nu}_e\) rate as a function of the distance from the reactor, normalized to the theoretical prediction with the Huber+Mueller model. The rate is corrected for 3-flavor neutrino oscillations at each baseline. The blue shaded region represents the global average and its 1\(\sigma\) uncertainty. The 2.7\% model uncertainty is shown as a band around unity. Measurements at the same baseline are combined for clarity. The Daya Bay measurement is shown at the flux-weighted baseline (573 m) of the two near halls. The plot is from [10].

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**References**

[1] Daya Bay collaboration 2013 *Preprint* arXiv:1309.7961
[2] Abe K et al (T2K Collaboration) 2014 *Phys. Rev. Lett.* **112** 061802
[3] An F et al (Daya Bay collaboration) 2015 *Preprint* arXiv:1508.03943
[4] An F et al (Daya Bay collaboration) 2015 *Phys. Rev. Lett.* **115** 111802
[5] Adamson P et al (MINOS Collaboration) 2014 *Phys. Rev. Lett.* **112** 191801
[6] Abe K et al (T2K Collaboration) 2014 *Phys. Rev. Lett.* **112** 181801
[7] An F et al (Daya Bay collaboration) 2014 *Phys. Rev. D* **90** 071101
[8] An F et al (Daya Bay collaboration) 2014 *Phys. Rev. Lett.* **113** 141802
[9] Declais Y et al 1995 *Nucl. Phys. B* **434** 503
[10] An F et al (Daya Bay collaboration) 2015 *Preprint* arXiv:1508.04233