Recent Results from the Daya Bay Experiment

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Abstract. The Daya Bay reactor neutrino experiment was designed to precisely measure the neutrino oscillation parameter $\theta_{13}$ via the relative comparison of neutrino rates and spectra at different baselines. Eight identically designed detectors were deployed in two near experimental halls and a far hall. Six 2.9 GW$_{th}$ nuclear power reactors served as intense $\bar{\nu}_e$ sources. Since Dec. 2011, the experiment has been running stably. The latest neutrino oscillation results were based on 1230 days of data. Analysis using a three-flavor oscillation model yielded $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027$ (stat.) $\pm 0.0019$ (syst.), and effective neutrino mass-squared difference $|\Delta m^2_{ee}| = (2.50 \pm 0.06$ (stat.) $\pm 0.06$ (syst.)) $\times 10^{-3}$ eV$^2$. Besides, results from the absolute measurement of reactor $\bar{\nu}_e$ flux and energy spectrum, and a search for a light sterile neutrino are also presented.

1. Introduction

The neutrino oscillation framework has been well established with experimental inputs from solar, atmospheric, reactor and accelerator neutrino experiments. The phenomenon arises from two remarkable characteristics: small mass differences between the three neutrino states, $m_1 \neq m_2 \neq m_3$, and an inequivalence between neutrino flavors and mass eigenstates. The neutrino oscillation is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, which is commonly parameterized by three mixing angles, $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, and a CP-violating phase $\delta_{CP}$.

The Daya Bay Reactor Neutrino Experiment was designed to answer the question whether the parameter $\theta_{13}$ is zero. Previous experiments found no evidence of $\bar{\nu}_e$ disappearance at about 1 km from reactors, limiting $\sin^2 2\theta_{13} \leq 0.17$ at the 90% C.L [1][2]. A non-zero value of $\theta_{13}$ makes it possible for future experiments to determine the neutrino mass hierarchy and to search for the neutrino CP-violation.

Six nuclear reactors of the Daya Bay and Ling Ao nuclear power facilities serve as intense and pure $\bar{\nu}_e$ sources. $\bar{\nu}_e$ are detected via inverse beta decay (IBD) reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$. The oscillation is observed as a disappearance of the expected $\bar{\nu}_e$ rate, and in the three-flavor neutrino oscillation model, the probability of detect an $\bar{\nu}_e$ of energy $E_{\nu}$ at a distance L can be expressed as:

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

where $\Delta_{ji} \simeq 1.267 \Delta m^2_{ji}(\text{eV}^2) L(\text{m})/E_{\nu}(\text{MeV})$. The flux-weighted baseline of Daya Bay far experiment hall is about 1580 m. At this distance, the two oscillation phases $\Delta_{31}$ and $\Delta_{32}$ are indistinguishable. Hence, the expression can be approximated using an effective phase $\Delta_{ee}$:

$$P_{\text{sur}} \simeq 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$ (2)
which is independent of the neutrino mass hierarchy.

2. Daya Bay Experiment

To overcome the large uncertainty of reactor $\bar{\nu}_e$ flux, a differential comparison with an additional near detector was proposed [3]. The Daya Bay experiment was constructed based on this technique. Eight identically designed detectors were deployed at three experiment halls, as shown in Fig. 1. The key to the relative measurement is the identical nature of the detectors. With careful construction and calibration, the relative detection efficiency uncertainty between detectors is controlled to 0.13% for Daya Bay.

![Figure 1: Layout of Daya Bay experiment.](image)

![Figure 2: The cross-section diagram of an antineutrino detector (AD).](image)

2.1. Experiment setup

To monitor the $\bar{\nu}_e$ flux from Daya Bay and Ling Ao nuclear power facilities, two near experimental halls (EH1 and EH2) were constructed, with 510 m and 560 m flux-weighted baselines, and each hall consisted of two antineutrino detectors (AD). A far hall, with a 1580 m flux-weighted baseline, consisted of four AD. The reactors’ and detectors’ coordinates were surveyed, with a precision of 18 mm.

Each AD had three zones, as shown in Fig. 2. The innermost one was the $\bar{\nu}_e$ target, filled with 20 tons of linear-alkyl-benzene-based liquid scintillator, loaded with 0.1% of $^{nat}$Gd by mass (GdLS). The middle zone was filled with scintillator without Gd-loading, to increase the gamma detection efficiency. The outer zone was filled with mineral oil, to shield the scintillation region from gamma rays from radioactivity in the stainless steel vessel and photomultipliers (PMTs).

Scintillation light was detected with 192 8-inch PMTs, which were immersed in the mineral oil. Three automated calibration units were used to deploy calibration sources ($^{60}$Co, $^{68}$Ge, $^{241}$Am-$^{13}$C) to the GdLS and LS regions. The antineutrino detectors were installed in a 10 m deep water pool in each experimental hall. The water shielded the detector from gamma rays and fast neutrons from the cavern rock walls, and also served as a Cherenkov detector to tag the passing through muons. Details of the detector system can be found in [4][5].

2.2. Detector calibration

For the near and far relative comparison, the most critical task was to reduce any potential differences in reactor $\bar{\nu}_e$ detection efficiency between ADs. Therefore, a calibration process
was implemented to reduce the detector-to-detector variations. First of all, PMT gains were calibrated with PMT dark noises. Then, two independent methods, one with spallation neutrons, and the other one with calibration sources, were utilized to calibrate the temporal and spatial dependence of the energy response. The AD-to-AD differences were estimated with 13 difference calibration sources, both deployed and naturally occurring, expanding the energy range for both the prompt and delayed signals from inverse beta decay. Systematic variations were less than 0.2%, as shown in Fig. 3. Therefore, a conservative 0.2% systematic uncertainty was used as the potential relative energy scale variations.

Aside from the relative energy response between detectors, it was also necessary to calibrate the detectors in the absolute sense. The characterization of the relationship between true $\bar{\nu}_e$ energy and reconstructed IBD positron energy influences the measurement of the neutrino mass-squared differences. The primary energy response non-linearity sources are due to LS and readout electronics. The former consists of the quenching effects for low-energy electrons, and the energy-dependent contribution of Cherenkov light. The latter arises from a complex interplay of the time profile of scintillation light and the response of readout electronics. Twelve gamma lines and the continuous $^{12}$B spectrum were utilized to calibrate the absolute energy response, and results are shown in Fig. 4.

2.3. Inverse beta decay event selections

In the antineutrino detector, reactor $\bar{\nu}_e$ are detected via the inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$, which provides a unique characteristic pattern of two time-correlated signals with specific energies. The prompt signal is $e^+$ ionization and annihilation, generating 1 to 8 MeV visible energy. The delayed signal is the neutron capture, by Gd or $^1$H, releasing multiple $\gamma$-rays with a total energy of 8.05 MeV (average of $^{157}$Gd and $^{155}$Gd) or a single 2.26 MeV $\gamma$-ray, respectively.

The first step of IBD selection was to remove PMT instrumental backgrounds, due to the light emission from periodic discharges in the circuitry within the PMT bases. To remove backgrounds induced by cosmic muon spallation products, the muons were classified as Water Shield Muon, AD Muon and AD Shower Muon, and different veto strategies were applied to them. Then, the prompt energy cut (0.7 to 12 MeV), the delayed energy cut (6 to 12 MeV) and the prompt-delayed time interval cut (1 to 200 $\mu$s) were utilized to select IBD candidates.

![Figure 3: Comparison of the mean reconstructed energy between antineutrino detectors.](image.png)

![Figure 4: The estimated ratio of the reconstructed over true energy for positrons (red solid line).](image.png)
with neutron capturing on Gd, as shown in Fig. 5. To have a clean sample, a multiplicity cut, requiring no other events 200 µs before and after the prompt-delayed pair, was also applied. In the 1230 days data, a total of about $2.5 \times 10^6$ IBD candidates were identified, while the background contamination was less than a few percent with an uncertainty $\leq 0.2\%$.

The efficiency for detection of $\bar{\nu}_e$ inverse beta decay in the GdLS target is estimated to be 80.6%, with a 1.93% correlated uncertainty and a 0.13% uncorrelated uncertainty among detectors. The designed goal of uncorrelated uncertainty was less than 0.2%, but the actual detectors has exceeded the goal, so it is important to have an independent method to validate the 0.13% estimation. Comparison of the $\bar{\nu}_e$ rates observed in detectors located side-by-side within the same experimental hall provides a direct test, as shown in Fig. 6. Slight differences in distances from reactors and target protons predict about 1% deviations between detectors. The consistency of the detected rates provides independent confirmation of the 0.13% estimation of uncorrelated efficiency.

3. Recent results

3.1. Neutrino oscillation results

Standard statistical techniques were applied to the 1230 days data set, providing the best estimates and confidence intervals of $\theta_{13}$ and $\Delta m^2_{32}$, as shown in Fig. 7. The amplitude of the reactor $\bar{\nu}_e$ disappearance determines $\theta_{13}$, while the $\Delta m^2_{32}$ is measured from the spectral distortion.

The parameters of the three-flavor model in best agreement with the observed rate and energy spectra were

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.),$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} \text{eV}^2,$$
$$\Delta m^2_{32}(\text{NH}) = [2.45 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} \text{eV}^2,$$
$$\Delta m^2_{32}(\text{IH}) = [-2.55 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} \text{eV}^2.$$

The $\Delta m^2_{32}$ values were obtained using the full three-flavor expression from Eq. 1, under the assumptions of normal (NH) and inverted (IH) mass hierarchy. $|\Delta m^2_{ee}|$ was obtained from

![Figure 5: Distribution of the prompt versus delayed energy for signal pairs which satisfy the $\bar{\nu}_e$ selection criteria. Events in the red dotted box are used for the neutrino oscillation analysis.](image1)

![Figure 6: Ratios of the $\bar{\nu}_e$ interaction rates observed by detectors in the same hall, $r_{obs}$ (black points). The uncertainties are dominated by statistics and the estimated 0.13% variation of the detection efficiencies.](image2)
comparison of the observation with the effective oscillation model given in Eq. 2. The result gave the most precise values for both $\sin^2 2\theta_{13}$ and $\Delta m^2_{32}$.  

![Figure 7: Confidence intervals for $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ from comparison of the $\bar{\nu}_e$ rate and prompt positron spectra observed in the far versus near detectors.](image)

The measured $\bar{\nu}_e$ spectra distortion was also displayed as the oscillation probability versus $L_{\text{eff}}/\langle E_{\nu}\rangle$, as shown in Fig. 8. The effective propagation distance $L_{\text{eff}}$ was estimated for each bin in the observed prompt positron spectrum based on the energy response model. The measured $\bar{\nu}_e$ survival probability covers nearly one full oscillation cycle, demonstrating distinct evidence in support of neutrino flavor oscillations.

### 3.2. Measurement of reactor $\bar{\nu}_e$ flux and spectrum

With 621 days data, the reactor $\bar{\nu}_e$ flux and spectrum were measured. After correcting the detection efficiency and $\bar{\nu}_e$ oscillation probability, the measured IBD yield was $(1.55 \pm 0.03) \times 10^{-18} \text{ cm}^2/\text{GW/day}$. The ratio of measured flux to the Huber+Mueller model [6][7] predictions was $0.946 \pm 0.020$, consistent to the global average of previous short baseline experiments.

The predicted and measured spectra were also compared, as shown in Fig. 9, and a discrepancy of $2.9\sigma$ was found. An excess of events was found in the 4-6MeV region, with a local significance of $4.4\sigma$. Detailed investigations, including energy response model, potential backgrounds, characteristic distributions of events in the region, revealed possible problems that the origin of the discrepancy is from the reactor antineutrino flux predictions.

### 3.3. Search for a light sterile neutrino

The three-flavor neutrino oscillation framework is successful in explaining most of the experimental results, however, possible existence of additional neutrinos is under active considerations, which is called sterile neutrino. In the simplest extension of the Standard Model, where only one sterile neutrino is considered, the mixing matrix is expanded to $4 \times 4$. The majority of experimental searches have centered on mass-squared differences around 1 eV$^2$ and higher, whereas Daya Bay and other medium baseline reactor antineutrino experiments can make unique contributions in the sub-eV scale.

The search for sterile neutrino mixing at Daya Bay was carried out through a relative comparison of the antineutrino rates and energy spectra at the three experimental halls. The unique configuration of multiple baselines allowed exploration of $\Delta m^2_{41}$ spanning more than
three orders of magnitude. Two independent analyses yield consistent results. No evidence of a light sterile neutrino was found, and the most stringent limit was set on $\sin^2 2\theta_{14}$ in the $|\Delta m^2_{41}|$ 2 × $10^{-4}$ eV$^2$ to 0.2 eV$^2$ region, as shown in Fig. 10.

4. Summary

With one of the most intense reactor $\bar{\nu}_e$ sources on Earth, and a total of 160 tons of target mass in eight detectors, the Daya Bay experiment provided the most precise measurement of neutrino mixing angle $\theta_{13}$ and the neutrino mass-squared difference $|\Delta m^2_{32}|$. The latter one is consistent with GeV-scale accelerator and atmospheric experiments. In addition, measurements of reactor $\bar{\nu}_e$ flux and spectra is presented, and an excess of events in the region of 4-6MeV was observed. Daya Bay’s multiple baselines allow a search for a light sterile neutrino, and no evidence is found.

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