# Recent Results from the Daya Bay Reactor Neutrino Experiment

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**Abstract.** The Daya Bay Reactor Neutrino Experiment is designed to precisely measure the mixing parameter $\sin^2 2\theta_{13}$ via relative measurements with eight functionally identical antineutrino detectors (ADs). In 2012, Daya Bay has first measured a non-zero $\sin^2 2\theta_{13}$ value with a significance larger than $5\sigma$ with the first six ADs. With the installation of two new ADs to complete the full configuration, Daya Bay has been continuing to increase statistics and lower systematic uncertainties for better precision of $\sin^2 2\theta_{13}$ and for the exploration of other physics topics. In this proceeding, the latest analysis results of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$, including a measurement made with neutron capture on Gadolinium and an independent measurement made with neutron capture on hydrogen are presented. The latest results of the search for sterile neutrino in the mass splitting range of $10^{-3}$ eV$^2$ $< |\Delta m^2_{41}| < 0.3$ eV$^2$ and the absolute measurement of the rate and energy spectrum of reactor antineutrinos will also be presented.

## 1. Introduction

Neutrino oscillation between three active neutrinos has been well established by experiments. Among them, Daya Bay first observed the non-zero value of the mixing angle $\theta_{13}$ [1]. Encouraged by several experimental anomalies, the possible existence of sterile neutrino, neutrinos that do not interact via weak interaction, is also actively considered. The "Reactor Neutrino Anomaly" [2] found that the predicted reactor neutrino flux, derived from the ILL beta spectra measurements [3–5], is higher than the measured rate. Precision measurement at Daya Bay can precisely determine the oscillation parameters $\theta_{13}$ and $\Delta m^2_{ee}$, search for sterile neutrino, and provide reactor neutrino flux and energy spectrum.

In the standard framework of neutrinos mixing, the three flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ mix with the three mass eigenstates $(\nu_1, \nu_2, \nu_3)$ via the PMNS matrix [6, 7], which contains three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$) and one CP phase. The survival probability $P_{\bar{\nu}_e\rightarrow\bar{\nu}_e}$ for electron antineutrino can be written as

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right), \quad (1)$$

where $\Delta_{ij} = \Delta m^2_{ij}L/E_\nu$. The $\Delta m^2_{ij}$ is the mass-squared difference between mass eigenstates $i$ and $j$, while $L$ and $E_\nu$ are the baseline and $\bar{\nu}_e$ energy, respectively. For Daya Bay, the oscillation due to $|\Delta m^2_{32}|$ is indistinguishable from the one due to $|\Delta m^2_{31}|$; therefore, the term in the parenthesis in Eq. (1) can be approximated as $\sin^2\Delta_{ee}$. For reactor neutrinos with $E_{\bar{\nu}_e} \approx 3$ MeV, the first oscillation minimum happens at $L \approx 1.6$ km.

## 2. Daya Bay Experiment

The Daya Bay reactor neutrino experiment [8] is designed to precisely determine $\sin^2 2\theta_{13}$ via relative measurement. Daya Bay nuclear power plant has six 2.9 $GW_{th}$ reactor cores, and the reactor cores are grouped by two into the Daya Bay cores, Ling Ao I cores, and Ling Ao II cores. Eight identically-designed antineutrino detectors (ADs) are placed at three experimental halls (EHs). EH1 (EH2), the near site to Daya Bay (Ling Ao) cores, has two ADs, while EH3, the far site located around the first oscillation minimum, has four ADs. Figure 1 shows the relative position of Daya Bay nuclear power plant to Hong Kong and the configuration of the Daya Bay experiment.

Each AD consists of three concentric cylindrical vessels. The inner most vessel, having a diameter of 3.1 meters, is filled with 20 tons of Gadolinium-doped liquid scintillator (Gd-LS), serving as the $\bar{\nu}_e$ target. The intermediate vessel with a diameter of 4 meters is filled with LS to catch gammas escaping from the target zone. The outermost vessel with a diameter of 5 meters contains mineral oil to shield radiation from surrounding materials. Eight rows of PMTs, each row with 24 equal-spacing PMTs, are installed on the vertical wall within each AD. Optical reflectors are installed on top and bottom of the AD to maximize the photoelectrons collected. On top of each AD, three automatic calibration units can deploy calibration sources into different regions of the AD. All the ADs in one EH are immersed in a water pool, acting as a water Cherenkov detector. Figure 2 shows the schematic of an AD.

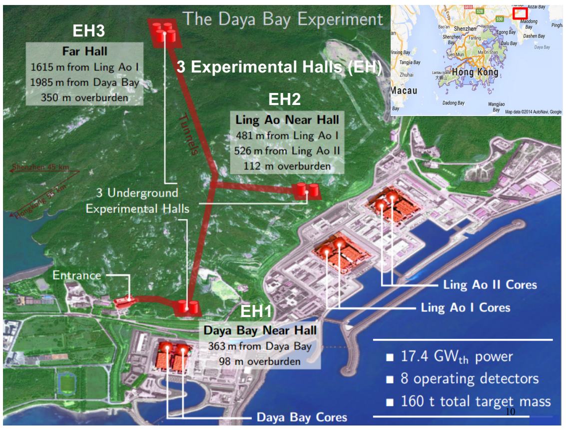


**Figure 1.** The configuration of the Daya Bay reactor neutrino experiment and the relative position to Hong Kong. The Daya Bay nuclear power plant, consisting six 2.9-$GW_{th}$ reactor cores, sits northwest to Hong Kong. Eight identically-designed antineutrino detectors (ADs) are placed in three experimental halls (EHs).

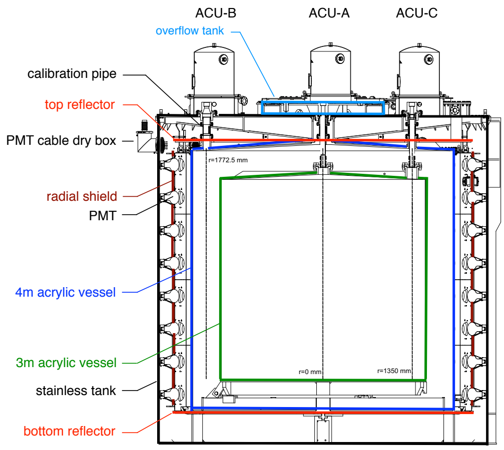


**Figure 2.** The design of Daya Bay antineutrino detector (AD). Each AD is separated into three concentric zones. The 3m innermost zone is filled with Gd-doped liquid scintillator (LS), and the intermediate zone is filled with LS. The outermost zone is filled with mineral oil.

## 3. Inverse Beta Decay Events

The reactor $\bar{\nu}_e$ is observed via inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The $e^+$ annihilates with an electron within a few nanoseconds, generating a prompt signal. The prompt energy $E_p$ can be related to the $\bar{\nu}_e$ energy $E_\nu$ as $E_p \approx E_\nu - 0.8$ MeV. The $n$ can be captured by either gadolinium or hydrogen. For neutron captured by gadolinium, which is 0.1% by weight in the target zone, the capture time is about 30$\mu$s with a delayed energy, $E_d$, around 8 MeV. For

**Table 1.** Number of IBD and background events for each data set.

| | IBD Candidates | | | Backgrounds | | |
|---|---|---|---|---|---|---|
| Data set | EH1 | EH2 | EH3 | EH1 | EH2 | EH3 |
| 217 days(6AD) | 203809 | 92912 | 41589 | $4076.6 \pm 462.4$ | $1580.3 \pm 147.8$ | $1878.9 \pm 94.6$ |
| 621 days | 613813 | 477144 | 150255 | $11624.5 \pm 968.8$ | $7371.5 \pm 530.0$ | $3984.1 \pm 152.3$ |
| 1230 days | 1203969 | 1033209 | 308150 | $21451.4 \pm 1359.9$ | $14911 \pm 944.2$ | $6011.9 \pm 154.1$ |

neutron captured by hydrogen in the LS zone, capture time is $\sim$200 $\mu$s with a delayed energy at $\sim$2.2 MeV.

### *3.1. Selection Criteria*

The selection criteria for IBD events with neutron captured on Gd requires that $E_p$ is within $(0.7, 12)$ MeV, $E_d$ is within $(6, 12)$ MeV, and the capture time is in the $(1, 200)$ $\mu$s window. For neutron captured on hydrogen, the IBD selection criteria requires that $E_p$ is within $(1.5, 12)$ MeV, $E_d$ is within $3\sigma$ of the hydrogen 2.2 MeV peak, the capture time is in the $(1, 400)$ $\mu$s window, and distance between the prompt and the delayed signal is within 50 cm. The higher $E_p$ threshold and the vertex cut for n-H events are to avoid accidental events, events that are physically-unrelated but accidentally appear in the selection window. Furthermore, an event is rejected if it is within the cosmic muon window determined by the water pool or the AD, or if it is determined to be a flasher event, that is, spontaneous PMT light emission, or if there is more than one coincidence pair.

### *3.2. Data Sets*

Daya Bay started data-taking with 6 ADs installed, 2 in EH1, 1 in EH2, and 3 in EH3. With 217 days of data taken in the 6AD period, Daya Bay conducted the measurement of $\sin^2 2\theta_{13}$ and $\Delta m^2_{ee}$ using spectral information [9], the search for sterile neutrino [10], and the measurement of reactor flux [11]. The last two ADs were installed in the summer of 2012. The 621 days of data, combining both 6-AD period and 8-AD period, was analyzed for the 3-$\nu$ oscillation. In this proceeding, the results for the 3-$\nu$ oscillation analysis is updated with the 1230 days of data from the previous 621-day analysis. For sterile neutrino search and the measurement reactor antineutrino flux and spectrum, the results are updated with the 621 days of data from the 6-AD analysis. Table 1 lists the number of IBD events and backgrounds for each data period.

### *3.3. Energy Calibration*

The relative energy scale, the energy difference between ADs, is determined by measuring peaks from calibration sources, spallation neutrons, and natural radioactivity. The uncertainty of relative energy scale was found to be less than 0.2%. The absolute energy scale, connecting the reconstructed energy to true energy, includes the nonlinearity from both LS and electronic readouts. The absolute energy scale is determined by the measured $\gamma$ peaks and the continuous $\beta$ spectrum from $^{12}$B, validated with Michel electrons and the continuous $\beta + \gamma$ spectra from $^{212/214}$Bi and $^{208}$8Tl.

## 4. Recent Results

### *4.1. Measurement of* $\sin^2 2\theta_{13}$ *and* $\Delta m^2_{ee}$

With the 1230 days of data, the measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ yielded

$$\begin{aligned} \sin^2 2\theta_{13} &= [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2} \\ |\Delta m^2_{ee}| &= [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\ \text{eV}^2 \end{aligned} \quad (2)$$

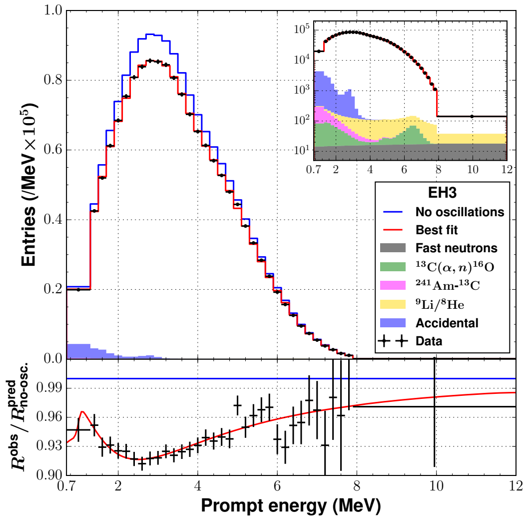


**Figure 3.** (1230 days) Observed energy spectra at EH3 and the best-fit curve.

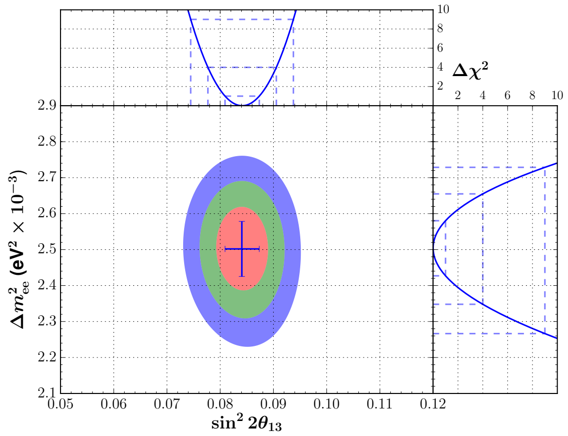


**Figure 4.** (1230 days) Allowed regions at the 68.3%, 95.5%, and 99.7% confidence levels in the $|\Delta m^2_{ee}| - \sin^2 2\theta_{13}$ plane.

Figure 3 shows the observed energy spectra at the far site, EH3. A clear deficit compared with the no-oscillation prediction and the energy dependence of the oscillation probability can be observed. Figure 4 shows the allowed region at 1, 2, and 3 $\sigma$ in the plane of $|\Delta m^2_{ee}| - \sin^2 2\theta_{13}$. Daya Bay has the most precise measurement on $\sin^2 2\theta_{13}$. The experiment is still statistics-dominant, while the largest systematic contribution is the uncertainty in relative energy scale. For $|\Delta m^2_{32}|$, Daya Bay has achieved similar precision as those measured in the muon neutrino channel, as shown in Figure 5.

For neutron captured on hydrogen, the rate analysis, updated with the 621 days of data from the 6-AD only data, yielded $\sin^2 2\theta_{13} = 0.071 \pm 0.011$, consistent with the analysis with neutron captured on gadolinium.

### *4.2. Search for Sterile Neutrino*

With a minimum extension to the standard three active neutrino framework, Daya Bay searched for sterile neutrino in a 3(active)+1(sterile) framework. The $\bar{\nu}_e$ survival probability can be approximated with the convention in Ref. [12] as:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \sin^2 2\theta_{14} \sin^2 \Delta_{41}. \quad (3)$$

Therefore, if light sterile neutrino exists, it would distort the observed energy spectra. With ADs at multiple baselines, Daya Bay compares the difference in the measured energy spectra to exclude a large range of $|\Delta m^2_{41}|$ in the sub-eV region. Figure 6 shows that two independently-developed analyses at Daya Bay show consistent exclusion region [13]. The constraints set on $\sin^2 2\theta_{14}$ for $2 \times 10^{-4}$ eV$^2 \lesssim \Delta m^2_{41} \lesssim 0.3$ eV$^2$ is about 50% smaller than the constraints set by the analysis using the 6-AD data set [10].

### *4.3. Absolute Neutrino Flux*

With the 621 days of data, Daya Bay has also released a new measured reactor antineutrino flux and energy spectrum. The measured IBD yield $Y$ was found to be $Y$(cm$^2$/GW/day) =

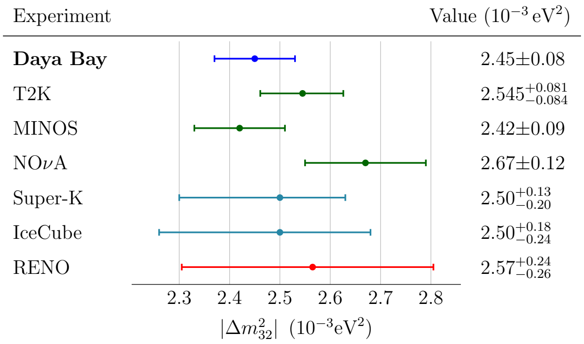


**Figure 5.** (1230 days) The global measurements on $|\Delta m^2_{32}|$. Daya Bay has achieved similar precision on $|\Delta m^2_{32}$ with experiments in the muon neutrino channel.

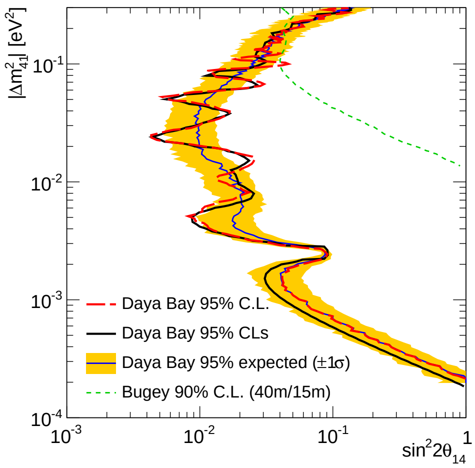


**Figure 6.** (621 days) The exclusion contour [13] for the sterile neutrino search at Daya Bay in the plane of $|\Delta m^2_{41}| - \sin^2 2\theta_{14}$. Figure is extracted from Ref. [13].

$(1.55 \pm 0.03) \times 10^{-18}$ [14]. Compared with the Huber+Mueller [15, 16] (ILL+Vogel [3–5, 17]) model, the ratio of the measured flux to predicted flux was found to be 0.946±0.020 (0.992±0.021), a 2.9 $\sigma$ deviation from Huber+Mueller prediction, consistent with the global average of measured reactor neutrino flux [2]. The measured yields for each AD at 6-AD only and 6 plus 8 AD periods are consistent, as shown in Figure 7. Compared with the Huber+Mueller model, the measured energy spectra was found to have a 4.4 $\sigma$ excess in the region of 4-6 MeV, as shown in Figure 8.

## 5. Acknowledgment

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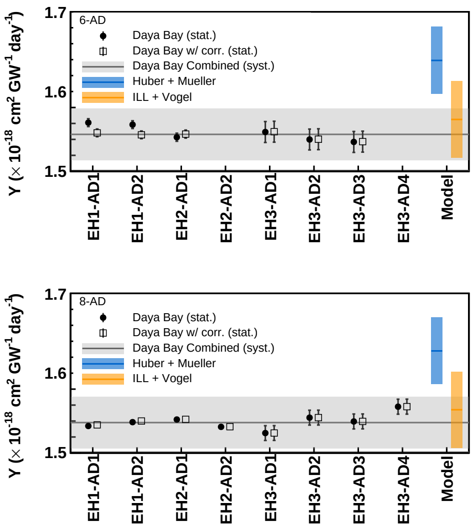


**Figure 7.** (621 days) The measured reactor flux for each AD at both 6-AD (top) and 6+8 AD (bottom) period. The closed circles show the measured rates corrected by the 3-$\nu$ oscillation, while the open squares show the results corrected by flux-weighted fission fraction. The horizontal lines show the average for the period, and the gray band shows the 1-$\sigma$ uncertainty. Figure is extracted from Ref. [14].

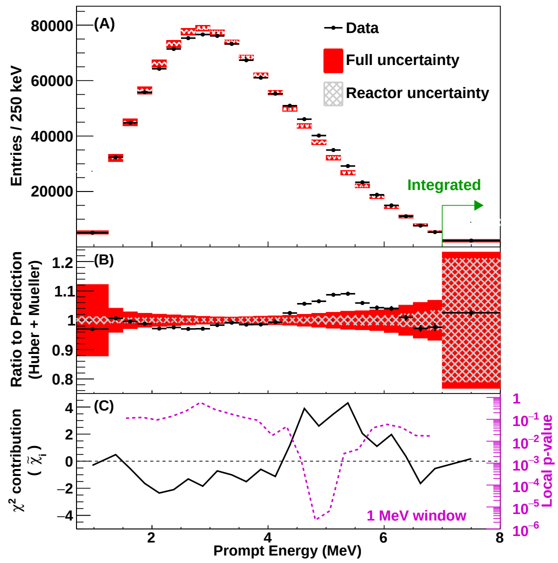


**Figure 8.** (621 days) (A) The measured reactor neutrino flux compared with the Huber+Mueller model. (B) The ratio of the measured energy spectrum to the Huber+Mueller prediction. (C) The $\chi^2$ distribution and local p-value. A 4.4 $\sigma$ excess is observed in the 4 to 6 MeV window. Figure is extracted from Ref. [14].


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