Abstract

With 217 days of data-taking, using six antineutrino detectors deployed in three experimental halls near the Daya Bay Nuclear Power Plant complex, the Daya Bay experiment has obtained $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ from the rate and energy spectra analysis under the three-neutrino framework. In addition, the value of effective mass-squared difference $|\Delta m_{ee}^2| = (2.59^{+0.17}_{-0.20}) \times 10^{-3} \text{ eV}^2$ is directly measured through $\nu_e$ disappearance channel for the first time, which is consistent with the $|\Delta m_{\mu\mu}^2|$ measured by muon neutrino disappearance channel.

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1. Introduction

The theory of neutrino mixing and neutrino oscillation [1, 2, 3] has been very successful in explaining the experimental observation of atmospheric, solar, reactor and accelerator neutrinos [4]. The discovery of the relatively large value of the neutrino mixing angle $\theta_{13}$, through the recent reactor and accelerator neutrino experiments [5, 6, 7], opens the gateway for the experimental search for neutrino mass hierarchy and Charged-Parity (CP) violation in the leptonic sector [8, 9, 10], which might be able to explain the predominance of matter over antimatter in the current universe through the leptogenesis. The precision measurement of neutrino mixing parameters could also lead to a test of the unitarity of the PMNS matrix [11, 12] and search for new physics beyond the Standard Model.

Compared with accelerator experiments, reactor experiments provide a clean approach to measure the value of $\theta_{13}$. It is independent of the CP-violating phase and has negligible matter effect. Equation 1 shows the survival probability of electron antineutrino $\bar{\nu}_e$ with energy $E$ over a distance $L$ from the reactor.

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m_{ee}^2 L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{\mu\mu}^2 L}{4E}),$$

(1)

where $\sin^2(\frac{\Delta m_{ee}^2 L}{4E}) = \cos^2 \theta_{12} \sin^2(\frac{\Delta m_{\mu\mu}^2 L}{4E}) + \sin^2 \theta_{12} \sin^2(\frac{\Delta m_{\tau\tau}^2 L}{4E}).$

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Previously, Daya Bay experiment reported the value of $\sin^2 2\theta_{13}$ using only the event rate information recorded by six antineutrino detectors (ADs) with different baselines from the reactor complex [5, 13]. The most precise measurement of $\sin^2 2\theta_{13}$ can be achieved by combining the relative rate deficit and the energy spectra distortion information [14]. In addition, due to the relatively short baselines, Daya Bay experiment can measure the effective mass-squared difference $|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 5 \times 10^{-5}\text{eV}^2$, which has a constant shift from $|\Delta m^2_{32}|$ for two neutrino mass hierarchy cases (+ and − for normal and inverted mass hierarchy respectively). Comparing the value of $|\Delta m^2_{ee}|$ with $|\Delta m^2_{\mu\mu}|$ through the muon neutrino $\nu_\mu$ disappearance channel, we can also test the validity of three-flavor neutrino oscillation model.

In this paper I will report the most recent Daya Bay measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with the combined rate and spectra information for the full 6 AD data-taking period from December 24th, 2011 to July 28th, 2012, which is about 4 times the statistics of the first Daya Bay result [5].

2. Detector

The Daya Bay experiment has three experimental halls (EHs) near the Daya Bay nuclear power plant complex, which has 3 pairs of reactor cores (Daya Bay, Ling Ao and Ling Ao-II) with the maximal thermal power 17.4 GWth in total. Six functionally identical, three-zone antineutrino detectors are installed, three of them are located at the two near sites (EH1 and EH2) close to the reactors to monitor the reactor antineutrino flux before oscillation, and the other three are installed in the far site (EH3) near the maximal oscillation distance. The layout of the Daya Bay experiment is shown in Figure 1 and Table 1. All the ADs are submerged in pools of ultra-pure water segmented into two optically decoupled regions, which can shield the ambient radiation. Those water pools also serve as active Cherenkov detectors using photomultiplier tubes (PMTs) to veto cosmic-ray induced backgrounds. The central target region of each AD is filled with 20 ton Gd-doped liquid scintillator in a 3.1 m diameter acrylic vessel, which is surrounded by the pure liquid scintillator and mineral oil. Reactor antineutrinos are detected via the inverse $\beta$-decay (IBD) interaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The energy and time coincidence signature of prompt ($e^+$ ionization and annihilation) and delayed ($n$ captured on Gd) signals can efficiently suppress most of the backgrounds. The prompt signal determines the original $\bar{\nu}_e$ energy with a reconstructed resolution $\sigma_E/E \approx 8\%$ at 1 MeV. Three automated calibration units (ACUs) are mounted along different axis on top of each AD with an LED, a $^{68}\text{Ge}$ source and a combined source of $^{241}\text{Am}-^{13}\text{C}$ and $^{60}\text{Co}$.

3. Energy Calibration

Two independent energy reconstructions are used, one is based on the calibration source deployed at the detector center and the other uses spallation neutrons captured by the Gd inside of the whole target volume. For both methods, the visible energy is corrected based on its vertex position to minimize the energy non-uniformity [15].

In order to convert the reconstructed energy to the true neutrino energy, an intensive study has been done to understand the energy nonlinearity response due to the scintillator quenching, Cherenkov light
emission and the readout electronics effect. An empirical energy model is constructed with two parts, one is the intrinsic scintillation/Cherenkov process, which is particle dependent; the other is the electronics effect, which is affected by the readout electronics charge collection efficiency due to scintillator time profile and PMT shaping, etc. For the scintillation process, a GEANT4-based Monte-Carlo simulation is used to correlate the $e^-$ scintillator nonlinearity to the response for $\gamma$ and $e^+$. In order to better understand the detector energy response through the whole IBD prompt energy range, besides the regular ACU calibration sources, more gamma and neutron sources ($^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{241}$Am-$^9$Be and Pu-$^{13}$C) were deployed in a special calibration campaign during summer 2012. In addition, the radiation singles spectrum from $^{40}$K/$^{208}$Tl and the $\beta$ spectrum from $^{12}$B isotope produced by cosmic-ray muons are also included. All these calibration data are used to constrain the energy model. As shown in Figure 2, the energy model can describe both the single gamma energy data points and the $^{12}$B spectrum quite well.

![Fig. 2](image_url)

**Fig. 2**: (a) Ratio of the reconstructed to best-fit energies of $\gamma$ lines from calibration sources and singles spectra. The error bars represent the total uncertainty on each ratio. The $\gamma$ from the second-excited state of $^{16}$O in the Pu-$^{13}$C source is denoted $^{16}$O$^*$. The $n^{56}$Fe$_1$ and $n^{56}$Fe$_2$ labels denote the $\sim$6 MeV and $\sim$7.6 MeV $\gamma$s, respectively, resulting from the capture of neutrons from the AmC sources parked on top of the AD. (b) Reconstructed energy spectrum (points) compared to the sum (shaded area) of the $^{12}$B (solid line) and $^{12}$N (dashed line) components of the best-fit energy response model. The error bars represent the statistical uncertainties. (c) AD energy response model for positrons. The absolute energy scale uncertainty for positrons is estimated to be around 1.5% through a combination of the uncertainties of calibration data and the various energy models [14]. The absolute energy response has a marginal effect on the sensitivity of the oscillation analysis due to the correlation among detectors. The uncertainty of the relative energy scale is determined from the relative response of all ADs to different calibration sources that span the IBD positron energy range [5, 13] and is found to be 0.35%.
4. Analysis

The IBD candidates are selected, after the water pool and AD muon veto cut, with the time coincidence of a prompt-like signal (0.7 - 12 MeV) and a delayed-like signal (6 - 12 MeV) separated by 1-200μs. In order to remove the ambiguities in the coincidence pairs, we apply a multiplicity cut to require no additional prompt-like signals 400μs before the delayed signal, and no delayed-like signals 200μs after the delayed signal. With those fixed time window, both the muon veto efficiency ($\epsilon_\mu$) and multiplicity cut efficiency ($\epsilon_m$) are calculated directly from data with negligible uncertainties.

For the oscillation analysis, the relative AD event rates will be only affected by the AD detection efficiency difference, which is dominated by the delayed-energy cut (0.12%) and Gd capture fraction (< 0.1%).

<table>
<thead>
<tr>
<th></th>
<th>EH1</th>
<th>AD2</th>
<th>EH2</th>
<th>AD3</th>
<th>EH3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
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<tr>
<td>IBD candidates</td>
<td>101290</td>
<td>102519</td>
<td>92912</td>
<td>13964</td>
<td>13894</td>
<td>13731</td>
<td></td>
<td></td>
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<tr>
<td>DAQ live time (days)</td>
<td>191.00</td>
<td>189.65</td>
<td>189.78</td>
<td></td>
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<tr>
<td>$\epsilon_\mu \cdot \epsilon_m$</td>
<td>0.796</td>
<td>0.793</td>
<td>0.828</td>
<td>0.958</td>
<td>0.957</td>
<td>0.957</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidentals (/day)</td>
<td>9.54±0.03</td>
<td>9.36±0.03</td>
<td>7.44±0.02</td>
<td>2.96 ± 0.01</td>
<td>2.92 ± 0.01</td>
<td>2.87 ± 0.01</td>
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<tr>
<td>Fast-neutron (AD/day)</td>
<td>0.92±0.46</td>
<td>0.62±0.31</td>
<td>0.04±0.02</td>
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<tr>
<td>$^9$Li/$^8$He (AD/day)</td>
<td>2.40±0.86</td>
<td>1.20±0.63</td>
<td>0.22±0.06</td>
<td></td>
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<tr>
<td>$^{241}$Am-$^{13}$C (AD/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.26±0.12</td>
<td></td>
<td></td>
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<tr>
<td>$^{12}$C($\alpha$, n)$^{16}$O (/day)</td>
<td>0.08±0.04</td>
<td>0.07±0.04</td>
<td>0.05±0.03</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
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<td>IBD rate (/day)</td>
<td>653.3±2.3</td>
<td>664.2±2.3</td>
<td>582.0±2.0</td>
<td>73.3 ± 0.7</td>
<td>73.0 ± 0.7</td>
<td>72.2 ± 0.7</td>
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Table 2: Summary of signal and backgrounds. The background and IBD rates are corrected for the product of the muon veto and multiplicity cut efficiencies $\epsilon_\mu \cdot \epsilon_m$.

The detailed event rate and background estimation are summarized in Table 2 and displayed in Figure 4. In Daya Bay, the total background rate is small, about 5% (2%) of the entire IBD candidates in the far (near) sites. Although the accidentals are the dominate background, both the rate and spectrum of the accidentals can be accurately measured in each AD. The relative uncertainty of the accidentals is 0.3% and is dominated by the statistics of the rate of delayed-like singles. The correlated backgrounds are dominated by the calibration sources $^{241}$Am-$^{13}$C sitting on top of each AD and the cosmogenic isotopes. The other background such as $^{12}$C($\alpha$, n)$^{16}$O are quite small, only about 0.01% (0.05%) of the total IBD candidates in the near (far) site.

Neutrons from $\sim 0.7$Hz $^{241}$Am-$^{13}$C sources can mimic the IBD signals by inelastically scattering off the nuclei of the shielding material and then capturing on Fe/Cr/Mn/Ni. It is the largest correlated background at the Far site. The background rate is estimated using the delayed-like singles rate with the correction from the MC simulation. During the summer 2012, a special Am-C source, about 80 times more potent than the ACU source, was temporarily put on top of one AD to benchmark the MC simulation and provides a 45% uncertainty on the rate estimation.

The $\beta$-n decays of $^9$Li and $^8$He isotopes can also mimic the IBD signals. These long-lived isotopes generated by cosmic-ray muons, are impractical to be directly vetoed through muon triggers. The rate of $^9$Li/$^8$He background is evaluated using the time of the IBD candidates since the prior muon showers, which is usually most effective in producing $^9$Li/$^8$He. 20% systematic uncertainty is assigned for those which are associated with the non-shower muons. The spectrum of $^9$Li and $^8$He starting from the theoretical calculation is convoluted with the electron energy nonlinearity model and smearing. The spectrum systematic uncertainty is dominated by ratio of $^9$Li/$^8$He and the neutron and $\alpha$ energy deposition.

Some energetic neutrons generated by cosmic-ray muons, which do not trigger the muon veto system, can also mimic the IBD signal. The proton recoiling through neutron elastic scattering gives the prompt like signal, and after thermalization, the neutron captured on the Gd generates the delayed like signal. The rate of the fast neutron background is estimated with a linear extrapolation of the prompt spectrum of the AD-tagged “fast neutron” sample, which shows a flat distribution from 12 to 50 MeV. By requiring coincidence...
with the water pool muon, we can get the water pool tagged “fast neutron” sample, which also shows a relatively flat distribution in the 0.7 to 12 MeV prompt energy spectrum. A conservative 50% systematic uncertainty is assigned.

The predicted $\nu_e$ flux takes into account the daily livetime-corrected thermal power, the fission fractions of each isotope as provided by the reactor company, the fission energies, and the number of neutrons produced per fission per isotope. For a relative measurement, the reactor flux model has only marginal impact on the analysis result. Figure 3 presents the background-subtracted and efficiency-corrected IBD rates in three EHs. Relative reactor flux predictions are shown for comparison.

![IBD Rate Graph](image)

**Fig. 3:** Measured Daily-averaged IBD rates per AD in the three experimental halls as a function of time. The black curves represent no-oscillation predictions based on reactor flux analyses and detector simulation for comparison. The predictions have been corrected with the best-fit normalization parameter in determining $\sin^2 2\theta_{13}$. The red curves represent the best-fit oscillation based on the rate-only analysis.

5. Result

The oscillation parameters are extracted from a fit that takes into account the antineutrino rate, spectral information and $\bar{\nu}_e$ survival probability. A binned log-likelihood $\chi^2$ is constructed with nuisance parameters corresponding to the constraints from the detector response and the backgrounds, and with a covariance matrix encapsulating the reactor flux uncertainties as given in the P. Huber [16] and T. Mueller’s [17] flux models. Taking into account the possible underestimation of the uncertainty of the reactor neutrino flux model calculation [18], the absolute normalization of $\bar{\nu}_e$ flux is a free parameter in the fit. The fit uses $\sin^2 2\theta_{12} = 0.857 \pm 0.024$ and $\Delta m^2_{12} = (7.50 \pm 0.20) \times 10^{-5} \text{eV}^2$ [4]. The best-fit values are $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ and $|\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3} \text{eV}^2$ with $\chi^2/\text{NDF} = 163/153$ (68.3% confidence level (C.L.) intervals). The prompt energy spectra observed in each experimental hall are compared to the spectra expected for no oscillation and with the best-fit oscillation parameters in Fig. 4. The 68.3%, 95.5%, and 99.7% C.L. allowed regions in the $|\Delta m^2_{ee}|$ vs. $\sin^2 2\theta_{13}$ plane are shown in Fig. 5. The result is consistent with $|\Delta m^2_{\mu\mu}| = (2.41^{+0.09}_{-0.10}) \times 10^{-3} \text{eV}^2$ as measured via $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance [19].

The total uncertainty on both oscillation parameters is dominated by statistics. The most significant contributions to the $\sin^2 2\theta_{13}$ systematic uncertainty are the reactor flux, relative detector efficiency, and
 uncertainties on both oscillation parameters. Combined such a precision measurement with future neutrino

6. Prospect

Following a special calibration campaign in summer 2012, two more ADs were installed in EH2 and EH3, data collection using all eight antineutrino detectors began in October 2012. Figure 6 shows the evolution of the estimated errors of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ assuming no improvement on the current systematic uncertainties. Several major improvements have been made to enhance the final precision of those two oscillation parameters. As the dominant background at Far site, two out of three $^{241}$Am-$^{13}$C sources of each AD at Far site were removed during the summer installation. With the great effort of energy calibration with quality control, the eventual relative energy scale uncertainty can be reduced to 0.1-0.2% level. In addition, there is an on-going neutron captured on Hydrogen analysis, which has about the same statistics as the nGd sample. The combined analysis of those two samples will further improve the final precision of the oscillation parameters. With total 4 years of data taking, Daya Bay will eventually get a few percent uncertainties on both oscillation parameters.
accelerator experiments, it can largely improve the sensitivity of neutrino mass hierarchy, CP-violating phase and \( \theta_{23} \) octant determination.

Besides the oscillation analysis, the on-going analysis of the special calibration data is expected to yield improvements in the energy response model and the knowledge of the absolute \( \bar{\nu}_e \) detection efficiency. These improvements will enable a high-statistics measurement of the absolute reactor \( \bar{\nu}_e \) flux and energy spectra that will provide a valuable reference for future studies of reactor neutrinos.

7. Summary

In summary, the relative deficit and spectral distortion observed between three far and three near antineutrino detectors at Daya Bay provides the first independent measurement of \( |\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3} \text{ eV}^2 \) and the most precise determination of \( \sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009} \) to date.

8. Acknowledgments

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Fig. 6: The evolution of Daya Bay sensitivities of the errors of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ assuming no improvement of the systematics uncertainties.

References