PROCEEDINGS OF SCIENCE

Precision Measurement of $\sin^2(2\theta_{13})$ and $|\Delta m^2_{ee}|$ from Daya Bay

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The Daya Bay experiment was designed to measure the neutrino mixing angle $\sin^2(2\theta_{13})$ with unprecedented precision through a relative measurement with eight functionally identical electron anti-neutrino detectors deployed at three experimental halls near three high-power nuclear reactor complexes in south China. In March 2012, the Daya Bay experiment discovered the non-zero value of $\sin^2(2\theta_{13})$ with 5.1σ significance with 55 days data taking with partially installed six electron anti-neutrino detectors. After that, Daya Bay experiment installed the remaining two detectors in the summer of 2012. With 1230 days of data-taking since December 2011, the Daya Bay experiment has accumulated more than 2.5 million reactor electron anti-neutrino inverse-beta-decay events, hence obtained the most precise measurement of $\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$ and effective mass-squared difference $|\Delta m^2_{ee}| = (2.50 \pm 0.08) \times 10^{-3}$ eV^2 up to date.

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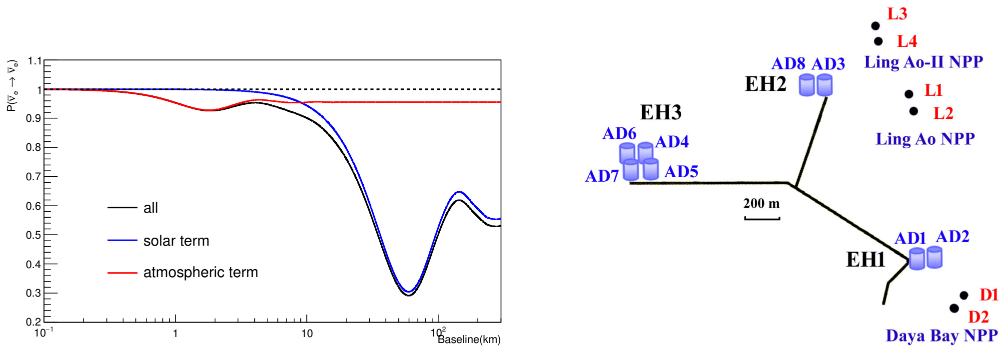
1. Introduction

Neutrino mixing and neutrino oscillation has provided a compelling evidence that neutrinos have nonzero mass, which is clearly beyond the standard model. Neutrino might also be the key to explain the predominance of matter over antimatter in the current universe. In the three-neutrino flavor framework, the lepton mixing matrix (PMNS matrix) can be parameterized in terms of the three mixing angles, θ_{23}, θ_{12} and θ_{13} and one Charged-Parity-Violating phase δ_{CP}. The precision measurement of neutrino mixing parameters could lead to a test of the unitarity of the PMNS matrix and search for new physics beyond the standard model.

The Daya Bay reactor neutrino oscillation experiment was designed to measure θ_{13} with unprecedented precision in electron antineutrino $\overline{\nu}_e$ disappearance channel. The survival probability of $\overline{\nu}_e$ with energy E over a distance L from a reactor is shown in Equation. 1.1.

$$P_{sur}(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{ee} L}{4E}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m^2_{21} L}{4E}), \tag{1.1}$$

where $\sin^2(\frac{\Delta m^2_{ee} L}{4E}) \approx \cos^2\theta_{12}\sin^2(\frac{\Delta m^2_{31} L}{4E}) + \sin^2\theta_{12}\sin^2(\frac{\Delta m^2_{32} L}{4E})$, and $\Delta m^2_{ij} = m^2_i - m^2_j$ is the mass-square difference between two mass eigenstates ν_i and ν_j. Compared to $\nu_\mu \to \nu_e$ appearance channel in the accelerator experiments, the survival probability of $\overline{\nu}_e$ is independent of the *CP*-violating phase δ, and has negligible matter effect. So reactor neutrino experiments provides a very clean way to measure θ_{13}.



(a) (b)

Figure 1: (a) Averaged $\overline{\nu}_e$ survival probability as a function of distance from reactor. (b) Layout of the Daya Bay experiment.

The reactor spectrum averaged $\overline{\nu}_e$ survival probability is shown in Figure 1(a), the red curve corresponds to the θ_{13} oscillation term with the large atmospheric mass splitting , and the blue curve corresponds to the θ_{12} term with small solar mass splitting. In order to have the best sensitivity to measurement θ_{13}, the flux-weighted baseline of the Daya Bay experiment far experimental hall is located at the first oscillation maximal of the red curve, $\sim$ 1.6 km away from reactor.

For the precision measurement of θ_{13}, two major systematic uncertainties associated with reactor neutrino flux prediction and detector efficiencies can be largely cancelled through a far versus near relative measurement.

$$\frac{N_F}{N_N} = \left(\frac{N_{p,F}}{N_{p,N}}\right)\left(\frac{L_N}{L_F}\right)^2\left(\frac{\varepsilon_F}{\varepsilon_N}\right)\left[\frac{P_{sur,F}(E_\nu,L_F)}{P_{sur,N}(E_\nu,L_N)}\right], \tag{1.2}$$

where $N_{F(N)}$ is the number of observed neutrino events at far (near) detector; $N_{p,F(p,N)}$, $L_{F(N)}$, $\varepsilon_{F(N)}$, represent the numbers of protons, baselines, detector efficiencies of far (near) detector; $P_{sur,F(N)}$ is $\overline{\nu}_e$ survival probability at far (near) detector.

In March 2012 the Daya Bay reactor neutrino experiment discovered the non-zero value of $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ with significance better than 5σ with 55 days of data [1]. In this proceeding the most recent Daya Bay measurements of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with the combined rate and spectra information for a total 1230 days from December 2011 to July 2015, are presented [2].

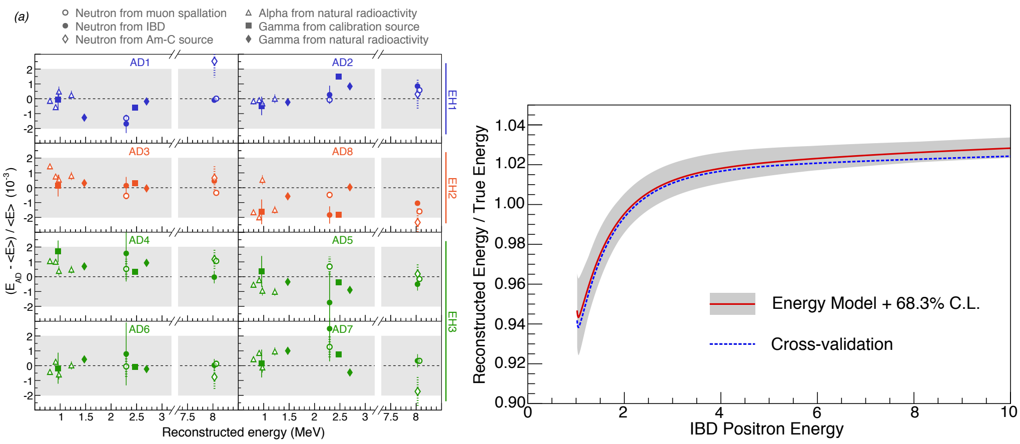
2. Daya Bay experiment

The Daya Bay experiment [3] 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 $\mathrm{GW_{th}}$ in total. Eight functionally identical, three-zone antineutrino detectors are installed. Two pair 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 four are installed in the far site (EH3) near the maximal oscillation distance, as shown in Figure 1(b) 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 β-decay (IBD) interaction $\overline{\nu}_e + p \to e^+ + n$. 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 $\overline{\nu}_e$ 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}Ge source and a combined source of ^{241}Am-^{13}C and ^{60}Co.

3. Detector 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 for spatial and time dependence to minimize the energy non-uniformity. The relative energy difference among eight detectors, in the energy range of the reactor neutrino IBD signals, were estimated with various deployed calibration sources and natural radioactivity. As shown in Figure 2(a), the systematic uncertainty on the relative energy scale is within 0.2%.

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. As shown in Figure 2(b) The absolute energy scale uncertainty for positrons is estimated to be around 1% through a combination of the uncertainties of calibration data and the various energy models.



(a) (b)

Figure 2: (a) Comparion of the mean reconstructed energy between antineutrino detectors for a variety of calibration references using calibration with ^{60}Co sources. (b) Estimated ratio of reconstructed over true energy for positron interactions.

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 other events 200μs before and after the prompt-delayed signal pair.

The detailed event rate and background estimation are summarized in Table 1. 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 correlated backgrounds are dominated by the long-lived cosmogenic isotopes, ^{9}Li/^{8}He, and fast neutrons. The systematic uncertainties of them are conservatively estimated to be 45% and 30%. The other backgrounds, such as the calibration sources ^{241}Am-^{13}C sitting on top of each AD, and ^{13}C(α, n)^{16}O are quite small, only about 0.04% (0.1%) of the total IBD candidates in the near (far) site.

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 (0.08%) and Gd capture fraction (0.1%).

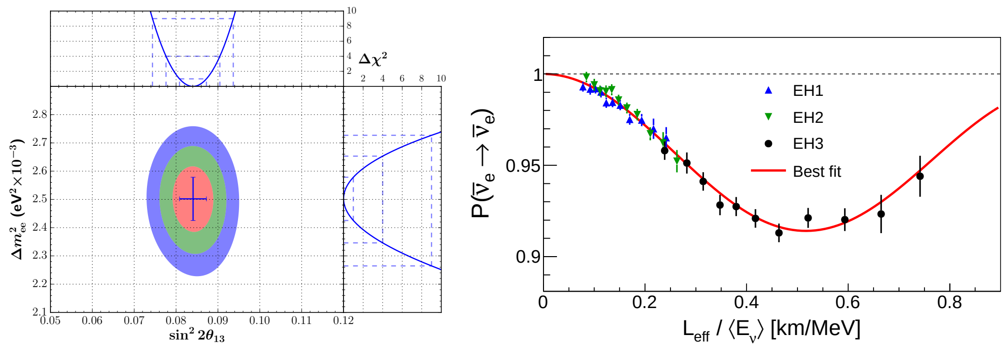
5. Result

The oscillation parameters are extracted from a fit that takes into account the antineutrino rate, spectral information and $\overline{\nu}_e$ survival probability. The best-fit values are $\sin^2 2\theta_{13} = 0.0841 \pm$

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	597616	606349	567196	466013	80479	80742	80067	66862
DAQ live time (days)	1117.18	1117.18	1114.34	924.93	1106.92	1106.92	1106.92	917.42
$\varepsilon_\mu \cdot \varepsilon_m$	0.804	0.801	0.836	0.836	0.959	0.959	0.958	0.959
Accidentals (day^{-1})	8.46±0.09	8.46±0.09	6.29±0.06	6.18 ± 0.06	1.27 ± 0.01	1.19 ± 0.01	1.20 ± 0.01	0.98 ± 0.01
Fast-neutron(day^{-1})	0.79±0.10		0.57±0.07		0.05±0.01			
^{9}Li/^{8}He (day^{-1})	2.46±1.06		1.72±0.77		0.15±0.06			
^{241}Am-^{13}C, 6-AD (day^{-1})	0.27 ± 0.12	0.25 ± 0.11	0.28 ± 0.13		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.10	
^{241}Am-^{13}C, 8-AD (day^{-1})	0.15 ± 0.07	0.16 ± 0.07	0.13 ± 0.06	0.15 ± 0.07	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.05 ± 0.02
^{13}C(α, n)^{16}O (day^{-1})	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate (day^{-1})	653.0 ± 1.4	665.4 ± 1.4	599.7 ± 1.1	593.8 ± 1.2	74.3 ± 0.3	74.6 ± 0.3	74.0 ± 0.3	74.7 ± 0.3

Table 1: Summary of signal and backgrounds. The background and IBD rates are corrected for the product of the muon veto and multiplicity cut efficiencies $\varepsilon_\mu \cdot \varepsilon_m$.

0.0027(stat.) ±0.0019 (syst.), and $|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06\ (\text{syst.})\ ] \times 10^{-3}$ eV^2. Assuming normal mass hierarchy ($m_3 > m_2 > m_1$), $\Delta m^2_{32} = [2.45 \pm 0.06(\text{stat.}) \pm 0.06\ (\text{syst.})\ ] \times 10^{-3}$ eV^2; Assuming inverted mass hierarchy ($m_2 > m_1 > m_3$), $\Delta m^2_{32} = [-2.55 \pm 0.06(\text{stat.})\ \ \pm 0.06\ (\text{syst.})\ ] \times 10^{-3}$ eV^2. They are consistent with the $|\Delta m^2_{32}|$ measured by muon neutrino disappearance channel. 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. 3(a).



(a) (b)

Figure 3: (a) Allowed regions for the neutrino oscillation parameters $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ at the 68.3, 95.5 and 99.7% confidence level, obtained from comparison of the rates and prompt energy spectra at Daya Bay. The best estimate and error of the oscillation parameters are given by the blue cross mark. The adjoining panels show the dependence of $\Delta\chi^2$ on $|\Delta m^2_{ee}|$ (right) and $\sin^2 2\theta_{13}$ (top). (b) Prompt positron energy spectra in the three experimental halls, re-expressed as the electron antineutrino survival probability versus propagation distance L_{eff} over antineutrino energy E_ν.

6. Prospect

In December 2015, a flash ADC readout system was installed in parallel to the current readout on AD1. It will improve the electronics nonlinearity measurement and hence furthur reduce the detector absolute energy scale uncertainty. As shown in Figure 4, the estimated errors of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ will reach $\sim 3\%$ by the year of 2020. In addition, Daya Bay experiment has been carring other important physics topics, including neutron captured on Hydrogen analysis [4], light sterile neutrino search [5, 6] and reactor neutrino flux measurement [7].

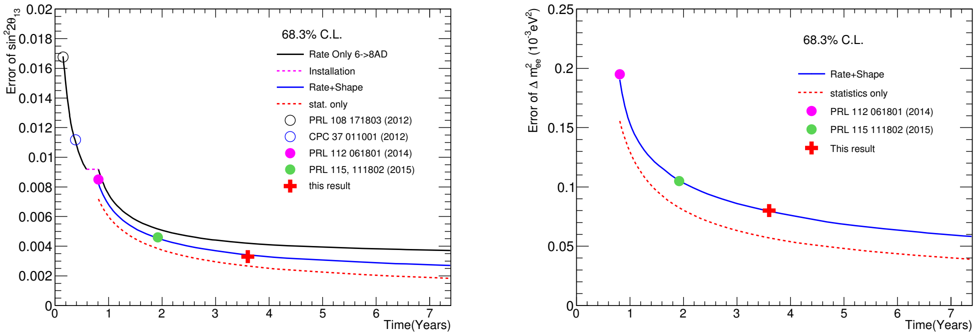


Figure 4: The evolution of Daya Bay sensitivities of the errors of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$.

7. Summary

In summary, With 1230 days of data taking, the Daya Bay experiment provides the most precise measurement of $\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$, and $|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3}$ eV^2 to date.

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