

# Recent results from Daya Bay reactor neutrino Experiment

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**Abstract.** Neutrinos are elementary particles in the standard model of particle physics. There are 3 flavors of neutrinos that oscillate among themselves and their oscillation can be described by a  $3 \times 3$  unitary matrix, containing three mixing angles  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ , and one CP phase. Both  $\theta_{12}$  and  $\theta_{23}$  are known from previous experiments. The Daya Bay experiment gave the first definitive non-zero value in 2012. Daya Bay use the 1230 days data to obtain the most precise measurement of  $\sin^2 2\theta_{13} = 0.08421 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$  and  $|\Delta m_{ee}^2| = (2.50_{-0.06}^{+0.06}) \times 10^{-3} \text{eV}^2$ . Experiment has measured the flux and spectrum of the reactor antineutrino. Flux is consistent with previous short baseline experiments and spectrum different from prediction with significance  $4.4\sigma$  in 4-6 MeV energy region. Experiment also measure the IBD yield per fission from individual isotopes ( $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{238}\text{U}$ ,  $^{241}\text{Pu}$ ) and found that IBD yield of  $^{235}\text{U}$  is 7.8% lower than prediction. For light sterile neutrino search, there are no hint of light sterile neutrino observed from Daya Bay data and give the most stringent limit for  $|\Delta m_{41}^2| < 0.2 \text{eV}^2$ .

## 1. Introduction

The neutrino is a fundamental particle and was first discovered in 1956 [1, 2]. It has been proven that the observed neutrino oscillations can be described in a 3-flavor neutrino framework in past experiments. A parameterization of the standard Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix describing the unitary transformation relating the mass and flavor eigenstates, defines the three mixing angles ( $\theta_{23}$ ,  $\theta_{12}$ , and  $\theta_{13}$ ) and one charge-parity (CP)-violating phase [3, 4].  $\theta_{12}$  is about  $34^\circ$  and determined by solar and reactor neutrino experiments.  $\theta_{23}$  is about  $45^\circ$  and determined by atmospheric and accelerator neutrino experiments. The value of  $\theta_{13}$  is so small that was observed until 2012 [5, 6] by reactor anti-neutrino experiments.

Reactor antineutrino experiments can provide a clear and accurate measurement of  $\theta_{13}$ , due to their pure antineutrino source, clear determined in terms of the survival probability of  $\bar{\nu}_e$  at certain distances from the reactors,

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

where  $\Delta_{ji} \equiv 1.267 \Delta_{ji}^2 (\text{eV}^2) L(\text{m}) / E(\text{MeV})$ ,  $E$  is the  $\bar{\nu}_e$  energy in MeV and  $L$  is the distance in meters between the  $\bar{\nu}_e$  source and the detector.  $\Delta m_{ji}^2$  is the difference between the mass-squares of the mass eigenstates  $\nu_j$  and  $\nu_i$  ( $\Delta m_{ji}^2 = \Delta m_j^2 - \Delta m_i^2$ ). Since  $\Delta m_{21}^2 \ll |\Delta m_{31}^2| \approx |\Delta m_{32}^2|$  [7], the short distance ( $\sim \text{km}$ ) reactor  $\bar{\nu}_e$  oscillation is mainly determined by the  $\Delta_{3i}$  terms.

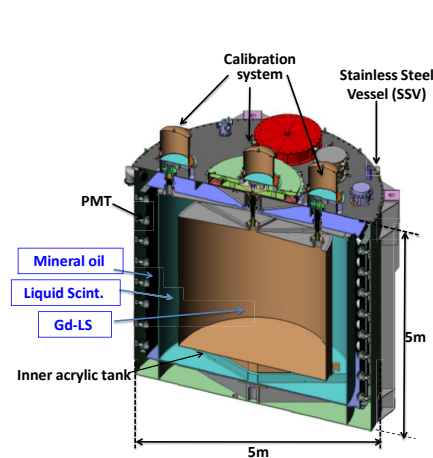


Most reactor antineutrino oscillation experiments measure antineutrino events via the inverse beta decay (IBD) reaction  $\bar{\nu} + p \rightarrow e^+ + n$ . The IBD reaction is characterized by two time correlated events, the prompt signal coming from the production and subsequent annihilation of the positron, and the delayed signal from the capture of the neutron in the liquid scintillator. For the Daya Bay experiment, 0.1% gadolinium (Gd)-doped liquid scintillator is used to increase the capture cross section of thermal neutrons on Gd and reduce the capture time (about 30  $\mu\text{s}$ ) to suppress accidental coincidence backgrounds. The following content of this paper mainly focuses on recent results from Daya Bay experiment.

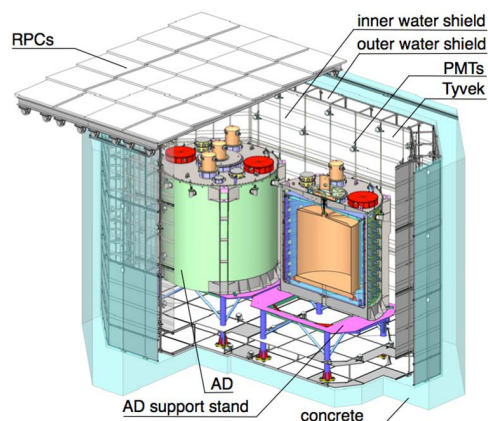
## 2. Daya Bay experiment

The Daya Bay experiment is designed to explore the unknown value of  $\theta_{13}$  by measuring the survival probability of electron antineutrinos from the nuclear reactors in Daya Bay, China. The Daya Bay Nuclear Power Plant complex, one of the 5 most prolific sources of reactor neutrinos in the world, consists of 6 reactors producing 17.4 GW of total thermal power. Multiple sites (one far experimental hall (EH3) and two near experimental halls (EH1, EH2)) are used to effectively cancel the flux uncertainty by relative measurements. The experiment employs 8 identically designed detectors to decrease detector related errors. The detectors are installed underground to reduce the cosmic-ray muon flux. There are 6 detectors were deployed before August, 2012. All 8 detectors were installed by October, 2012.

### 2.1. Detector



**Figure 1.** Antineutrino detector of Daya Bay experiment.



**Figure 2.** Veto system of Daya Bay experiment. It includes the inner water shield, outer water shield and top RPC detector.

**2.1.1. Antineutrino detector** The antineutrino detectors (ADs) are filled with Gd doped liquid scintillator for antineutrino event detection[8]. The experiment uses 8 functionally identical detectors (2 at EH1, 2 at EH2 and 4 at EH3), which are cylindrical stainless steel vessels(SSV) with a 5 m diameter and 5 meter height (Fig. 1). Each detector is instrumented with 192 8-inch photomultiplier tubes (PMTs). The detector has a three-zone structure, including a Gd-doped liquid scintillator (GdLS) zone, liquid scintillator (LS) zone and mineral oil (MO) zone. The inner region is the primary target volume filled with 0.1% Gd-LS. The middle layer is LS and act as a gamma catcher, and the outer layer is filled with MO which reduces the impact of radioactivity from PMT glass and the SSV. Two acrylic tanks are used to separate

each layer. There are two reflectors at the top and bottom of an AD to improve light collection and uniformity of detector response.

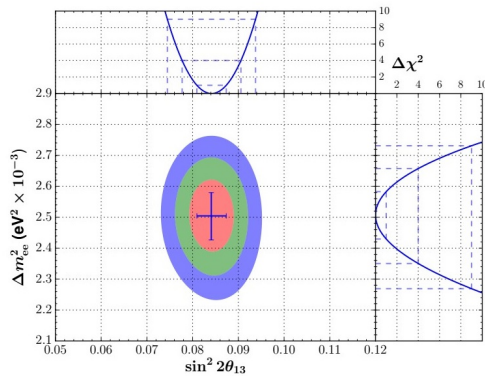
**2.1.2. Muon veto system** The muon veto system [9] of the Daya Bay experiment is shown in Fig. 2. The ADs are immersed in an octagonal pool of ultrapure water. The pool is divided into outer Tyvek sheet with very high reflectivity (>95%) can increase light collection efficiency. At least 2.5 m of water surrounds each AD to shield against ambient radioactivity. 288 8-inch PMTs are installed in each near hall pool and 384 in the Far Hall. There is a water circulation and purification system in each hall to maintain water quality. The tops of the water Cherenkov detectors are covered by Resistive plate chambers (RPCs) detectors. There are 54 modules in each near hall and 81 modules in the Far Hall. The designed efficiency is >99.5% with uncertainty less than 0.25% by combining the water Cherenkov and RPC detectors. From muon data analysis, water Cherenkov detector efficiency is >99.7% for long track muons [8], which is better than the design requirement.

### 3. Results

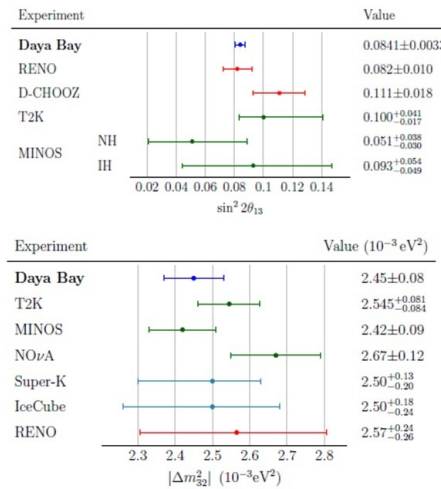
#### 3.1. Oscillation results

The latest results from Daya Bay is from the 1230 days dataset, using 217 days 6 AD period and 1013 days 8 AD period data [10]. The  $\sin^2 2\theta_{13}$  is  $0.08421 \pm 0.0027$  (stat.)  $\pm 0.0019$  (syst.) and  $|\Delta m_{ee}^2|$  is the value of  $[2.50 \pm 0.06$  (stat.)  $\pm 0.06$  (syst.)  $\times 10^{-3} \text{eV}^2$  from this analysis. The Fig. 3 shows combine analysis of  $\sin^2 2\theta_{13}$  and  $|\Delta m_{ee}^2|$ . They are the most precise measurement in the world. The uncertainty of  $\sin^2 2\theta_{13}$  and  $|\Delta m_{ee}^2|$  is 3.9%, 3.4%, respectively. The Fig. 4 shows the global comparison with the other experiments of the two parameters, which are consist with reactor and accelerator experiments results.

Beside the neutron capture (delay signal) on Gd measurement, we have an independent measurement of  $\theta_{13}$  by neutron capture on hydrogen [11]. The value of  $\sin^2 2\theta_{13}$  was  $0.071 \pm 0.011$  by rate analysis.



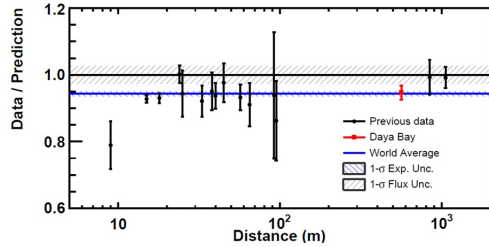
**Figure 3.** Confidence regions of  $\sin^2 2\theta_{13}$  and  $|\Delta m_{ee}^2|$  from a combined analysis of the prompt positron spectra and rates. The  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  two-dimensional confidence regions are estimated using  $\Delta\chi^2$  values of 2.30 (red), 6.18 (green), and 11.83 (blue) relative to the best fit.



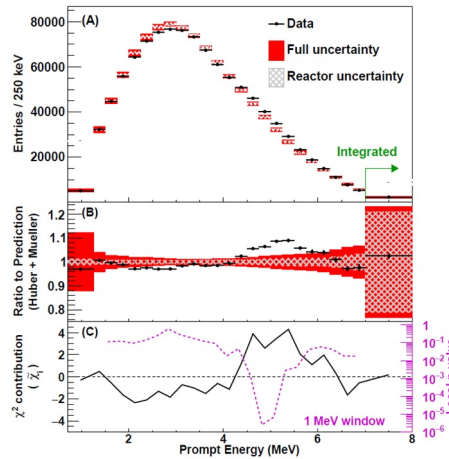
**Figure 4.** Global comparison of  $\sin^2 2\theta_{13}$  and  $|\Delta m_{32}^2|$  with the other experiments. The  $|\Delta m_{32}^2|$  value is based on normal hierarchy.

### 3.2. Reactor Antineutrino Flux and Spectrum measurement

Using 621 days data (217 days  $\times$  6AD + 404 days  $\times$  8AD), more than 1.2 million IBDs were detected. The measured IBD yield is  $(1.53 \pm 0.03) \times 10^{-18} \text{cm}^2/\text{GW}/\text{day}$  or  $(5.91 \pm 0.12) \times 10^{-43} \text{cm}^2/\text{fission}$ , consistent among 8 ADs. The ratio of measured flux to the predictions is  $0.946 \pm 0.020 (0.992 \pm 0.021)$  for the Huber+Mueller (ILL+Vogel) model, which is consistent with the global average of previous short baseline experiments (Fig.5)[12]. For the spectrum measurement (Fig.6), the predicted and measured spectra were compared, and a deviation of  $2.9\sigma$  was found. We found an excess of events in the region of 4-6 MeV with a local significance of  $4.4\sigma$ .



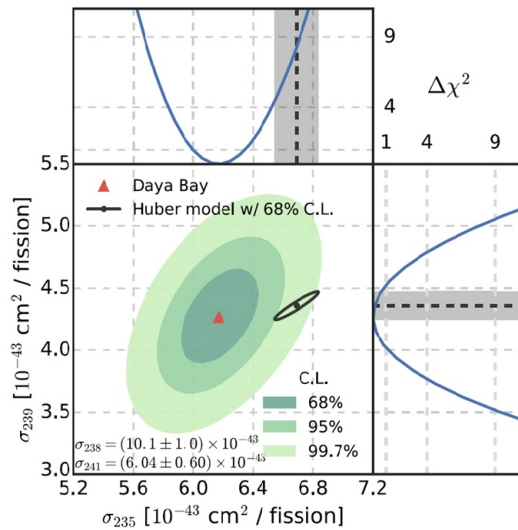
**Figure 5.** The measured reactor antineutrino rate as a function of the distance from the reactor, normalized to the theoretical prediction of Huber+Mueller model. The rate is corrected by 3-flavor neutrino oscillations at the distance of each experiment. The Daya Bay measurement is shown at the flux-weighted baseline (573 m) of the two near halls.



**Figure 6.** (A) Comparison of predicted (Huber+Mueller) and measured prompt energy spectra. (B) Ratio of the measured prompt energy spectrum to the predicted spectrum (Huber+Mueller model). (C) The defined  $\chi^2$  distribution of each bin (black solid curve) and local p-values for 1 MeV energy windows (magenta dashed curve).

### 3.3. Reactor antineutrino flux evolution

The IBD yield and energy spectrum has been measured using 2.2 million IBD candidates (1230 days data set). A total IBD yield  $\bar{\sigma}_f$  of  $(5.90 \pm 0.13) \times 10^{-43} \text{cm}^2/\text{fission}$  was measured with average effective fission fractions  $F_{235}$ ,  $F_{238}$ ,  $F_{239}$ , and  $F_{241}$ . The yield is consistent with the previous measurement [12]. A change in the IBD yield,  $d\sigma_f/dF_{239}$ , of  $(-1.86 \pm 0.18) \times 10^{-43} \text{cm}^2/\text{fission}$  was observed over a range of effective  $^{239}\text{Pu}$  fission fractions from 0.25 to 0.34. These yield measurements were used to calculate IBD yield per fission values of  $(6.17 \pm 0.17)$  and  $(4.27 \pm 0.26) \times 10^{-43} \text{cm}^2/\text{fission}$  for fits to individual isotopes  $^{235}\text{U}$  and  $^{239}\text{Pu}$ , assuming loose (10%) uncertainties on sub-dominant  $^{238}\text{U}$ ,  $^{241}\text{Pu}$  as Fig.7 shown. The measurement of  $^{235}\text{U}$  yield is 7.8% lower than predicted, significantly larger than the 2.7% measurement uncertainty which indicated that overestimated contribution from  $^{235}\text{U}$  and it may be the primary contributor to the reactor antineutrino anomaly. It needs new measurements of the  $^{235}\text{U}$  antineutrino flux by the future experiments.



**Figure 7.** Combined measurement of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  IBD yields per fission  $\sigma_{235}$  and  $\sigma_{239}$ . The red triangle indicates the best fit  $\sigma_{235}$  and  $\sigma_{239}$ , while green contours indicate two-dimensional  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  allowed regions.

### 3.4. Light sterile neutrino search

For light sterile neutrino study, there are no hint of light sterile neutrino observed from Daya Bay data and give the most stringent limit for  $|\Delta m_{41}^2| < 0.2\text{eV}^2$ [14]. The combine analysis(DayaBay + MINOS + Bugey-3) excludes parameter space allowed by MiniBooNE and LSND for  $|\Delta m_{41}^2| < 0.8\text{eV}^2$ [15].

## 4. Summary

Daya Bay use the 1230 days data to obtain the most precise measurement of  $\sin^2 2\theta_{13}$  and  $|\Delta m_{ee}^2|$ . The experiment measures the reactor antineutrino flux and spectrum. The results show that flux is consistent with previous short baseline experiments and spectrum different from prediction with significance  $4.4\sigma$  in 4-6 MeV energy region. The IBD yield per fission from individual isotopes ( $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{238}\text{U}$ ,  $^{241}\text{Pu}$ ) has been measured and found that IBD yield of  $^{235}\text{U}$  is 7.8% lower than prediction. There are no hint of light sterile neutrino observed from experiment data and it gave more stringent limit for light sterile neutrino search. The experiment is expected to continue running until 2020 and expected to get uncertainty in oscillation parameters to below 3%

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