PROCEEDINGS OF SCIENCE

The lastest results from Daya Bay

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The Daya Bay reactor neutrino experiment, operated from December 2011 to December 2020, has gathered a record amount of statistical data on reactor neutrino interactions. Antineutrinos from 6 reactor cores were detected through inverse beta decay and identified through neutron capture on gadolinium or hydrogen using eight functionally identical detectors located in three experiment halls. Thanks to the high statistics, well-controlled systematic errors, effective background suppression and precise evaluation, Daya Bay has been providing the most precise measurements of the neutrino mixing angle θ_{13} in the world. This contribution presents the latest results on the measurement of neutrino oscillation parameters within the three-neutrino oscillation framework, the search for sterile neutrinos, and measurements of reactor flux and spectra.

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PoS(PIC2024)019

1. Introduction

Neutrino oscillation has been experimentally established since its discorvery in 1998 [1]. In the standard three neutrino oscillation frame work, neutrino oscillation can be described by PMNS matrix [2] with 6 independent paramters: three oscillation angles($\theta_{12}, \theta_{23}, \theta_{13}$), two mass square differences $\Delta m^2_{21}, \Delta m^2_{31}$ and a CP violation phase δ_{CP}. Accurate determination of θ_{13} is essential for testing the three-neutrino paradigm of oscillations and providing important constraints for model building and experiments, particularly in resolving the neutrino mass ordering [3] and exploring CP phase [4] [5] in neutrino oscillations.

Daya Bay experiment is one of the three so-called θ_{13} experiments that aimed to precisely determine θ_{13} by detecting neutrinos from reactors of about a few kilometers away. At this baseline, θ_{13} dominants the reactor $\overline{\nu}_e$ oscillation without dependence on unknown neutrino mass ordering or CP violation phase:

$$\begin{aligned} P_{\text{sur}} \approx 1 \quad &- \quad \sin^2 2\theta_{13}(cos\theta^2_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}) \\ &- \quad \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21} \end{aligned} \tag{1}$$

where $\Delta_{ji} \equiv 1.267\Delta m^2_{ji}(\text{eV}^2)L(\text{m})/E(\text{MeV})$, with Δm^2_{ji} the difference between the mass-squares of the mass eigenstates ν_j and ν_i, E is the $\overline{\nu}_e$ energy and L is the distance between the $\overline{\nu}_e$ source and the detector (baseline).

2. The Daya Bay Experiment

The Daya Bay experiment, located near the Daya Bay nuclear power plant about 50 km from Hongkong, China, uses six reactor cores with a total thermal power of 17.4 GW. Closeby mountains provide natual shielding against cosmic backgrounds. Detectors were placed approximately 370 m and 500 m from the two clusters of reactors at the Daya Bay and Ling Ao nuclear power plants(NPP) for precise monitoring. The far site, located 1912 m from the Daya Bay NPP and 1540 m from the Ling Ao NPP, was selected based on oscillation maximum and topography. The overburden for the three experimental sites are 250 m.w.e. (EH1), 265 m.w.e. (EH2), and 860 m.w.e. (EH3).

Multiple functionally identical antineutrino detectors (ADs) were built to minimize detector-related systematic errors. Each AD consists of three concentric vessels containing different liquids. The innermost vessel, a 3-meter diameter acrylic cylinder, holds 20 tons of 0.1 Gd-doped liquid scintillator (GdLS). Surrounding this is a 4-meter diameter acrylic vessel containing 20 tons of liquid scintillator (LS), which serves as a gamma catcher. The outermost stainless steel vessel, measuring 5 meters in diameter, contains 37 tons of mineral oil (MO) that shields the GdLS and LS from external radioactivity. Each AD is equipped with three automatic calibration units (ACUs) on top and features 192 8-inch photomultipliers (PMTs) on the side, along with optical reflectors at the top and bottom, providing a total photo coverage of 12%. Each detector collects an average of 160 photoelectrons per MeV, yielding an energy resolution of about 8% at 1 MeV. The ADs are located in water pools filled with ultrapure water, providing at least 2.5 meters of shielding against ambient radioactivity and equipped with additional PMTs to act as Cherenkov detectors.Resistivity

PoS(PIC2024)019

plate chambers(RPCs) on top of the water pool give independent muon tagging.Details on the Daya Bay experiment can be found in [6].

MeV-scale electron antineutrinos ($\overline{\nu}_e$s) are detected via the inverse beta-decay reaction(IBD),$\overline{\nu}_e + p \rightarrow e^+ + n$. The positron's rapid energy loss and subsequent annihilation gamma rays create a prompt signal, while the neutron scatters and typically captures on gadolinium (nGd-IBD) or hydrogen (nH-IBD), generating a delayed signal. The positron carries most of the energy from neutrino, allowing the neutrino energy $E_{\overline{\nu}_e}$ to be inferred from the detected prompt signal energy E_p using the relation $E_{\overline{\nu}_e} \approx E_p + 0.78MeV$. Reactor neutrinos undergo flavor oscillations and demonstrate an energy-dependent event deficit, which is most pronounced at the far site.

The measured energies were calibrated through a comprehensive program that included the routine deployment of calibration sources along the vertical axis at the detector center (ACU-A), the edge of the GdLS volume (ACU-B), and the LS volume (ACU-C), as well as a manual calibration in EH1AD1and a dedicated calibration campaign to remove electronics nonlinearity, along with naturally occurring sources. The relative energy scale uncertainty is constrained to within 0.2% [7], and the energy nonlinearity uncertainty is within 0.5% for positrons with kinetic energies exceeding 1 MeVs [8].

3. The Lastest results

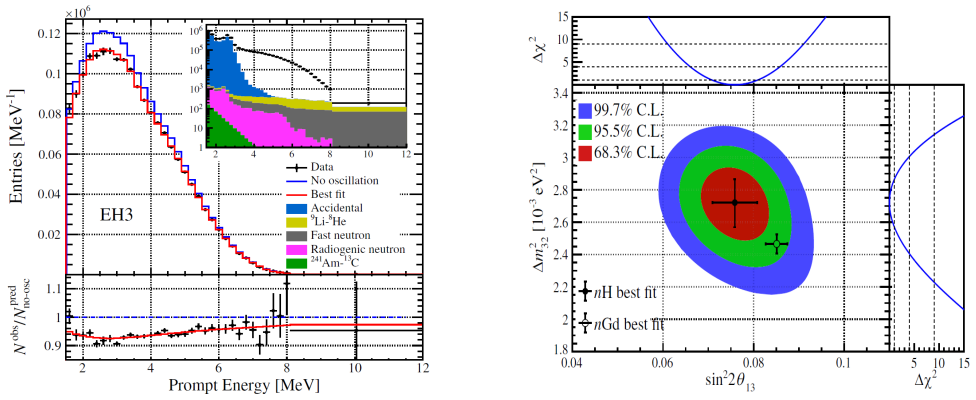


Figure 1: (a): The nH-IBD positron spectrum(background subtracted)in the far site is shown on the top panel, with the predicted spectrum based on near site data both without (blue line) and with best-fit oscillation(red line). The bottom panel shows the ratio of the far site spectrum to the weighted near site spectrum. The red curve shows the expectation at the best-fit oscillation values. (b): The error ellipses in the $(\Delta m^2_{32}, sin^2 2\theta_{13})$ space assuming normal mass ordering with best fit point indicated. The best fit from nGd sample [9] is also shown. The colored contours correspond to 1,2,and 3 standard deviations.

The experiment collected data from December 2011 to December 2020 using three different detector configurations: 6 ADs for 217 days, 8 ADs for 1524 days, and 7 ADs for 1417 days.A final sample of approximately 5.55×10^6 nGd-IBD candidates were selected from the total 3158 operational days of the Daya Bay experiment. This sample provides the world's most precise measure of $sin^2 2\theta_{13}$ with the measured value of $sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ and $\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3} eV^2$ for the normal mass ordering or $\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3} eV^{-2}$ for inverted

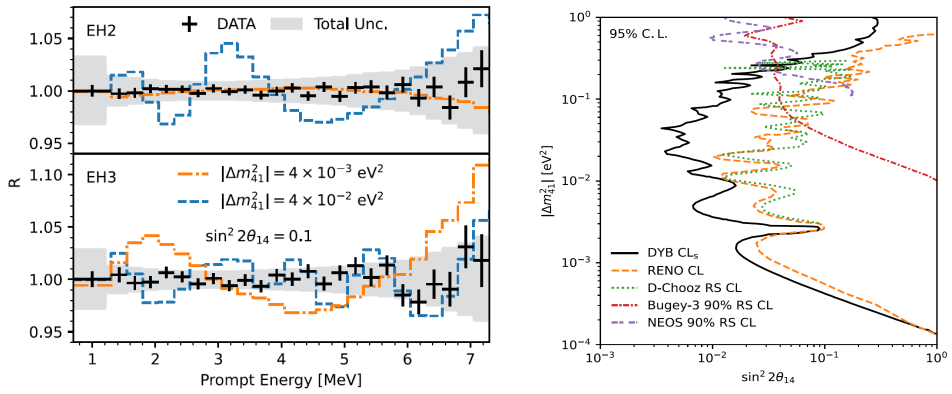
PoS(PIC2024)019

mass ordering [9]. This sample were also used for testing the 3+1 sterile neutrino hypothesis [10], and updating the reactor neutrino flux and spectra measurement with 4 near AD subset [11]. An independent nH-IBD samples were selected from 1958 days of data collection and yielded consistant oscillation results [12]. The first measurement of ^8He isotope produced in liquid scintillator by cosmic ray muon at Daya Bay can be found in [13]. The selected lastest results are presented below.

3.1 An independent measurment of reactor $\overline{\nu}_e$ Oscillation using nH sample

Compared to nGd-IBDs, IBDs with neutron captures on hydrogen predominantly occur in the LS region, which experiences greater energy leakage and substantial background from natural radiactivity near the neutron capture signal of 2.2 MeV. Optimized selection cuts were applied to minimize these backgrounds. A dedicated energy response model was developed to account for the enlarged target volume. The measured far site prompt energy spectrum is shown in the left pannel of Fig 1. The variations in the relative $\overline{\nu}_e$ rates and energy spectra between the prediction from near data and measurement from far detectors gives $sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$ and $\Delta m^2_{32} = (2.72^{+0.14}_{-0.15}) \times 10^{-3} eV^2$ for the normal neutrino mass ordering , and $\Delta m^2_{32} = (-2.83^{+0.15}_{-0.14}) \times 10^{-3} eV^2$ for the inverted neutrino mass ordering. The best fit value and the 68.3%, 95.5% and 99.7% confidence level allowed regions in the $(\Delta m^2, sin^2 2\theta_{13})$ plane assuming normal neutrino mass odering are shown in the right panel of Fig 1. The estimation of $sin^2 2\theta_{13}$is consistent with and largely independent of the Daya Bay results based the nGd-IBD full dataset, with an approximately 8% improvement in precision when these two results are combined. Details of this analysis can be found in [12].

3.2 Sterile Neutrino Search



(a) (b)

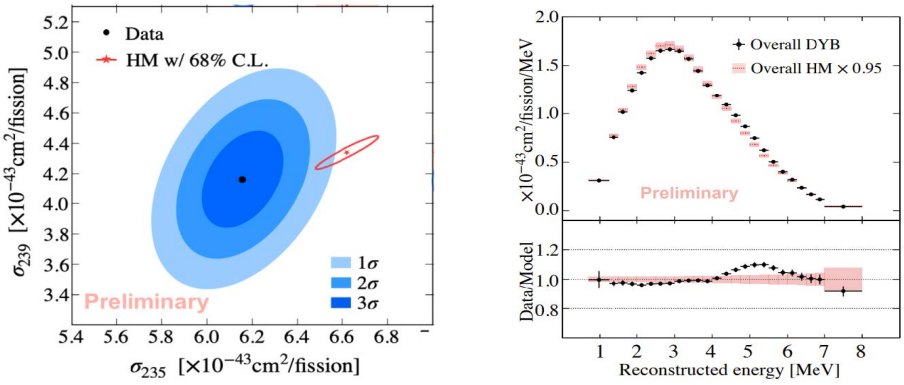
Figure 2: (a) Double Ratio (R) of the spectra, obtained at EH2(3) to EH1 as $R = (M_{EH2(3)}/P^{3\nu}_{EH2(3)})/(M_{EH1}/P^{3\nu}_{EH1})$, where M is the measured prompt energy spectrum, and $P^{3\nu}$ is the three-neutrino prediction with best fit parameters. (b) The exclusion curve with other reactor experiments.See [10] and the references therein.

The 3+1 model allows a light sterile neutrino with a mass of approximately 1 MeV. For baselins less than a few hundred meters, the suvival probability of reactor neutrinos in Eq 1 is then modifed to : $P_{\text{sur}} \approx 1 - \sin^2 2\theta_{14}(cos^2\theta_{13} sin^2\Delta_{41} + sin^2\theta_{13} sin^2\Delta_{43}) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2 \Delta_{32}$. Baselines,

PoS(PIC2024)019

ranging from a few hundred to nearly two thousand meters at Daya Bay, present an opportunity to investigate the active(3)-sterile(1) neutrino mixing within the range $10^{-3}eV^{-2} < |\Delta m^2_{41}| < 0.3eV^{-2}$. As shown in Fig 2(a), the double ratio of the measured to three-neutrinopredicted prompt energy spectra of EH2 and EH3 to that of EH1 provides sensitivity to $sin^2 2\theta_{14}$. No significant oscillation indicative of a sub-eV sterile neutrino mixing with active neutrinos was observed. Exclusion limits were established using both Feldman-Cousions and CLs methods Fig 2(b) shows that the mixing parameter $sin^2\theta_{14} \gtrsim 0.01$ is exlucded at 95% confidence level within the range of $0.01eV^2 \lesssim |\Delta m^2_{41}| \lesssim 0.1eV^2$. These findings provide world-leading constraints in the interval $2 \times 10^{-4}eV^2 \lesssim |\Delta m^2_{41}| \lesssim 0.1eV^2$. Further details of this analyis can be found in [10].

3.3 Reactor Neutrino flux and spectrum measurement



(a) (b)

Figure 3: (a) The combined measurement of ^{235}U and ^{230}Pu IBD yields per fission σ_{235} and σ_{239}. The best fit(dot) and $1\sigma, 2\sigma, 3\sigma$ allowed regions for measurement (in Blue) and 1 $\sigma$for HM prediction. (b) The measured the prompt energy spectrum together with HM prediction scaled to match the total rate of data.

Accurate reactor flux and spectrum are important for reactor neutrino oscillation experiments. Discrepancies have been observed between meaurements and theoretical predictions from both conversion model such as Huber-Mueller model (HM) and summation models regarding both the predicted neutrino rate and its energy spectrum. Approximately 4.7 million nGd-IBDs collected at Daya Bay near detectors over their operational lifetime have been analyzed, resulting in preliminary measurements. The total flux is measured as the IBD yield per fission, denote as σ_f. The evolution of σ_f with respect to the ^{239}Pu fission fraction,F_{239}, has been studied. The averaged IBD yield is determined to be $\overline{\sigma}_f = (5.84 \pm 0.07) \times 10^{-43} cm^2 fission^{-1}$, which is approximately 5% lower than the HM model prediction. This analysis enables the extraction of the IBD yield for two dominant isotopes,^{235}U,^{239}Pu. As shown in Fig 3(a), the dominant discrepency originates in σ_{235}. Additionally, the average prompt energy spectrum has been measured and compared with the HM prediction,which is normalized to the overall rate observed in data. The shape discrepency with respect to the HM prediction is about 10 σ in 4-6 MeV prompt energy range with systmatic uncertainties dominanting the overall error. Fig 3(b) shows the comparison. Further extractions of $\overline{\nu}_e$ from individual isotope of ^{235}U,^{239}Pu are also performed. Comparisons with other theoretical model are under way.

PoS(PIC2024)019

4. Summary

With over ten years of operation, the Daya Bay experiment had collected a significant amount of high-resolution inverse beta interactions. The oscillation analysis based on the nGd-IBD full dataset has provided the world's most precise measurement of $sin^2 2\theta_{13}$with a precision of 2.8%. Analysis of the full dataset are still ongoing, including the independent oscillation studies using nH-IBDs, seasonal variations of the muon flux underground.

Acknowledgments

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PoS(PIC2024)019