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Reactor Neutrino Oscillations in Daya Bay

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We report the latest Daya Bay results of a determination of the smallest neutrino mixing angle θ_{13} and the mass-squared difference Δm^2_{32} at kilometer-scale baseline using the full data sample of 5.55×10^6 inverse bata-decay (IBD) candidates with neutron captured on gadolinium in liquid scintillator detectors. The final data sample was selected from the complete data set obtained by the Daya Bay reactor neutrino experiment in 3158 days of operation between Dec. 24, 2011 and Dec. 12, 2020. We have optimized the IBD candidates selection, refined the energy calibration, and improved the background treatment, and finally determined the oscillation parameters to be $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$, 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 the inverted mass ordering. The reported $\sin^2 2\theta_{13}$ with a precision of 2.8% will likely remain the most precise measurement of θ_{13} in the foreseeable future and will be crucial to the investigation of the mass hierarchy and CP violation in the neutrino oscillation. The agreement in $\sin^2 2\theta_{13}$ and Δm^2_{32} between Daya Bay measurements using reactor $\overline{\nu}_e$ and the muon neutrino and antineutrino measurements from accelerators and atmosphere experiments provides strong support of the three-neutrino paradigm.

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1. Introduction

The discovery of third mixing angle by Daya Bay experiment in 2012 [1] after the discovery of bi-maximal neutrino mixings at the end of last century [2], holds the key to the possibility of observing CP violation in the lepton sector as well as leads to the determination of the mass hierarchy (ordering) of three neutrinos. Although it is not described by the Standard Model, the phenomenon offers the possibility to search for new interactions and physical principles. The oscillation of three-neutrino generations can be described and parametrized by three mixing angles, two mass-squared differences, and a CP phase [3]. This description has been quite successful in explaining most of the observations made with accelerator, atmospheric, reactor and solar neutrinos. Besides being the best-measured neutrino mixing angle at present, precise knowledge of θ_{13} is important for testing the three-neutrino paradigm of neutrino mixing and is the input to model-building and to other experiments, e.g. in solving the neutrino mass ordering [4] and the search for CP violation in neutrino sector [5].

The low-energy electron antineutrinos, $\overline{\nu}_e$s, produced by nuclear reactors, are ideal for determining θ_{13} and the mass-squared difference Δm^2_{32} through the study of $\overline{\nu}_e$ disappearance. This is best accomplished by comparing the energy spectra obtained via identically designed detectors positioned at proper near and far distances from the reactor cores. This relative approach cancels the uncertainties in the absolute detection efficiency that are correlated between detectors and heavily suppresses the effect of uncertainty in the reactor $\overline{\nu}_e$ flux determination, therefore enabling precision measurement of the oscillation parameters. The $\overline{\nu}_e$s are detected via the inverse beta-decay reaction (IBD), $\overline{\nu}_e + p \rightarrow e^+ + n$, with annihilation of the e^+ giving rise to a prompt-energy (E_p) signal, and the subsequent neutron capture to a delayed-enegy (E_d) signal. The energy of $\overline{\nu}_e$, $E_{\overline{\nu}_e}$ is inferred from E_p with $E_{\overline{\nu}_e} \approx E_p + 0.78$ MeV.

2. The Daya Bay Experiment

The Daya Bay experiment located in Shenzhen, China, utilized up to 8 antineutrino detectors (ADs) to detect $\overline{\nu}_e$s emitted from 3 pairs of 2.9-GW_{th} reactors at Daya Bay-Ling Ao nuclear power plants. The ADs were installed in 3 underground experimental halls, EH1, EH2, and EH3 with averaged baseline distances of about 500 m, 500 m, and 1650 m from the reactors, respectively. The ADs were submerged in water pools to suppress the ambient radiation. Each pool was optically divided to inner (IWS) and outer (OWS) water Cherenkov detectors for detecting cosmic-ray muons. Four layers of Resistive Plate Chambers (RPCs) covering the top of each water pool provided another independent muon detector. The IBD events were detected with 20 tons of liquid scintillator doped with 0.1% gadolinium by weight (GdLS) in each AD [6]. GdLS was contained in a 3-m-diameter acrylic cylinder vessel enclosed inside a 4-m-diameter acrylic cylinder vessel filled with 22 tons undoped liquid scintillator (LS). LS consisted the LAB base solution mixed with 3 *g/l* PPO + 15 *mg/l* Bis-MSB. Optical photons produced in the scintillator were detected with 192 photomultiplier tubes (PMTs), covering the barrel surface of the AD, arranged in 8 horizontal rings and 24 vertical columns.. Calibration sources and LEDs can be deployed in 3 automatic calibration units (ACUs) on top of each AD were used for weekly calibration runs. Detailed information of the experiment can be found in Ref. [6].

The Daya Bay experiment was operated with 3 different configurations of ADs (6, 8 and 7 respectively) in the 3 EHs, from Dec. 24, 2011 to Dec. 12, 2020 corresponding to 3158 days of operation with a collection of 5.55×10^6 IBD candidates with the final-state neutron captured on gadolinium (nGd). Details of the analysis process and techniques can be found in Ref. [7] and the results presented here have been validated and cross-checked with multiple groups within the collaboration and have been reported in Neutrino2022 [8] as well as in a detailed letter for publication [9]. The prompt energy E_p was measured accurately via the PMT single photo-electron gain correction and electronics (flash-ADC) non-linearity correction for each ADC channel. The observed charge profile was then used to reconstruct the position of the event in a cylindrical coordinate centered at each AD using the method in Ref. [7] . To obtain the reconstructed energy, the non-uniformity correction of the detector response was applied to the energy deposited by spallation neutron captured on Gd in the GdLS volume and delayed αs from correlated decays of natural radioactivity in the LS volume as additional position-dependent correction in z and r^2 bins of the active volume in each AD. The time dependence of this correction was also done in two calibration periods, before and after Mar. 31, 2017. The prompt energy was obtained by directly correcting the reconstructed energy for non-linear response of LS which was determined from the weekly calibration. The positron response model took into account the measured response of γ-rays from various sources and electrons from β-decay of cosmogenic ^{12}B of the full dataset. The improved energy response model for the positron achieved a precision of $< 0.5\%$ for $E_p > 2$ MeV.

IBD candidate pairs were selected with the following criteria: (i) flasher events were removed; (ii) $0.7 < E_p < 12$ MeV prompt signal separated by 1 to 200 μs from a delay-like signal with (iii) $6 < E_d < 12$ MeV of the delayed nGd peak; (iv) pairs were vetoed by a muon-like signal if their delay-like events fall into the time-windows (multiplicity cut in Ref. [9]) before and after the trigger of IWS, OWS and same AD. Such muon vetoes removed efficiently spurious triggers that followed a muon as well as most muon-induced spallation products and muon decays. To remove any ambiguity of IBD pair selection, no additional AD triggers with delayed energy, $0.7 < E_d < 20$ MeV, were allowed within -400 to 200 μs. The selection efficiency of genuine IBD candidates was over 99.99% which rejected 99% flashers with small amount background events remained. The background comprised uncorrelated accidental pairs, and correlated prompt-and-delayed signals coming from fast neutrons, β-n decays of spallation ^{9}Li/^{8}He, neutrons leaking from the ^{241}Am-^{13}C calibration sources in early run period, as well as ^{13}C(α,n)^{16}O with the α coming from natural radioactivity. The muon detection efficiency of IWS and OWS dropped with time due to the gradual loss of functional PMTs near the top of the water pools, therefore, a new background, named "muon-x" became apparent due to low-E_μ cosmic muons that passed through the IWS undetected, especially in the 7-AD period. We tightened the IWS nHit veto requirements, did a thorough check in each configuration period to deduce the combined fast-n and muon-x background of each AD and their systematics. Improved determination of the largest correlated background, ^{9}Li/^{8}He, was also performed to reduce its rate uncertainty to $< 25\%$.

Detailed IBD candidate signal and background are summarized in Ref. [9] for the final nGd sample. We obtained a total of 4.8 million IBD candidates at near halls and 0.76 million at the far hall with less than 2% background. The $\overline{\nu}_e$ flux without oscillation at each AD was predicted by using the thermal-power data and fission fractions of each fuel cycle, provided by the power plant operator, as a function of burn-up. The power data had an uncorrelated uncertainty of 0.5% per core plus a 0.6% uncertainty per core in the $\overline{\nu}_e$ yield due to the fission fractions. However, due to the nature of near-far relative measurement, 95% of the uncorrelated uncertainty of each core cancelled and the extraction of the oscillation parameters was insensitive to the spectral shape of the on-oscillation prediction.

3. Results of Oscillation Parameters

We extracted the oscillation parameters using the survival probability of three-neutrino-flavor oscillation given by

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}),$$

where $\Delta_{ij} = 1.267\Delta m^2_{ij}L/E$ with Δm^2_{ij} in eV^2, L is the baseline in meters between an AD and a reactor core and E is the energy of the $\overline{\nu}_e$ in MeV. We used $\sin^2\theta_{12} = 0.307 \pm 0.013$ and $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2 [3]. For short baselines of a few kilometers, the survival probability can also be parametrized by $P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$. Here the effective mass-squared difference Δm^2_{ee} is related to the wavelength of the oscillation observed at Daya Bay, and is independent of the choice of neutrino mass ordering as well as the value and uncertainty of the mixing angle θ_{12} [7].

We adopted fitting Method B in Ref. [7] to extract the oscillation parameters by minimizing a χ^2 function defined in Ref. [9] on the measured background-subtracted prompt-energy spectra with the predictions. For each period of operation, the spectrum of each AD was divided into 26 bins. The predictions were derived from the calculated reactor $\overline{\nu}_e$ flux, survival probability, IBD cross section [10] and detector response obtained with a detailed Geant4 based simulation. Figure 1 shows the covariance contours in the Δm^2_{ee} vs $\sin^2 2\theta_{13}$ plot and the best-fit point with $\chi^2/\mathrm{ndf} = 559/518$ yields $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$, 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 the inverted mass ordering. Results determined with the other fitting methods described in Ref. [7] were consistent to $< 0.2\sigma$.

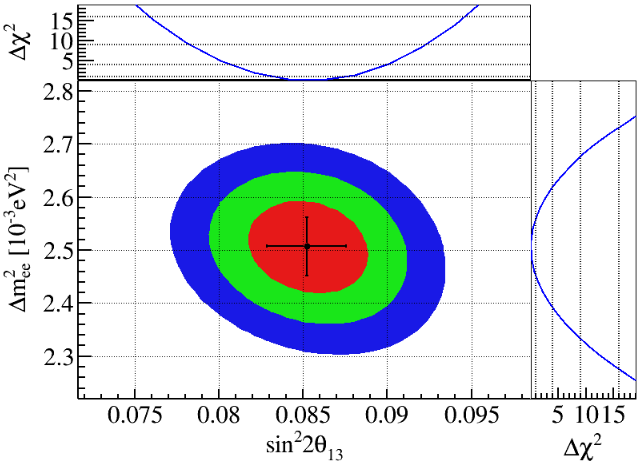

Figure 1: Error ellipses in the $\Delta m^2_{ee} - \sin^2 2\theta_{13}$ space with the best-fit point indicated with 1σ errors. The colored contours correspond to 1σ, 2σ and 3σ regions. The $\Delta\chi^2$ distribution are also shown.

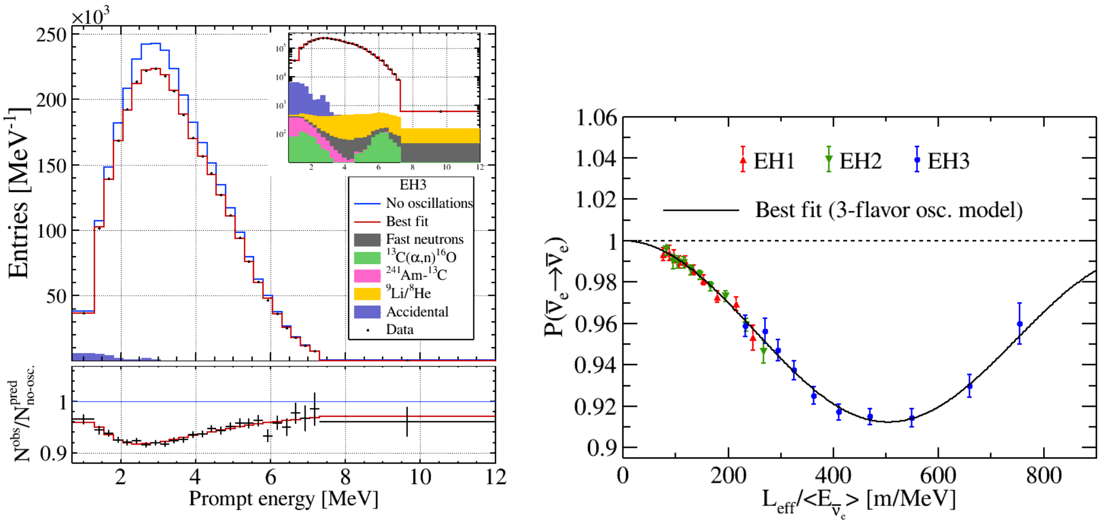

Figure 2: (a) Measured prompt-energy spectra of EH3 with the best-fit comparing with no-oscillation curve superimposed in upper panel. Backgrounds in the spectra are shown in the inset. Lower panel shows the ratio of the observed spectrum to the predicted no-oscillation distribution. The error bars are statistical. (b) Measured disappearance probability as a function of the ratio of effective baseline L_{eff} to the mean antineutrino energy $\langle E_{\overline{\nu}_e} \rangle$.

The best-fit prompt-energy distributions is in excellent agreement with the observed spectra in each experimental hall. Figure 2(a) shows the measured EH3 spectra. Figure 2(b) shows the normalized signal rate of the three halls as a function of $L_{\text{eff}}/\langle E_{\overline{\nu}_e} \rangle$ with the best-fit curve superimposed, where L_{eff} and $\langle E_{\overline{\nu}_e} \rangle$ are the effective baseline and average $\overline{\nu}_e$ energy, respectively. The oscillation pattern related to θ_{13} is unambiguous.

4. Conclusion

We report a new determination of $\overline{\nu}_e$ with a precision of 2.8% and the mass-squared differences reaching a precision of about 2.4%. The reported $\sin^2 2\theta_{13}$ will most likely remain the most precise measurement of θ_{13} in the foreseeable future and will be crucial to the upcoming investigations of the mass hierarchy and *CP* violation in the neutrino oscillation. The agreement in $\sin^2 2\theta_{13}$ and Δm^2_{32} between Daya Bay measurements using reactor $\overline{\nu}_e$ and the measurements of muon neutrino and antineutrino determined from accelerators and atmosphere experiments provides strong support of the three-neutrino paradigm.

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