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Measurement of $\sin^2(2\theta_{13})$ via neutron capture on hydrogen at Daya Bay

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Abstract. An independent measurement of neutrino oscillation angle θ_{13} using samples based on neutron captured on hydrogen (nH) was performed at the Daya Bay Reactor Neutrino Experiment. To deal with the challenges due to larger backgrounds, longer neutron capture time and lower detection efficiency, the nH analysis developed several data-driven techniques to precisely measure backgrounds and to control systematic uncertainties. This statistically independent and largely systematically uncorrelated independent analysis provides a firm confirmation of the nGd result and improves the overall uncertainty of $\sin^2(2\theta_{13})$. With 621 days of data and two newly installed antineutrino detectors, nH analysis yields $\sin^2(2\theta_{13}) = 0.071 \pm 0.011$ in the three neutrino oscillation framework.

1. Introduction

It had been established that neutrino have non-zero mass and three flavors mix. The neutrino oscillation indicates non-zero neutrino masses, which is a breakthrough of the Standard Model. The neutrino mixing parameters include three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), two mass-squared differences ($\Delta m^2_{12}, \Delta m^2_{31}$) and a leptonic CP phase (δ). Precise measurements of all these values are one important sector of future experiments.

The Daya Bay Reactor Neutrino Experiment measures θ_{13} through inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) (IBD) at ~kilometer baseline. This measurement is independent of θ_{23} and CP violating phase δ, and it is the cleanest way to detect θ_{13}. The survival probability is given by

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

where $\Delta_{ij} \equiv 1.267\Delta m^2_{ij}L/E, E$ [MeV] is the energy of the neutrino, L [m] is the baseline between reactors and detectors, and Δm^2_{ij} [eV^2] is the the difference between the squared masses of mass eigenstates ν_i and ν_j.

Daya Bay gave the first measurement of θ_{13} with a significance of 5.2 standard deviation with 55 days of data [1] and provided the word's most precise measurement of θ_{13} [2] among the existing and future experiments. Daya Bay has eight functionally identical antineutrino detectors (ADs). Each detector has three nested cylindrical volumes, the innermost layer holds 20-ton gadolinium-doped liquid scintillator and is used to identify electron antineutrinos by inverse beta decay with neutron captured on gadolinium (nGd), the middle layer is filled with 22-ton liquid scintillator to detect γ's that escape from the doped volume, this layer combined with gadolinium-doped layer also can independently identify electron antineutrinos with neutron captured on hydrogen (nH). (A detail of Daya Bay experiment can be found in Ref [4]). The different neutron captured target yields that nH measurement is statistically independent and largely systematically independent with nGd measurement. In this article, we report the new results of nH analysis with 621 days of data including 217-day data with six detectors.

2. Data Analysis

IBD candidates are selected with the following criteria. AD events caused by PMT light emission are efficiently removed. Then, candidates are selected by requiring to have E $>$ 1.5 MeV to exclude low energy backgrounds. These AD events are grouped within a (1-400) μs time window to identify double coincidence after muon veto. Candidates are rejected if the first (prompt) signal occur within (-400, 400) μs to a water pool muon ($N_{PMT} > 12/15$ in the inner/outer water pool), within (-400, 800) μs to an AD muon (E $>$ 20 MeV), or within (-400 μs, 1 s) to an AD shower muon (E $>$ 2.5 GeV). These remaining events are required to have E $<$ 12 MeV and energy of the second (delayed) signal within three standard deviations of the fitted nH γ energy in each AD. Finally, a 500 mm distance between the prompt and delayed signals is performed to suppress accidental backgrounds. A total of 780,000 nH-IBD candidates are selected and then introduces 49% reduction of statistical uncertainty compared with the previous nH-IBD result [5]. For the far site, the prompt-energy distribution of selected IBD candidates including all backgrounds is illustrated in figure 1.

In nH analysis, four sources of background are identified. The largest background comes from accidental background caused by two uncorrelated single events, which accounts for about 12% (54%) of the candidates in the near (far) site. The high accidental background rate is because that the delayed energy (2.22 MeV) overlaps with spectrum of natural radioactivity. The accidental background is estimated for each run

$$N_{Acc} \equiv R_{Acc} \cdot T_{DAQ} \cdot \epsilon_{\mu} \cdot \epsilon_{ABS}$$

where, N_{Acc} and R_{Acc} are the number and rate of accidental background respectively, T_{DAQ} is the data dating time and ϵ_{μ} is muon veto efficiency. The R_{Acc} and ϵ_{ABS} can be statistically calculated using the rate of uncorrelated single events. The second background comes from cosmogenic muon-induced ^{9}Li/^{8}He and fast neutron background. Cosmogenic muons interact with the ^{12}C in liquid scintillator, producing isotopes and neutrons through hadronic and electromagnetic processes. Among these isotopes, ^{9}Li and ^{8}He beta decay and followed by the ejection of a neutron, this beta decay and neutron process mimics the IBD reaction (^{9}Li/^{8}He). ^{9}Li/^{8}He is about 0.45% (0.2)% of IBD candidates in near (far) site. In addition to isotopes, these produced neutrons may scatter off a proton and then captured on hydrogen, miming the IBD candidates (Fast neutron), which is about 0.4% and 0.15% of selected candidates in near and far site respectively. The AmC background is the smallest background among four backgrounds and largely reduced after summer 2012 when two off-central-axis ACUs AmC sources were removed in the far hall. The AmC sources can occasionally mimic IBD reaction by inelastically scattering with nuclei in the shielding material and then capturing on Fe/Cr/Mn/Ni, two gamma rays are produced and then both enter the scintillator region. It amounts to about 0.015% and 0.03% of selected IBD candidates in near and far site, respectively. The contribution of backgrounds to the total uncertainty of $\sin^2(2\theta_{13})$ are about 4.4%(^{9}Li/^{8}He), 0.4%(accidental), 0.3%(fast neutron) and 0.1%(AmC) respectively.

For the detection efficiency, the detector-uncorrelated uncertainties are determined by comparing data among the eight detectors. The coincidence distance (0.4%) and delayed energy cut (0.35%) dominate the total detector-uncorrelated uncertainties (0.57%).

For the reactor uncorrelated uncertainty, a 0.9% total uncertainty in antineutrino flux due to reactor power, fission fractions, and nonequilibrium and SNF corrections is treated to be uncorrelated among reactors [6], and it contributes about 4.2% to the total uncertainty of $\sin^2(2\theta_{13})$.

To fit θ_{13}, the χ^2 with pull terms for detector uncorrelated, reactor uncorrelated and background uncertainties is constructed, and the best fit value is

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

with a χ^2_{min} per degree freedom of 6.3/6. The top of figure 2 shows the backgrounds subtracted prompt spectrum (solid blue points) and the predicted spectrum of far site based on two near sites (empty black points). The bottom gives the ratio between far and near sites and the curve representing the best-fit value of $\sin^2(2\theta_{13})$.

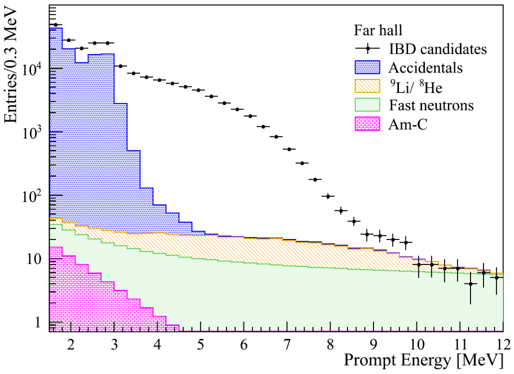

Figure 1. Reconstructed prompt-energy distribution of the IBD candidates (black points) and estimated backgrounds, for the sum of all ADs in EH3.

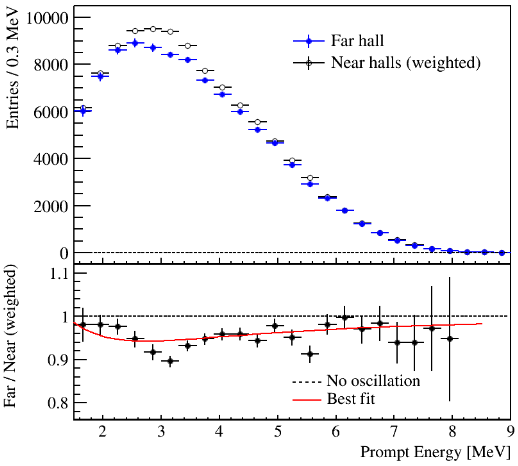

Figure 2. Top: Reconstructed prompt-energy spectrum of the far hall and the expectation based on the measurements of the two near halls. Spectra are background-subtracted. Error bar are purely statistical. Bottom: Ratio of Far/Near halls and the curve representing the best-fit value of $\sin^2(2\theta_{13})$.

3. Summary

More details of nH analysis can be found in Ref [3][5]. The nH analysis result is $\sin^2(2\theta_{13}) = 0.071 \pm 0.011$. It is consistent with nGd-IBD analysis from Daya Bay and provides a valuable confirmation of the nGd-IBD result. The total uncertainty of $\sin^2(2\theta_{13})$ is dominated by the statistical uncertainty (51.8%) and detector-related systematic uncertainty (39.2%).

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