BNL-102325-2013-CP

Observation of electron antineutrino disappearance by the Daya Bay Reactor Neutrino Experiment

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Presented at the DPF 2013 Meeting of the American Physical Society Division of Particles and Fields
Santa Cruz, California
August 13-17, 2013

September 2013

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U.S. Department of Energy
USDOE Office of Science

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DPF2013-243
September 24, 2013

Observation of electron antineutrino disappearance by the Daya Bay Reactor Neutrino Experiment

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This presentation describes a measurement of the neutrino mixing parameter, $\sin^2(2\theta_{13})$, from the Daya Bay Reactor Neutrino Experiment. Disappearance of electron antineutrinos at a distance of $\sim$2 km from a set of six reactors, where the reactor flux is constrained by near detectors, has been clearly observed. The result, based on the ratio of observed to expected rate of antineutrinos, using 139 days of data taken between December 24, 2011 and May 11, 2012, is $\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$. Improvements in sensitivity from inclusion of additional data, spectral analysis, and improved calibration are expected in the future.

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1 Introduction

It is well-established experimentally that the flavor composition of neutrinos change as they propagate[1]. In the three-neutrino framework, the three flavor states $(\nu_e, \nu_\mu, \nu_\tau)$ are superpositions of the three mass states (ν_1, ν_2, ν_3). The PMNS[2, 3] matrix describes this mixing with three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, which have all been measured experimentally, and a CP-violating phase, δ_{CP}, which is unknown. The differences between the mass states have also been measured, though the true mass hierarchy, i.e., the sign of Δm^2_{32}, is unknown.

The Daya Bay collaboration has measured the value of $\sin^2(2\theta_{13})$ by observing the disappearance of electron antineutrinos produced at the Daya Bay nuclear power complex in Guangdong, China [4, 5]. The survival probability for electron antineutrinos is:

$$P_{sur} \approx 1 - \sin^2(2\theta_{13})\sin^2(\frac{\Delta m^2_{31} L}{4E_\nu}) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\frac{\Delta m^2_{21} L}{4E_\nu}) \quad (1)$$

The Daya Bay experiment makes use of functionally-identical antineutrino detectors (ADs) placed at several hundred meters from the reactors to constrain the reactor flux and at several kilometers from the reactors to observe antineutrino disappearance. This presentation reports the Daya Bay measurement of $\sin^2(2\theta_{13})$ using data taken between December 24, 2011 and May 11, 2012, which is described in [5].

2 The Daya Bay Experiment

The Daya Bay nuclear power complex consists of six functionally-identical pressurized water reactors, producing a total of up to 17.4 GW thermal power. The reactors are grouped into three pairs, each of which is referred to as a "nuclear power plant" (NPP): Daya Bay, Ling Ao, and Ling Ao II. The Daya Bay detectors are located in underground experimental halls (EHs) that are connected by horizontal tunnels and are located underneath nearby mountains, which provide shielding from cosmic-ray induced background. The experimental halls are arranged such that EH1, containing two ADs, is near to Daya Bay NPP, EH2, containing one AD during the period reported here, is near to Ling Ao and Ling Ao II NPPs, and EH3, containing three ADs during the period reported here, is the far site. Figure 1 (left panel) is a schematic of the experiment layout.

Daya Bay detects antineutrinos in the ADs using the inverse β-decay (IBD) interaction in gadolinium-doped liquid scintillator[6, 7]. In the IBD interaction, an antineutrino interacts with a proton to produce a positron and a neutron. The positron produces a prompt scintillation signal with energy related to that of the antineutrino. The neutron thermalizes and is captured on gadolinium (Gd) with a characteristic capture time of 30 μs. This prompt-delayed coincidence provides a distinct signature for antineutrino interaction.

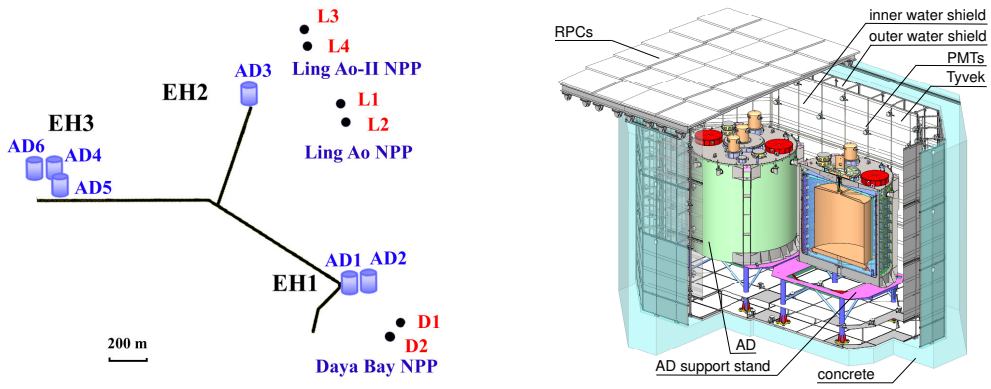

Figure 1: (left) Schematic of the layout of Daya Bay experimental halls and their location relative to the nuclear reactor cores. (right) Schematic of AD location in water pool.

The ADs are three-zone detectors; the central region contains ∼20 tons of Gd-doped liquid scintillator to detect IBD events, the middle region contains ∼20 tons of undoped liquid scintillator to detect γ rays that escape the target volume, and the outer region contains ∼40 tons of mineral oil to shield the inner volumes from radioactive decay originating outside the signal region. Each AD is instrumented with 192 8-inch photomultiplier tubes (PMTs) installed on the inner wall of the outer containment vessel and located in the mineral-oil region of the detector. Each AD is equipped with three "automated calibration units" (ACUs), which allow deployment of calibration sources along three vertical axes of the detector. In each EH, the ADs are placed in a water pool which is instrumented with PMTs; the water pools act both as passive shielding and as Cerenkov detectors to detect muons. Four-layer RPC modules are placed above each pool to provide additional muon information. Figure 1 (right panel) is a schematic of the placement of the ADs inside the water pool in EH1.

The Daya Bay ADs are calibrated using sources deployed by the ACUs in dedicated calibration periods: a ^{68}Ge source producing at-rest positrons, a ^{241}Am $-^{13}$ C source that produces 3.5 MeV neutrons, a ^{60}Co source that produces two γs with total energy ∼2.5 MeV, and an LED diffuser ball. The calibration also makes use of spallation-neutron data taken simultaneously with IBD data during regular physics data collection.

3 Analysis

Event selection consists of the removal of instrumental background from the spontaneous emission of light by PMTs ("flashers"), which is done by identifying the topology of this type of event, removal of muon background, which is done by placing

various requirements on the energy deposit in the water pools and ADs, and selection of the characteristic prompt-delayed IBD signature by requiring a prompt energy deposit of 0.7-12 MeV, a delayed energy deposit of 6-12 MeV, and a capture time in the range 1-200 μs. We further require no other signal > 0.7 MeV within ± 200 μs of the IBD candidate. The result presented here is based on six-AD data taken between December 24, 2011 and May 11, 2012.

We identify five sources of background to the IBD event sample. The largest source of background is accidental coincidence, which contributes 1.5% of IBD candidates in the near halls and 4% of IBD candidates in the far hall. The other four sources of background, which are fast neutrons created by cosmic rays, β-n decay of cosmogenic ^{9}Li/^{8}He, capture on metal nuclei of neutrons emitted by the ^{241}Am $-^{13}$ C source in the ACUs, and ^{13}C$(\alpha, \mathrm{n})^{16}$O background, are all significantly smaller. The total background is 2%(5%) in the near(far) ADs.

Systematic uncertainties are quite small for this analysis because many uncertainties cancel in the near-far ratio method employed by Daya Bay. The two largest uncorrelated, i.e., different between ADs, systematic effects are from uncertainty in the delayed-energy selection requirement and in the fraction of IBD neutrons that capture on Gd. The combined, uncorrelated, detector-related uncertainty is about 0.2%. The effect of uncorrelated uncertainty in the reactor flux is 0.04%.

4 Results

The left panel of Fig. 2 shows the detected antineutrino rate per AD as a function of time for each experimental hall. For comparison, the predicted rates for a no-oscillation hypothesis and for the best-fit value of $\sin^2(2\theta_{13})$ are shown, where the normalization of these curves is determined by a fit to the data. The fluctuations in rate are the result of various reactor cores being powered on and off. The detected rate is strongly correlated with the reactor flux expectations.

The value of $\sin^2(2\theta_{13})$ is determined using a standard χ^2 approach, in which only the rate of detected antineutrinos in each experimental hall is considered. Pull terms are used to account for the correlation of the systematic errors. The quantity that is minimized is:

$$\begin{aligned} \chi^2 &= \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d + B_d} \\ &+ \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right), \end{aligned} \tag{2}$$

where M_d are the measured IBD events of the d-th AD with its backgrounds subtracted, B_d is the corresponding background, T_d is a prediction of the antineutrino

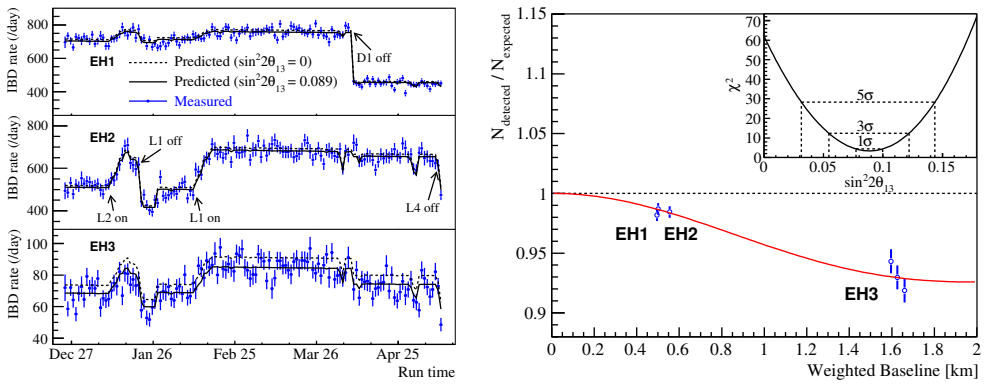

Figure 2: (left) The measured daily average IBD rates per AD in the three experimental halls as a function of time, compared to the expected reactor flux under the assumptions described in the text. (right) Ratio of measured to expected antineutrino rate in each AD, assuming no oscillation.

flux, ω_r^d is the fraction of IBD contribution of the r-th reactor to the d-th AD. The uncorrelated reactor uncertainty is σ_r (0.8%). The parameter σ_d (0.2%) is the uncorrelated detection uncertainty. The parameter σ_B is the background uncertainty. The corresponding pull parameters are $(\alpha_r, \varepsilon_d, \eta_d)$. The absolute normalization, ε, is determined from the fit to the data. The best-fit result is

$$\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.}), \tag{3}$$

with a χ^2/NDF of 3.4/4. This is the most precise measurement of $\sin^2(2\theta_{13})$ to date and is in excellent agreement with other measurements from reactor- and accelerator-based experiments[8, 9, 10, 11]. Figure 2 (right panel) shows the ratio of measured to expected antineutrino rate in each AD, assuming no oscillation; the nearly 6% deficit in the far experimental hall is clearly visible.

5 Future Plans

A spectral measurement of electron antineutrino oscillation amplitude and frequency at Daya Bay was underway at the time of this presentation. The result has since been announced; the spectral shape is consistent with the three-neutrino oscillation scenario, the value of $\sin^2(2\theta_{13})$ is consistent with the result presented here, and the measurement of the mass-splitting, when converted to a value of Δm^2_{32} assuming normal or inverted hierarchy, is consistent with the result from atmospheric neutrinos. A paper describing these results is in preparation.

In fall 2012, a set of special calibration data was taken, including a 4π calibration of one of the ADs using the "Manual Calibration System" (MCS) [12]. This data

may be used to improve understanding of the energy response and absolute efficiency of the Daya Bay detectors. The final two ADs were installed in fall 2012; Daya Bay has been taking data with all eight ADs since October 2012.

6 Summary

The Daya Bay experiment has measured $\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$ by observing a deficit in the rate of electron antineutrinos at a distance ~ 2 km from a nuclear reactor, relative to the rate expected with no oscillations. The is the most precise measurement of $\sin^2(2\theta_{13})$ to date. Additional improvements in sensitivity from inclusion of additional data, spectral analysis, and improved calibration are expected.

ACKNOWLEDGMENTS

The Daya Bay experiment is supported in part by the Ministry of Science and Technology of China, the United States Department of Energy, the Chinese Academy of Sciences, the National Natural Science Foundation of China, the Guangdong provincial government, the Shenzhen municipal government, the China Guangdong Nuclear Power Group, Shanghai Laboratory for Particle Physics and Cosmology, the Research Grants Council of the Hong Kong Special Administrative Region of China, University Development Fund of the University of Hong Kong, the MOE program for Research of Excellence at National Taiwan University, National Chiao-Tung University, NSC fund support from Taiwan, the U.S. National Science Foundation, the Alfred P. Sloan Foundation, the Ministry of Education, Youth and Sports of the Czech Republic, the Czech Science Foundation, and the Joint Institute of Nuclear Research in Dubna, Russia. We thank Yellow River Engineering Consulting Co., Ltd. and China railway 15th Bureau Group Co., Ltd. for building the underground laboratory. We are grateful for the ongoing cooperation from the China Guangdong Nuclear Power Group and China Light & Power Company.

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