IL NUOVO CIMENTO Vol. 36 C, N. 6 Novembre-Dicembre 2013
DOI 10.1393/ncc/i2014-11616-7

Colloquia: LaThuile13

Precise measurement of $\sin^2 2\theta_{13}$ at the Daya Bay Reactor Neutrino Experiment

Z. Y. Yu for the Daya Bay Collaboration
Institute of High Energy Physics - Beijing, China

ricevuto il 20 Giugno 2013; approvato l'1 Luglio 2013

Summary. — The Daya Bay Reactor Neutrino Experiment was designed to precisely measure mixing angle θ_{13}, with the sensitivity better than 0.01 in $\sin^2 2\theta_{13}$ at the 90% C.L. Eight functional identical anti-neutrino detectors are deployed in water pools underground at various baselines from the reactors, for the near-far relative measurement. The experiment began physics data taking on Dec. 24, 2011. With 55 days of data, the Daya Bay experiment observed a non-zero value of θ_{13} at 5.2 standard deviations. The most recent analysis with 139 days of data yields $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$, which is the most precise measurement to date.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 29.40.Mc – Scintillation detectors.
PACS 28.50.Hw – Power and production reactors.

1. – Introduction

Neutrino oscillation is a quantum phenomenon if the mass and flavor eigenstates of neutrinos are mixed. A 3×3 matrix, usually called the PMNS matrix [1, 2], is used to describe the neutrino oscillation. Parameters in the matrix consists of three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and a CP-violating phase. The oscillation also depends on the difference of the squared neutrino masses. In the last decade, three mixing angles and two squared-mass differences have been measured [3] except for θ_{13}, which only had an upper limit ($\sin^2 2\theta_{13} < 0.15$ at 90% C.L.) [4] before 2011. The CP-violating phase is currently unknown, and can be measured only if θ_{13} is not zero.

By the end of 2011, several hints for non-zero θ_{13} are reported by T2K [7], MINOS [8] and Double Chooz [9], with significances of 1.7σ to 2.5σ. Meanwhile, a global neutrino data analysis showed $> 3\sigma$ significance for non-zero θ_{13} [10].

As first proposed in ref. [5], the sensitivity of θ_{13} can be greatly improved if using the near-far relative measurement. This concept has been well utilized by later reactor neutrino experiments, such as Daya Bay and RENO [6].

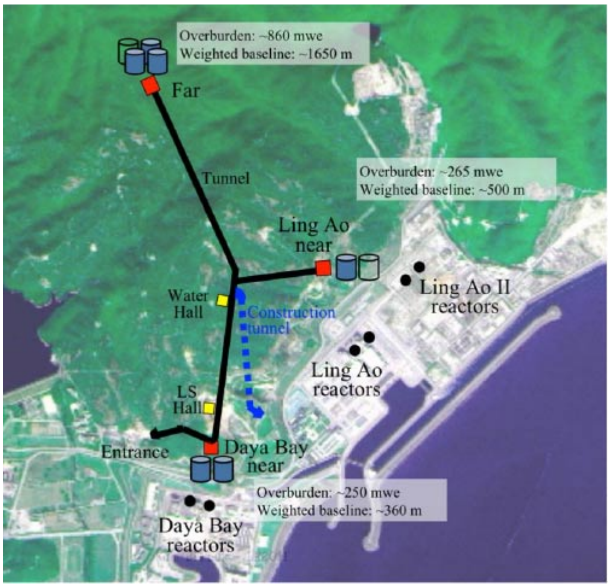

Fig. 1. – Layout of the Daya Bay experiment.

2. – The Daya Bay experiment

The Daya Bay experiment is located at the southern coast of China, 55 km to Hong Kong and 45 km to Shenzhen. A detailed description of the Daya Bay experiment can be found in [11,12]. The experiment was designed to precisely measure the neutrino mixing angle θ_{13} with a sensitivity of 0.01 or better in $\sin^2 2\theta_{13}$ at 90% C.L. The experiment has several key features to achieve such precision measurement: 1) Large statistics: as shown in fig. 1, the Daya Bay nuclear power complex consists of six reactors, each with a maximum of 2.9 GW thermal power, grouped into three pairs, and the total power is the 2^{nd} largest over the world, in addition the experiment has 80t target mass at the far site, as shown in fig. 1. 2) Near-far relative measurement: reactor-related systematic uncertainties can be minimized. Three experimental halls (EHs) are constructed and connected with horizontal tunnels. The Daya Bay near and Ling Ao near halls monitor the neutrino flux from rectors and the far hall measures the oscillation signal. 3) Multiple functional identical detectors: detector-related systematic uncertainties are minimized. 4) Large over burden: reduce cosmic muon rate, resulting less background rate and uncertainty from muons.

Figure 2 illustrates the layout of the Daya Bay detectors in a near hall. In each EH, multiple antineutrino detectors (ADs) sit side by side, allowing cross checks of detector-related uncorrelated systematic uncertainty. The $\bar{\nu}_e$ is detected via the inverse β-decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. Each AD has 20 t of gadolinium-doped liquid scintillator (Gd-LS) as target and 20 t of liquid scintillator (LS) as γ catcher. The coincidence of the prompt scintillation from e^+ and the delayed neutron capture on Gd provide a distinctive $\bar{\nu}_e$ signature. In each EH, the ADs are immersed in a water pool, which provides good shielding against ambient radiation with > 2.5 m of high-purity water in all directions. Each water pool is segmented into inner and out water shields (IWS and OWS) and instrumented with photomultiplier tubes (PMTs) to function as Cherenkov-radiation

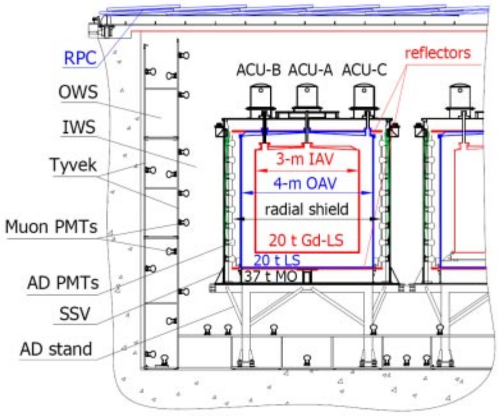

Fig. 2. – Schematic layout of the Daya Bay detectors in a near hall.

detectors, for the purpose of tagging cosmic muons and vetoing the cosmogenic backgrounds. Furthermore, an array of resistive plate chambers (RPC) covers on the top, providing a cross check to reduce the uncertainties of muon veto efficiency.

3. – Neutrino oscillation analysis

The detector energy calibration is performed by three automated calibration units (ACUs) mounted on each ADs lid. A light-emitting diode (LED), a ^{68}Ge source and a combined source of ^{241}Am-^{13}C and a ^{60}Co can be remotely deployed into the Gd-LS and LS liquid volumes along three vertical axes. The PMT gains are calibrated by low intensity LEDs. The energy calibration parameter (p.e. per MeV) is determined by deploying ^{60}Co source at the detector center. The sources are deployed once per week to correct the weak time dependence. A scan along the vertical axis using ^{60}Co source from each of the three ACUs is used to obtain a common non-uniformity correction function for all the ADs. The neutron energy scale is set by comparing ^{60}Co events with neutron capture on Gd events from the ^{241}Am-^{13}C source at the detector center. The energy scale uncertainty is studied by comparing the energy peaks for all types of events in all six ADs, using the neutron capture on Gd from anti-neutrinos and muon spallation products, each of calibration source, and alphas from Polonium decay in the Gd-LS [12,13]. The relative difference falls within a band of 0.5%, quoted as the same uncorrelated uncertainty among ADs, which lead to a 0.12% relative uncertainty of delayed energy cut efficiency among detectors. Currently we did not preform a nonlinearity correction *versus* energy.

$\bar{\nu}_e$ candidates are selected with the following criteria. The energy of the prompt and delayed candidates are required to satisfy $0.7\,\mathrm{MeV} < E_p < 12.0\,\mathrm{MeV}$ and $6.0\,\mathrm{MeV} < E_d < 12.0\,\mathrm{MeV}$, respectively. Time interval $\Delta t = t_d - t_p$ should satisfy a $1 < \Delta t < 200\,\mu$ s coincidence, where t_p and t_d are the timestamps of the prompt and delayed signals. A multiplicity cut requires no additional candidate with $E > 0.7\,\mathrm{MeV}$ in the interval $200\,\mu$s before t_p, $200\,\mu$s after t_d, or between t_p and t_d. The prompt-delayed pair is vetoed if the delayed candidate satisfied any of the conditions: $-2\,\mu\mathrm{s} < t_d - t_{\mu_{WS}} < 600\,\mu\mathrm{s}$ (*Pool muon*), $0 < t_d - t_{\mu_{AD}} < 1000\,\mu\mathrm{s}$ (*AD muon*), *or* $0 < t_d - t_{\mu_{sh}} < 1\,\mathrm{s}$ (*AD showering muon*). The prompt energy, delayed energy and capture-time distributions for data show good agreement with MC, respectively.

The absolute efficiencies are predicted by MC. The uncertainties from neutron spill-in (neutrons from IBD interactions outside the target volume are captured by Gd in the target volume) efficiency and Gd capture ratio are the two main sources of correlated uncertainties and estimated from the differences between data and MC. In the relative measurement, absolute efficiencies as well as correlated uncertainties are effectively canceled. Only uncorrelated uncertainties contribute to the final error. The total uncorrelated uncertainty is 0.2% [13, 14], better than our baseline design 0.38% [TDR]. The largest uncorrelated uncertainty is from delayed-energy cut (0.12%). The relative uncertainties are checked by a side-by-side comparison with two near detectors (AD1 and AD2) at Daya Bay near hall [12, 13]. The measured ratio of the total $\bar{\nu}_e$ rates in AD1 and AD2 is $0.987 \pm 0.004(\text{stat.}) \pm 0.003(\text{syst.})$, consistent with the expected ratio 0.982.

The largest background in the $\bar{\nu}_e$ candidates are accidental backgrounds, defined as any pair of otherwise uncorrelated signals that accidentally satisfied the anti-neutrino event selection criteria. The expected background rates are calculated using the rate of prompt-type and delayed-type signals. An alternate method, so-called off-window method, is developed to estimate such background. The background estimation is also validated by comparing the distributions of distance between the reconstructed vertices for the prompt and delayed signals of the antineutrino candidates and accidental coincidences selected by the off-window method. The Background/Signal ratio (B/S) for accidental backgrounds accounted for $4.0 \pm 0.05\%$ ($1.5 \pm 0.02\%$) of the far (near) halls.

The background uncertainty is dominated by the cosmogenic $\beta - n$ isotopes ^{9}Li/^{8}He and the ^{241}Am-^{13}C neutron sources inside the ACUs on top of each AD. The ^{9}Li/^{8}He background is evaluated using a method to fit the distribution of the time since the last muon. By assuming that most of the ^{9}Li/^{8}He production is accompanied with neutron generation, the AD tagged muon events with no follow-on neutron are rejected from the muon sample, resulting in an improvement of the fitting precision. The B/S for ^{9}Li/^{8}He background is estimated to be $0.3 \pm 0.2\%$ ($0.4 \pm 0.2\%$) at the far (near) halls. The formation of Am-C correlated backgrounds is a prompt gamma signal from neutron inelastic scattering on iron, followed by the delayed γ rays produced by capture on stainless steel. The B/S for Am-C correlated background is estimated to be $0.3 \pm 0.3\%$ ($0.03 \pm 0.03\%$) at the far (near) halls.

Other correlated backgrounds due to energetic neutrons from cosmogenic products (*i.e.* fast neutrons) and (α,n) nuclear interactions are negligible. The energetic cosmogenic neutrons could mimic $\bar{\nu}_e$ events by recoiling off a proton then being captured on Gd. Background from muon induced neutrons is estimated by extrapolating the prompt energy distribution between 12 and 100 MeV down to 0.7 MeV. Three additional methods are used to provide cross checks and the results are consistent. The B/S for fast neutron backgrounds is estimated to be $0.07 \pm 0.03\%$ ($0.12 \pm 0.05\%$) at the far (near) halls. The backgrounds caused by $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ reaction is calculated using the measured alpha-decay rates and neutron yield determined by MC. The B/S for such backgrounds is estimated to be $0.05 \pm 0.03\%$ ($0.01 \pm 0.006\%$) at the far (near) halls.

The $\bar{\nu}_e$ flux of each reactor is calculated from the simulated fission rate of four main isotopes (^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu) and the $\bar{\nu}_e$ sectrum per fission. The thermal power measured by the power plant is used for normalization when simulating the fission rate. The near-far relative measurement is independent of reactor flux models, and the uncorrelated reactor uncertainty is estimated to be 0.8%. The $\bar{\nu}_e$ rate in the far hall is predicted with a weighted combination of the two near hall measurements assuming no oscillation. The ratio of the observed to expected rate of all three ADs at the far hall is measured to be $R = 0.944 \pm 0.007(\text{stat.}) \pm 0.003(\text{syst.})$. Figure 3 shows the

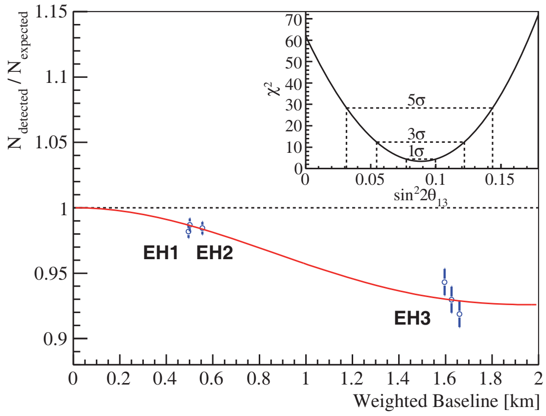

Fig. 3. – Ratio of measured *versus* expected (no oscillation) signals in each detector. The oscillation survival probability at the best-fit value is given by the smooth curve. The AD4 and AD6 data points were displaced by -30 and $+30$ m for visual clarity.

ratio of measured *versus* expected in each detector. In a three-neutrino framework, an analysis of relative anti-neutrino rates of the six detectors determined $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$, using a χ^2 method with pull terms accounting for the correlation of the systematic errors. The observed $\bar{\nu}_e$ spectrum in the far hall is compared to a prediction based on the near hall measurements. The distortion of the spectra is consistent with that expected due to oscillations at the best-fit θ_{13} obtained from the rate-based analysis, as shown in fig. 4.

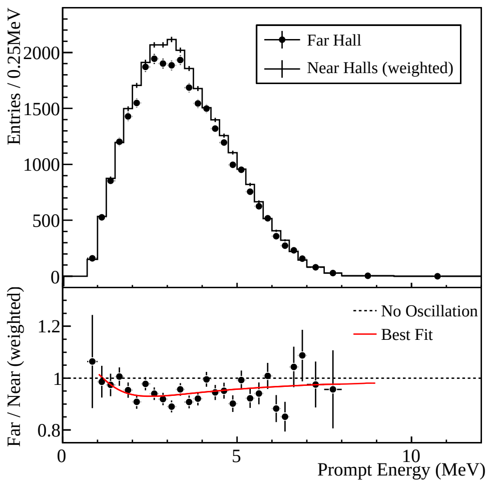

Fig. 4. – Top: Measured prompt energy spectrum of the far hall (sum of three ADs) compared with the no-oscillation prediction based on the measurements of the two near halls. Bottom: The ratio of measured and predicted no oscillation spectra. The solid curve is the expected ratio with oscillation for $\sin^2 2\theta_{13} = 0.089$.

Fig. 5. – Recent progresses of the Daya Bay experiment. Left: Install the Manual Calibration System on AD1; Right: Install the last AD in the far hall.

4. – Recent progresses, conclusion and outlook

In the summer of 2012, detailed calibration was done on the two ADs of EH1, including dedicated non-linearity calibration with different γ sources, and the Manual Calibration System, which can deploy a combined Pu-^{13}C and ^{60}Co source 3-D in the detector. The left plot in fig. 5 shows Manual Calibration System installation on AD1. The last two ADs were also installed in the summer, as shown in the right plot in fig. 5. After commissioning, the Daya Bay re-started physics data taking with eight ADs since Oct. 19, 2012.

Using 139 days of data, the Daya Bay experiment has confirmed the previous observation of reactor electron-antineutrino disappearance and has provided an improved measurement to θ_{13}. In a three-neutrino oscillation framework, the disappearance leads to $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$. The experiment will take a comprehensive calibration campaign to improve the energy reconstruction for spectral shape analysis.

With the last two ADs installed, the experiment will continue to run for at least 3 years to measure $\sin^2 2\theta_{13}$ to 5% precision, by both accumulating more statistics and reducing systematic uncertainties. The high statistics of near halls will also provide the most precise measurement of reactor anti-neutrino flux and spectrum at corresponding baselines. In addition, by measuring the neutrino spectrum distortion, the experiment could measure the effective squared-mass difference (a combination of Δm^2_{31} and Δm^2_{32}). The measured large θ_{13} stimulates the next round of experimental quests to measure mass hierarchy and CP violation phase.

* * *

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, and 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., Lt_d. and China railway 15th Bureau Group Co., Lt_d. for building the underground laboratory. We are grateful for the ongoing cooperation from the China Guangdong Nuclear Power Group and China Light & Power Company.

REFERENCES

[1] Pontecorvo B., *Sov. Phys. JETP*, **6** (1957) 429.
[2] Maki Z., Nakagawa M. and Sakata S., *Prog. Theor. Phys.*, **28** (1962) 870.
[3] Beringer J. *et al.* (Particle Data Group), *Phys. Rev. D*, **86** (2012) 010001.
[4] Apollonio M. *et al.* (CHOOZ Collaboration), *Phys. Lett. B*, **466** (1999) 415.
[5] Mikaelyan L. A. and Sinev V. V., arXiv:hep-ex/9908047 (1999).
[6] Ahn J. K. *et al.* (RENO Collaboration), *Phys. Rev. Lett.*, **108** (2012) 191802.
[7] Abe K. *et al.* (T2K Collaboration), *Phys. Rev. Lett.*, **107** (2011) 041801.
[8] Adamson P. *et al.* (MINOS Collaboration), *Phys. Rev. Lett.*, **107** (2011) 181802.
[9] Abe Y. *et al.* (Double Chooz Collaboration), *Phys. Rev. Lett.*, **108** (2012) 131801.
[10] Fogli G. L. *et al.*, *Phys. Rev. D*, **84** (2011) 053007.
[11] Guo X. H. *et al.* (Daya Bay Collaboration), arXiv:hep-ex/0701029 (2007).
[12] An F. P. *et al.* (Daya Bay Collaboration), *Nucl. Instrum. Methods A*, **685** (2012) 78.
[13] An F. P. *et al.* (Daya Bay Collaboration), *Chinese Phys. C*, **37** (2013) 011001.
[14] An F. P. *et al.* (Daya Bay Collaboration), *Phys. Rev. Lett.*, **108** (2012) 171803.