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An overview of the Daya Bay reactor neutrino experiment

Jun Cao [a], Kam-Biu Luk [b]

[a] *Institute of High Energy Physics, Beijing, China*

[b] *Department of Physics, University of California and Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

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Abstract

The Daya Bay Reactor Neutrino Experiment discovered an unexpectedly large neutrino oscillation related to the mixing angle θ_{13} in 2012. This finding paved the way to the next generation of neutrino oscillation experiments. In this article, we review the history, featured design, and scientific results of Daya Bay. Prospects of the experiment are also described.

1. Introduction

Neutrino oscillation was firmly established by 2002. Around that time, atmospheric and accelerator neutrino experiments, e.g. Super-K [1] and K2K [2], have determined the oscillation parameters θ_{23} and $|\Delta m^2_{32}|$ whereas solar and reactor neutrino experiments, such as SNO [3] and KamLAND [4], have measured θ_{12} and Δm^2_{21}. However, the mixing angle θ_{13}, the CP violating phase δ_{CP}, and the sign of Δm^2_{32} (aka the mass hierarchy) were unknown. In addition, θ_{13}, unlike the other two mixing angles, was expected to be small [5,6].

Among the three unknown quantities, θ_{13} plays a critical role in defining the future experimental program on neutrino oscillation. It is known that the CP-violating effect is proportional

E-mail addresses: caoj@ihep.ac.cn (J. Cao), k_luk@berkeley.edu (K.B. Luk).

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to

$$J = \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta_{CP} \approx 0.9 \sin 2\theta_{13} \sin\delta_{CP}\,. \quad (1)$$

Resolution of the mass hierarchy problem also relies on the size of θ_{13}. If it is too small, current technologies may not be able to determine δ_{CP} and the mass hierarchy.

The mixing angle θ_{13} can be measured by accelerator-based or reactor-based experiments. However, the appearance probability of $\nu_\mu \to \nu_e$ in an accelerator neutrino experiment also depends on the yet unknown δ_{CP} and the mass hierarchy. Hence, this type of experiments can only provide evidence for a non-zero θ_{13} but cannot measure its value unambiguously at this moment. On the other hand, reactor-based experiments can unambiguously determine θ_{13} via measuring the survival probability of the electron antineutrino $\overline{\nu}_e$ at short distance ($\mathcal{O}$(km)) from the reactors. In the three-neutrino framework, the survival probability is given by

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

where $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$ and $\Delta_{ji} \equiv 1.267\Delta m^2_{ji}L/E$ with Δm^2_{ji} being the mass-squared difference in eV^2, E is the energy of the $\overline{\nu}_e$ in MeV, and L is the distance in meters from the production point.

Pinning down θ_{13} by performing a relative measurement with a set of near and far detectors was suggested at the beginning of this millennium [7]. This method allows cancellation of most of the systematic uncertainties due to the reactor and the detector that previous experiments suffered. Since 2002, eight reactor experiments were proposed [8]; three of them, Daya Bay [9], Double Chooz [10], and RENO [11], were constructed.

Among the eight proposals, the Daya Bay experiment is the most sensitive for measuring θ_{13}. The nuclear-power complex is among the top five most powerful in the world, providing a very intense flux of antineutrinos. In addition, it is very close to a mountain range in which an array of horizontal tunnels can be built, providing sufficient overburden to attenuate cosmic rays and space to accommodate a relatively large-scale experiment.

The Daya Bay nuclear-power complex is located on the southern coast of China, 55 km to the northeast of Hong Kong and 45 km to the east of Shenzhen. As shown in Fig. 1, the nuclear complex consists of six reactors grouped into three pairs, with each pair referred to as a nuclear power plant (NPP). All six cores are functionally identical pressurized water reactors, each with a maximum of 2.9 GW of thermal power. The last core started commercial operation on 7 August 2011, a week before the start-up of the Daya Bay experiment. The distance between the cores for each pair is 88 m. The Daya Bay cores are separated from the Ling Ao cores by about 1100 m, while the Ling Ao-II cores are around 500 m away from the Ling Ao cores.

The Daya Bay experiment consists of three underground experimental halls (EHs) connected with horizontal tunnels. The overburden for the Daya Bay near hall (EH1), the Ling Ao near hall (EH2) and the far hall (EH3) are 250, 265, and 860 equivalent meters of water, respectively. Eight antineutrino detectors (ADs) are installed in the three halls, with two in EH1, two in EH2, and four in EH3. Each AD has 20-ton target mass to catch the reactor antineutrinos. The sensitivity to $\sin^2 2\theta_{13}$ was designed to be better than 0.01 at 90% confidence level in 3 years.

2. History of the Daya Bay experiment

The idea of determining θ_{13} using the Daya Bay reactor complex was proposed in 2003. The first dedicated workshop for the Daya Bay experiment was held in the University of Hong Kong in November 2003 [12]. It was immediately followed by the second one in January 2004