The Daya Bay Reactor Neutrino Experiment

Scientific Background

On Aug.15, 2011, a new large-scale scientific facility in China, Daya Bay Reactor Neutrino Experiment, started to operate. It is located in Daya Bay Nuclear Power Plant in Guangdong Province, around 50km to both Hong Kong and Shenzhen City. The main scientific goal is to precisely determine the neutrino mixing angle θ_{13} by detecting neutrinos from the reactors at different distances.

In particle physics, the material world consists of 12 kinds of elementary particles, including six quarks, three charged leptons, and three neutrinos. Neutrinos have very peculiar properties. Very light in mass, they hardly interact with materials, and can hardly be detected. However, they are as numerous as photons in our universe and play an important role in the formation and evolution of the universe. In 1930, Pauli suggested the existence of the tiny neutrino. Cowan and Reines first detected neutrinos in 1956, the latter of whom was awarded the Nobel Prize in 1995. Lederman, Schwartz, and Steinberger discovered the second kind of neutrino and received the 1988 Nobel Prize. In 1998, the Super-Kamiokande experiment in Japan found the "smoking-gun" evidence that neutrinos can oscillate, *i.e.* spontaneously transform from one type into

The world renowned Daya Bay Reactor Neutrino Experiment is located in the Daya Bay Nuclear Power Plant not far from Hong Kong and Shenzhen City, where the twin Daya Bay reactors yield copious amounts of electron antineutrinos (the antiparticle of the electron neutrino) – millions of quadrillions of them every second.

another. It also means that neutrino carries tiny but finite mass, which totally changed our past view on neutrino. Neutrino oscillation is the only observed phenomenon beyond Standard Model of particle physics. The leader of Super-Kamiokande experiment, Masatoshi Koshiba, won the Nobel Prize in 2002 together with Ray Davis, who first observed the deficit of solar neutrinos. Stepping into the 21st century, neutrino studies grow rapidly. Now it is one of the most important branches of particle physics, and extends to astrophysics, cosmology, geophysics, *etc*., forming a so-called "neutrino science".

Among the six parameters that describe the neutrino oscillation, four have been measured via atmospheric and solar neutrino oscillation. Two unknowns are the charge-parity (CP) phase and the mixing angle θ_{13}. The CP phase relates with the matter-antimatter asymmetry in the origin and the evolution of the universe. The mixing angle θ_{13} describes the size of the 3rd neutrino oscillation mode yet to be discovered. Furthermore, to measure the size of the CP phase, the mixing angle θ_{13} must be measured first. If θ_{13} is large, then it is possible to measure CP phase by improving the currently available accelerator technology. If it is too small, we need to invent new technologies. At the same time, too small θ_{13} also means that there exists a new symmetry in neutrinos. Therefore, precise determination of θ_{13} will provide a roadmap to future neutrino studies.

The Daya Bay Reactor Neutrino Experiment was proposed in 2003. Due to the obvious physics significance, there were eight proposals in the world to measuring θ_{13} using reactor neutrinos. Besides Daya Bay, two other experiments survive and have a similar schedule as Daya Bay experiment. They are Double Chooz experiment in France and RENO experiment in Korea.

Daya Bay Nuclear Power Plant is the best site for such a precision measurement. It is one of the most powerful reactor complexes in the world, providing large statistics. Adjacent to the reactor cores, there are hills suitable for underground laboratory construction, which is a must to reduce the backgrounds. The Daya Bay experiment is designed to have the best θ_{13} sensitivity in the world and be the only one that could serve as a roadmap to future studies, thus attracting broad international involvement.

After four years' preparation and four years' construction, the startup of the Daya Bay experiment in Aug. 2011 marks the first step in the international effort of the Daya Bay collaboration to measure the crucial quantity related to the third type of oscillation. A full operation is expected in 2012, which will lead to an unprecedented precision, measuring

Two more pairs of reactors at Ling Ao Nuclear Power Plant, a kilometer away from the Daya Bay Nuclear Power Plant, make the Daya Bay nuclear power complex one of the most powerful in the world. All the reactors sit close to a mountain. By putting their antineutrino detectors in tunnels under the mountain, the researchers can shield them from cosmic rays.

$\sin^2 2\theta_{13}$ to 0.01 or better in three years.

The Daya Bay experiment will be the starting point of neutrino experimental studies in China. The neutrino research is still in the ascendant. There are a lot of puzzles to be solved, such as the size of θ_{13}, the mass hierarchy, the size of the CP violation, the violation on CPT symmetry, the unitarity of the mixing matrix,the absolute mass, the origin of neutrino mass, Majorana or Dirac neutrino, sterile neutrino, *etc*. Every answer to these puzzles could change our view of the world. In the foreseeable future, neutrino physics will be on the frontier of particle physics. Neutrino astronomy and geo-neutrino studies are also developing fast. A new neutrino experiment, called Daya Bay II, is under investigation, aimed at several of these puzzles.

A temporary office on the construction scene shared by the international collaboration. The Daya Bay experiment grows to be an internaitonal collaboration of more than 250 scientists from 39 institutes in mainland China, Hong Kong, Taiwan, the United States, Russia and Czech.

Project Management

The Daya Bay experiment was proposed in 2003. Its R&D was initially supported by the CAS Institute of High Energy Physics (IHEP) in early 2004 under the CAS Knowledge Innovation Program, followed by supports from the National Natural Science Foundation of China (NSFC). The 250th Xiangshan Science Conference was dedicated to the experiment in Apr. 2005. The project was formally approved by CAS in May 2006 and by Ministry of Science and Technology in Jan. 2007. Thereafter, it was also funded by the NSFC, the Guangdong Province, the Shenzhen City, and the China Guangdong Nuclear Power Group. The groundbreaking of the experiment was held in Oct. 2007.

The Daya Bay experiment is hosted by IHEP. The international collaboration was formed in 2006, with some 120 collaborators from 25 institutions. Now it grows to be a collaboration of more than 250 scientists from 39 institutes in mainland China, Hong Kong, Taiwan, the United States, Russia and Czech. China shares all conventional construction of the experiment and about one half of the detectors. US shares also about one half of the detectors. The other parties all contribute hundreds of thousands and even millions of US dollars on various detectors and equipments. The Daya Bay experiment is the largest cooperation project between China and US in basic research. It is also the first time that a basic research project is supported jointly by Chinese central government, the local governments, and a business corporation.

The project is managed according to the international practice as most of the high energy physics experiments. IHEP signed a memorandum of understanding (MOU) with two US national laboratories that are on behalf of the Department of Energy of US. IHEP also signed MOUs with representative institutions of other countries or districts. The MOUs state explicitly the cost sharing and working scopes in the collaboration, for instance, the details of the detector components, as well as other cooperation details. The collaboration is governed by a bylaws formulated by the whole collaboration, including description of the collaboration and membership, the role of the collaboration meeting, the institutional board, the executive board, the spokespersons, as well as publication policies and conference presentations.

During the construction phase, the project is managed by the technical board led by the project managers. The technical board consists of project managers and sub-detector managers. A laboratory oversight group, consisting of directors of laboratories, oversees the effort of the project and is responsible to the government agencies in China and US. There are an international finance committee to coordinate the funding issues and a project advisory panel to review and provide insights and recommendations to the project.

At the experimental site, local installation manager and local project office are responsible for the day-to-day onsite management. The role will be replaced by an operation committee during the operation phase of the experiment.

The acquired data will be shared by all collaborating institutions. The collaboration is open for new membership applications, which should be approved by the institutional board.

Facility

The Daya Bay reactor complex consists of six cores from the Daya Bay Nuclear Power Plant (NPP), Ling Ao NPP, and Ling Ao-II NPP. Each NPP has two cores. All six cores are the same-type pressurized water reactor of 2.9 GW thermal power. The last core started commercial operation on Aug.7, 2011, right before the startup of the experiment. The total thermal power of the complex is 17.4 GW. The distance between the twin cores are 88m. The Daya Bay twin cores are separated from the Ling Ao cores by around 1,100m, while the Ling Ao-II twin cores are around 500m from the Ling Ao cores.

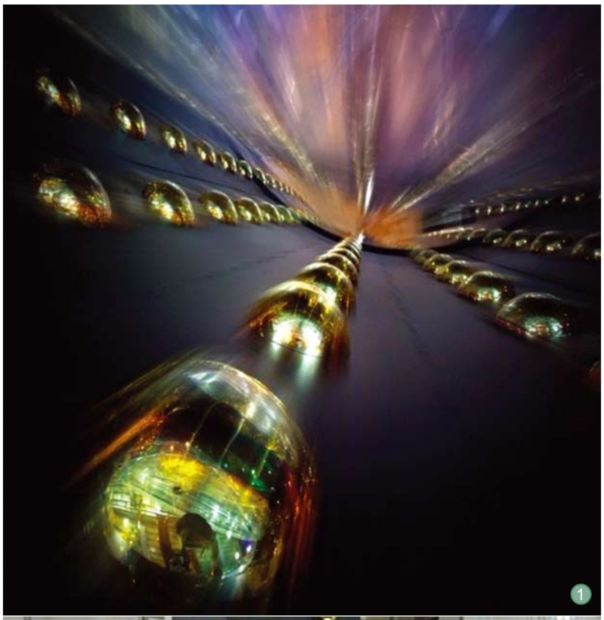
The Daya Bay experiment facility consists of a series of ground facilities, three underground experimental halls, a liquid scintillator hall, and a water hall. The ground facilities include a surface assembly building, a control room, and a ventilation facility room. Detectors are installed in the underground experimental halls. The Daya Bay near hall (EH1) is 100m deep under the mountain and 364m from the twin cores of the Daya Bay NPP. The Ling Ao near hall (EH2) is also 100m deep and around 500m in average from the four cores of the Ling Ao NPP and the Ling Ao-II NPP. The far hall (EH3) is 350m deep, 1,912m from the cores of the Daya Bay NPP and 1,544m from the cores of the Ling Ao and the Ling Ao-II NPPs. The liquid scintillator hall and the water hall are also underground, which are used to produce and store all liquid scintillator, and produce pure water for the water Cherenkov detectors in the experimental halls, respectively.

All underground halls are connected by a horizontal tunnel with a 0.3% slope. The access tunnel is 267m long with a 10% slope. Total length of the tunnel is 3,100m. The tunnel is 6.2m wide and 7m high, to allow transportation of the antineutrino detectors.

In each experimental hall there are three different kinds of detectors, the antineutrino detectors (AD), the water Cherenkov detector, and the Resistive Plate Chamber (RPC) detectors. In total, there are eight 110-ton ADs, three water pools filled with 4,400 tons of pure water in total, and three arrays of RPCs made of 3,600m^2 bare chambers.

In each near hall, two ADs are submerged in a water pool at least 2.5m in depth shielding from any side to protect the ADs from the ambient radioactivity from the

A pair of antineutrino detectors is positioned respectively in Daya Bay Hall (EH1)) and Ling Ao Hall (EH2), while another set of four is positioned in the Far Hall (EH3) almost two kilometers away.



granite rock and air. Without the shielding, the neutrino signal will be thoroughly buried in backgrounds since they are both in the energy region of several MeV. The water pool is optically divided into an inner layer and an outer layer by Tyvek film, both equipped with photomultiplier tubes (PMT), serving as Cherenkov detectors to veto the cosmic muon rays. Cosmic muons produce neutrons and long-lived isotopes that could mimic the neutrino signal when they pass the detector or neighborhood. With high muon detection efficiency, those backgrounds can be rejected from the neutrino signal sample.

Due to the extremely high requirements of background reduction, another muon detector, an array of RPC detectors, covers the water pool. Each RPC module consists of four layers in 2m×2m dimension. The combined muon detection efficiency of the water Cherenkov detector and RPCs is designed to be 99.5%.

The far hall is almost the same as the near halls except that it has four ADs and a larger water pool.

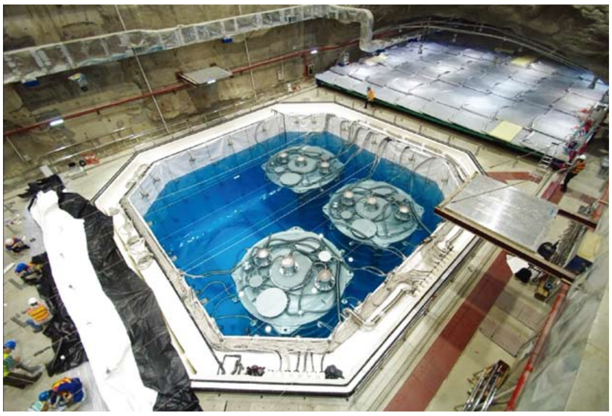
The antineutrino detector consists of three layers of concentric cylinders. Each is 5m in diameter and 5m high. The inner-most layer contains 20 tons of 0.1% Gadolinium-doped liquid scintillator in a 3m-in-diameter acrylic vessel (AV), as the antineutrino target. The middle layer is filled with 20 tons of undoped liquid scintillator for capturing gamma-rays that escape from the target, thereby improving the antineutrino detection efficiency. It is in a 4m-in-diameter AV. A total of 192 eight-inch PMTs are equipped along the circumference of the stainless steel tank in the outer-most layer, which contains ~40 tons of mineral oil to protect the liquid scintillator from natural radioactivity from the PMTs and stainless steel. At the top and bottom, two 4.5m-in-diameter, 2cm-thick reflective panels are

1 Each antineutrino detector at Daya Bay is lined with photomultiplier tubes (PMTs) to catch the faint trace of antineutrino reactions in the scintillator fluids that fill the detectors. (Courtesy of Roy Kaltschmidt, Lawrence Berkeley National Laboratory)

2 A PMT ladder is lowered into the narrow space between the acrylic vessels and the stainless steel vessel. Photomultiplier tubes convert incredibly faint flashes of light to electrical signals. Assembled on “ladders,” the walls of each detector are lined with 192 PMTs. (Courtesy of Roy Kaltschmidt, Lawrence Berkeley National Laboratory)

3 The antineutrino detectors were filled with three kinds of liquids in the liquid scintillator hall after they were assembled above the ground in the surface assembly building, and then they were transported to be installed in different experimental halls under the ground.

The filling equipment in the liquid scintillator hall.



The installation of the three anti-neutrino detectors in a water pool in the Far Hall (EH3), which started taking data on Dec. 24, 2011.

placed to increase the photo-statistics and improve the energy response uniformity. To reduce systematical error, all ADs are assembled in pairs in the surface assembly building and all are filled with three kinds of liquids in the liquid scintillator hall, before transported to different experimental halls.

The antineutrino detectors at three different sites will measure the neutrinos emitted from the reactor cores. Two near sites will monitor the neutrino flux from two clusters of cores. The far site locates close to the θ_{13} oscillation maximum. It will look for depletion in the expected antineutrino flux, an evidence of neutrino oscillation due to θ_{13}. Multiple ADs at each site is a unique feature of Daya Bay experiment. The side-by-side measurement will demonstrate the relative error of the ADs. Such redundancy is important for a precision measurement.

Researches and Prospect

The main goal of Daya Bay experiment is to precisely determine the neutrino mixing angle θ_{13} with a sensitivity of one percent, an order better than existing upper limit and much higher than other planned measurements. A full operation is expected in 2012 and will reach the designed sensitivity in three years.

Given the unprecedented precision of the detector and large statistic, near sites of the experiment will be able to measure the reactor neutrino flux to high precision. It will improve our knowledge on the reactor neutrino flux. It will also help to resolve the currently confusing reactor neutrino anomaly and sterile neutrino puzzle.

The experiment will directly measure Δm^2_{31}, the size of the mass squared difference between the 1st and 3rd neutrinos. Now this mixing parameter is approximated as Δm^2_{32}.

In case there is a supernovae explosion, Daya Bay experiment could detect some neutrinos from supernovae. The statistics will be low compared to large-scale neutrino detectors such as Super-K. However, measuring supernovae neutrino in a global network will help to determine the matter effect of the neutrino oscillation.

Furthermore, Daya Bay experiment will study the cosmic ray at different depths. The underground experimental halls could be used for other low background experiments.

Daya Bay experiment is the first large-scale neutrino experiment in China. We are considering further studies. For example, another reactor neutrino experiment located 60km away from the Daya Bay power plant, called Daya Bay II, is being considered. With a 10-50kton detector and 2-3% energy resolution, scientists will determine the neutrino mass hierarchy, measure four mixing parameters to 1% precision to check the unitarity and new physics possibility, study supernovae neutrino and geoneutrino, study sterile neutrino, *etc*. The optimal size of the detector and physics motivation will depend on the size of the mixing angle θ_{13} to be measured by the Daya Bay experiment.

(by CAS Institute of High Energy Physics)

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