Daya bay reactor anti-neutrino experiment

Christopher White, on behalf of the Daya Bay Collaboration

Associate Professor of Physics, Illinois Institute of Technology, 3101 S. Dearborn St, Chicago, IL 60616

E-mail: whitec@iit.edu

Abstract. The Daya Bay Reactor Anti-Neutrino Experiment is a neutrino oscillation experiment designed to observe and measure the neutrino mixing angle θ_{13}. The sensitivity goal is 0.01 in $\sin^2 2\theta_{13}$ at the 90% confidence level, a significant improvement over the current limit. This will be accomplished by measuring the relative rates and energy spectra of reactor electron antineutrinos with multiple detectors positioned at different baselines. Civil construction is currently under-way as detector designs and planning near completion. Commissioning activities should be completed by the end of 2010, followed by a three-year run.

1. Introduction

The neutrino oscillation parameter θ_{13} is the last of the neutrino mixing angles to be definitively measured. While the value is important in its own right we also need to know the value of θ_{13} with sufficient precision to guide the designs of future experiments and to access the feasibility of measuring δ_{CP}. The February 28, 2006 report of the Neutrino Scientific Assessment Group (NuSAG) [1], which advises the DOE Offices of Nuclear Physics and High Energy Physics and the National Science Foundation, and the APS multi-divisional study's report on neutrino physics, *The Neutrino Matrix* [2], both recommend with high priority a reactor antineutrino experiment to measure $\sin^2 2\theta_{13}$ at the level of 0.01. The Daya Bay Reactor Antineutrino Experiment (Daya Bay for short) has the potential to measure θ_{13} at relatively low cost and in a timely fashion.

Antineutrinos are created from the beta decay of short-lived radioisotopes produced by fission of uranium and plutonium isotopes in the core of a reactor, and can be observed via the inverse-beta decay process ($\overline{\nu}_e + p \rightarrow e^+ + n$) with a threshold energy of 1.8 MeV. The energy spectrum of antineutrinos depends on the isotopic composition of the fuel rods, which evolves in time. While the cross section for interaction increases sharply with energy, the production spectrum declines. The observed energy spectrum is proportional to the product of these and should be similar to that shown in Fig. 1. To extract the value of $\sin^2 2\theta_{13}$, we use the observed near detector rate and energy spectrum to predict the far detector rate and spectrum. We then compare the observed far detector rate and spectrum to the predicted spectrum, where the survival probability for $\overline{\nu}_e \rightarrow \overline{\nu}_e$ is given by Equation 1.

$$Prob = 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{31} L}{4E}) - \sin^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m^2_{21} L}{4E}). \quad (1)$$

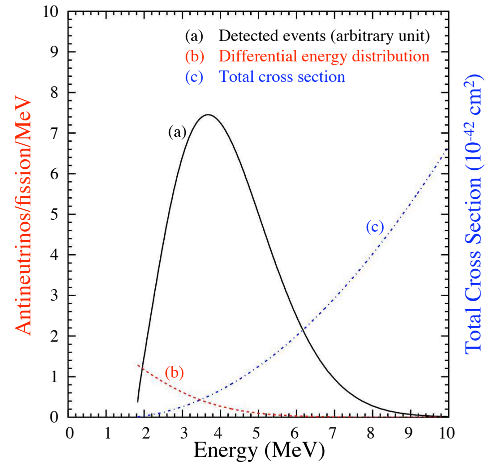

Figure 1. The observed $\overline{\nu}_e$ energy spectrum is dependent on the distribution of antineutrino energies coming from the reactor cores as well as the inverse beta decay cross section.

2. Experimental Site

The Day Bay nuclear power complex is located in southern China about 55 km north-east of Victoria Harbor in Hong Kong and is one of the most prolific sources of antineutrinos in the world. Currently the two pairs of reactor cores (Daya Bay and Ling Ao, separated by about 1.1 km) generate 11.6 GW_{th} of thermal power. This will increase to 17.4 GW_{th} by early 2011 when a third pair of reactor cores (Ling Ao II) is put into operation. The Daya Bay complex will then be among the five most powerful reactor complexes in the world.

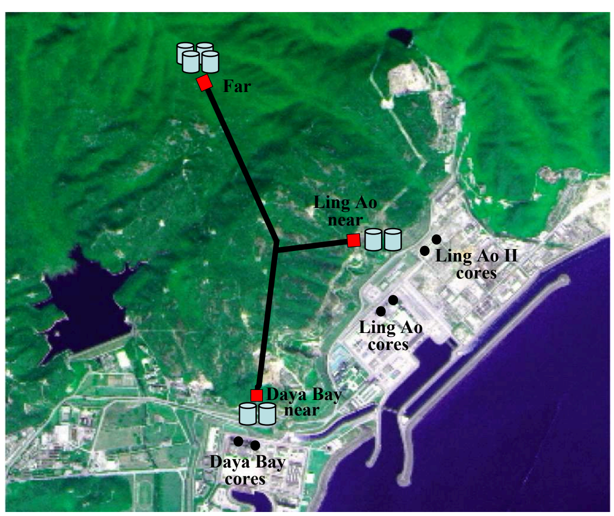

Figure 2. Default configuration of the Daya Bay experiment, optimized for best sensitivity in $\sin^2 2\theta_{13}$. Four antineutrino detector (AD) modules are deployed at the far site and two each at each of the near sites.

The experimental site is located within mountainous terrain allowing for deployment of detectors that are well shielded from cosmogenic backgrounds. The detector configuration consists of three underground experimental halls, two halls located near the reactor cores and one further away, linked by horizontal tunnels, as shown in Fig. 2. Eight cylindrical detectors, each consisting of three nested cylindrical zones contained within a stainless steel tank, will be deployed to detect antineutrinos via the inverse beta-decay reaction. To maximize the experimental sensitivity, four detectors will be deployed near the first oscillation maximum (within the far hall). The rate and energy distribution of antineutrinos from the reactors will be monitored with two detectors in each of the near halls, located at relatively short baselines from their respective reactor cores. Given this configuration, the systematic uncertainty in $\sin^2 2\theta_{13}$ due to uncertainties in the reactor power levels is estimated to be about 0.1%. This configuration significantly improves the statistical precision over previous experiments (0.2% in three years of running) and enables cross-calibration to verify that the detectors are identical.

Three major factors are involved in optimizing the locations of the detector halls. The first one is overburden. The locations of all the underground detector halls are optimized to provide sufficient overburden to reduce the cosmogenic backgrounds to a level that can be measured with certainty. The slope of the hills near the site is around 30 degrees. Hence, the overburden falls rapidly as the detector site is moved closer to the cores. The second concern is oscillation loss. The oscillation probability is appreciable even at the near sites. For example, for the near detectors placed approximately 500 m from the center of gravity of the cores, the integrated oscillation probability is $0.19 \times \sin^2 2\theta_{13}$ (computed with $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2). The oscillation contribution of the other pair of cores, which is around 1100 m away, has been included. The third concern is the near-far cancellation of reactor uncertainties. After careful study of many different experimental designs, the best configuration, as shown above, was selected. A summary of the distances to each detector is provided in Table 1. While the reactor-related systematic uncertainties cannot be cancelled completely, they can be reduced to a negligible level.

Table 1. Distances from each detector site to the centroid of each pair of reactor cores.

	DYB Hall	LA Hall	Far Hall
DYB cores	363 m	1347 m	1985 m
LA cores	857 m	481 m	1618 m
LA II cores	1307 m	526 m	1613 m

3. Experimental Design

Systematic uncertainties in the ratios of the near-to-far detector acceptance, antineutrino flux and background have to be controlled to a level almost an order of magnitude better than the previous experiments. Based on the recent single-detector reactor experiments such as Chooz, Palo Verde and KamLAND, there are three main sources of systematic uncertainty: reactor-related uncertainty of (2–3)%, background-related uncertainty of (1–3)%, and detector-related uncertainty of (1–3)%. Each source of uncertainty can be further classified into correlated and uncorrelated uncertainties. The experiment must be designed carefully with particular attention to the detector mass, efficiency and background control. The primary factors leading to the improved performance are:

- **identical near and far detectors:** Antineutrino detectors will be assembled, filled, and deployed in pairs with one at a near site and the other at the far site.
- **multiple modules:** Multiple identical modules will be installed at the near and far sites. The use of multiple modules at each site enables internal consistency checks (to the limit

of statistics). Furthermore, small detectors intercept fewer cosmic-ray muons, resulting in less dead time, less cosmogenic background and hence smaller systematic uncertainty.

- **three-zone detector module:** Each module is partitioned into three concentric zones. This arrangement can substantially reduce the systematic uncertainties related to the target volume and mass, positron energy threshold, and position cut, while also shielding against external γ rays entering the active LS volume.
- **shielding:** In addition to overburden, the antineutrino detector modules will be enclosed with sufficient amount of passive shielding to attenuate natural radiation and energetic spallation neutrons from the surrounding rocks and materials used in the experiment.
- **multiple muon detectors:** By tagging the incident muons, the associated cosmogenic background can be suppressed to a negligible level. This requires the muon detectors surrounding the antineutrino detectors to have a high efficiency that is known to high precision.

The total detector-related systematic uncertainty is expected to be $\sim$0.2% in the near-to-far ratio per detector site.

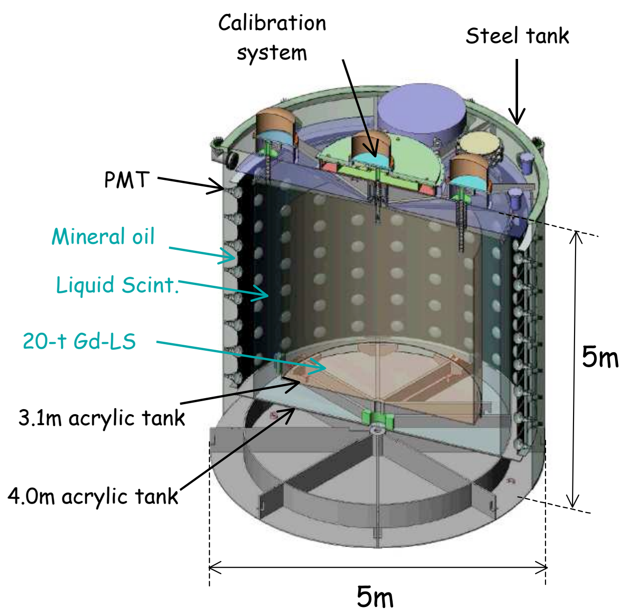

Figure 3. A cut-away representation of an antineutrino detector.

Each detector will have 20 metric tons of 0.1% Gd-doped liquid scintillator in the inner-most, antineutrino target zone. A second zone, separated from the target and outer buffer zones by transparent acrylic vessels, will be filled with undoped liquid scintillator for capturing γ rays that escape from the target, thereby improving the antineutrino detection efficiency. A total of 192 photomultiplier tubes are arranged along the circumference of the stainless steel tank in the outer-most zone, which contains mineral oil to attenuate γ rays from trace radioactivity in the photomultiplier tube glass and nearby materials including the outer tank. Careful construction, filling, calibration and monitoring of the detectors will reduce detector-related systematic uncertainties to a level comparable to or below the statistical uncertainty.

The muon detector consists of a cosmic-ray tracking device and active water shield. The antineutrino detector modules are submerged in the water pool, shielding them from ambient

Table 2. Signal and background rates.

	Daya Bay Near	Ling Ao Near	Far Hall
Radioactivity (Hz)	< 50	< 50	< 50
Muon Rate (Hz)	36	22	1.2
$\overline{\nu}_e$ events per day	840	740	90
Accidentals / Signal (%)	< 0.2	< 0.2	< 0.1
Fast neutrons / Signal (%)	0.1	0.1	0.1
$^8\mathrm{He} + ^9\mathrm{Li}$ / Signal (%)	0.3	0.2	0.2

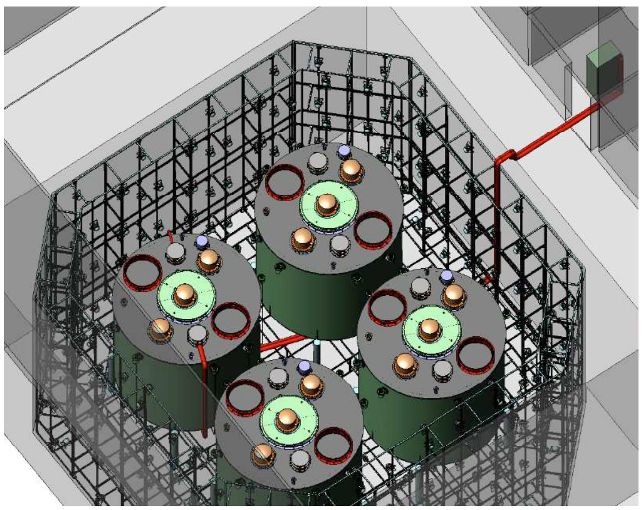

Figure 4. A drawing of the far detector hall showing the four ADs in a water pool instrumented with PMTs to detect cosmic muons.

radiation and spallation neutrons. The water shield is instrumented with photomultiplier tubes (PMTs) to serve as a Cherenkov detector. The outer region of the water pool is separated from the inner region by an optical barrier to provide two independent systems for detecting muons. Above the pool the muon tracking detector is made of light-weight resistive-plate chambers (RPCs). RPCs offer good performance and excellent position resolution at low cost.

4. Sensitivity and Status

Figure 6 shows the sensitivity contour in the $\sin^2 2\theta_{13}$ versus Δm^2_{31} plane for three years (we assume 1 year $\equiv$ 300 live days) of data. The green shaded area shows the 90% confidence region of Δm^2_{31} determined by atmospheric neutrino experiments. Assuming four 20-ton modules at the far site and two 20-ton modules at each near site, the statistical uncertainty is around 0.2%. The sensitivity of the Daya Bay experiment with this design can achieve the challenging goal of 0.01 with 90% confidence level over the entire allowed (90% C.L.) range of Δm^2_{31}. At the best fit $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2, the sensitivity is around 0.008 with 3 years of data. Figure 5 shows the sensitivity versus time of data taking. After one year of data taking, $\sin^2 2\theta_{13}$ sensitivity will reach 0.014 (1.4%) at 90% confidence level.

Civil construction is underway with beneficial occupancy of the surface assembly building expected by the end of 2008. Tunnel blasting is ongoing and we expect to take possession of the first detector hall by the middle of 2009. The PMTs have been ordered and are being delivered

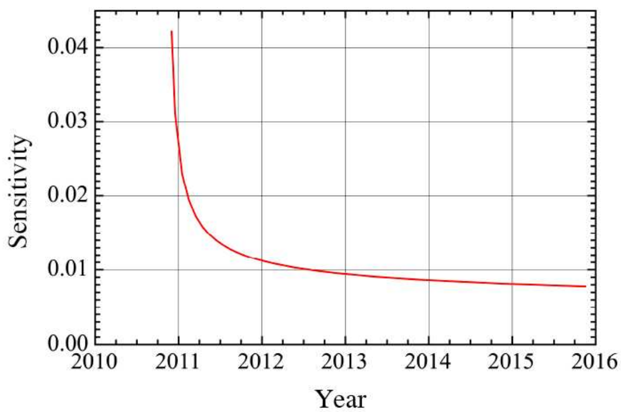

Figure 5. Expected $\sin^2 2\theta_{13}$ sensitivity at 90% C.L. versus time. The curve is calculated with the assumption of two near sites and one far site with data acquisition beginning in Dec. 2010 and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2.

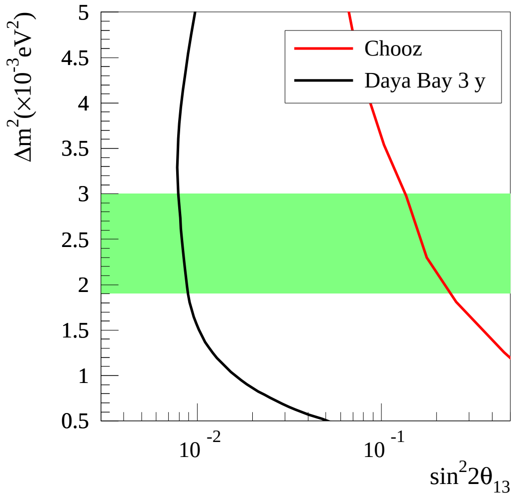

Figure 6. Expected $\sin^2 2\theta_{13}$ sensitivity at 90% C.L. with 3 years of data, as shown in solid black line. The red line shows the current upper limit measured by Chooz.

Table 3. Summary of systematic uncertainties.

Source	Uncertainty (%)
Energy Cuts	0.2
Time Cuts	0.1
H/Gd Ratio	0.1
n multiplicity	0.05
Trigger	0.01
Live Time	< 0.01
Total detector-related uncertainly	0.38
Number of protons	0.3
Reactor Power and location (6 cores)	0.13

and tested in China. The first AD pair will be assembled by the middle of 2009, followed by a dry-run (a top to bottom system test including automatic calibration and readout electronics). Detector filling, installation, and commissioning will follow thereafter, leading toward a fully deployed experiment by the end of 2010.

5. Acknowledgments

I am grateful to all my collaborators for their hard work and dedication. This work was supported in part by the Chinese Academy of Sciences, and the United States Department of Energy.

[1] 'Recommendations to the Department of Energy and the National Science Foundation on a U.S. Program of Reactor- and Accelerator-based Neutrino Oscillations Experiments', http://www.science.doe.gov/hep/NuSAG2ndRptFeb2006.pdf

[2] The Neutrino Matrix, http://www.aps.org/neutrino/