Reactor Neutrino Experiments

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Abstract
Precisely measuring $\theta_{13}$ is one of the highest priority in neutrino oscillation study. Reactor experiments can cleanly determine $\theta_{13}$. Past reactor neutrino experiments are reviewed and status of next precision $\theta_{13}$ experiments are presented. Daya Bay is designed to measure $\sin^2 2\theta_{13}$ to better than 0.01 and Double Chooz and RENO are designed to measure it to 0.02-0.03. All are heading to full operation in 2010. Recent improvements in neutrino moment measurement are also briefed.

1 Introduction
Reactor anti-neutrino experiments have played a critical role in the history of neutrinos. Among them, Savannah River Experiment [1] by Reines and Cowan in 1956 observed the first neutrino. Chooz [2] determined the most stringent upper limit of the last unknown neutrino mixing angle $\sin^2 2\theta_{13} < 0.17$ in 1998. KamLAND [3] observed the first reactor anti-neutrino disappearance in 2003 and precisely determined the $\Delta m_{12}^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}$ eV$^2$ recently [4]. Now reactor neutrino experiments become prominent again for measuring mixing angle $\theta_{13}$ precisely.

Savannah River experiment located 11 m from the reactor core and 12 m underground. The neutrino target is 200 liters CdCl$_2$ water solution in two tanks, sandwiched by 3 liquid scintillator (LS) layers which contained 110 5-inch photomultipliers (PMT). A reactor neutrino interact with a proton in the target via inverse beta decay (IBD), produce a positron and a neutron,

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$ (1)

The positron produces a prompt signal and the neutron forms a delayed signal after thermalization and capture on cadmium. The two-fold coincidence can greatly suppress the background, which is the key to the success. In a modern experiment to precisely determine $\theta_{13}$. The principle of detecting reactor neutrinos changes very little since Savannah River Experiment. Large volume of proton-rich liquid scintillator (LS) layers which contained 110 5-inch photomultipliers (PMT). A reactor neutrino interact with a proton in the target via inverse beta decay (IBD), produce a positron and a neutron. The electron antineutrino emitted by reactors are dominated by 4 isotopes, $^{235}$U, $^{239}$Pu, $^{241}$Pu, and $^{238}$U. Other isotopes contribute only at 0.1% level. The energy spectra of the first 3 isotopes are measured by ILL [5] while the $^{238}$U spectrum are calculated theoretically, as shown in Fig. 1. The cross section of IBD is calculated to $\sim 0.2\%$ precision with 1/M corrections [6]. The energy spectrum of reactor neutrinos observed in a detector based on
such reaction is shown in Fig. 2, which is peaked at around 4 MeV. Normally we can determine

\[ P = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \cos^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{32} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \sin^2 2\theta_{12} \sin^2 \Delta_{21}, \]
where $\Delta_{ij} = 1.27\Delta m^2_{ij}L/E$, $L$ is the baseline in km, $E$ is the antineutrino energy in MeV, and $\Delta m^2_{ij}$ is the difference of mass square in eV$^2$. The survival probability is shown in Fig. 3 for antineutrinos of energy 4 MeV, supposing $\sin^2 2\theta_{13} = 0.1$. The slow component is due to $\theta_{12}$ oscillation. The first maximum is at around 60 km. The fast component is due to $\theta_{13}$ oscillation, whose first maximum is at around 2 km. Past reactor neutrino experiments are shown at their baselines.

Figure 3: Survival probability of reactor antineutrinos of energy 4 MeV, supposing $\sin^2 2\theta_{13} = 0.1$. Past reactor neutrino experiments are shown at their baselines.

2 Recent Reactor Neutrino Experiments

There are three modern reactor neutrino experiments, Chooz, Palo Verde, and KamLAND, that can be used as references of the next precision $\theta_{13}$ experiments.

Chooz experiment [2] located at 1050 m from the reactor cores of the Chooz power plant in France. Two cores have thermal power of 8.5 GW. Chooz, as well as Palo Verde, is expired by the atmospheric neutrino anomaly. The baseline is not at the optimal baseline for $\theta_{13}$ measurement, which is about 2 km. The experiment took data from March 1997 until July 1998. A total of 2991 neutrino candidates was collected. The measured vs expected ratio, averaged over the energy spectrum, is $1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$. The upper limit of $\sin^2 2\theta_{13}$ is set to be 0.14 at $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$.

The Chooz neutrino detector, schematically shown in Fig. 4, was consisted of two layers: a central 5-ton target in a transparent acrylic container filled with 0.09% Gd-loaded scintillator (Gd-LS), surrounded by 70-cm thick undoped liquid scintillator, equipped with 192 eight-inch PMTs. Outside is the veto region, filled with 90-ton undoped liquid scintillator and equipped with 24 eight-inch PMTs. The detector design, a central volume of liquid scintillator surrounded by PMTs, common to many other neutrino experiments such as SNO, Borexino, LSND, as well as later KamLAND, provided a homogenous detector response. The detector located underground with 300 meter-water-equivalent (m.w.e) overburden. The cosmic muon flux is 0.4 Hz/m$^2$, a factor of 500 reduction from the sea level.

Chooz experiment is an excellent reference for future precision $\theta_{13}$ experiments. The largest drawback of the experiment is the Gd-LS. The Gd(NO$_3$)$_3$ and hexanol complex was dissolved in aromatic compounds and paraffin. The complex was not stable enough. The attenuation length dropped 0.42%/day, or 60%/year, which significantly degraded the detector performance and introduced additional detector errors.
Palo Verde experiment [8] was built at the Palo Verde Nuclear Generating Station, the largest nuclear plant in America. The total thermal power from three identical pressurized water reactors is 11.6 GWt. Two of the reactors were located 890 m from the detector, while the third was at 750 m. Data were collected in the period between October 1998 and July 2000. The detector located underground with only 32 m.w.e overburden, or a factor of 5 reduction of the cosmic muons. Extra efforts must be made to further reduce backgrounds. Thus the detector was designed to be segmented to take full advantage of the triple coincidence given by the $e^+$ ionization and two annihilation gammas. The detector consisted of 66 tanks filled with 0.1% Gd-LS. Each cell was 9 m long, with $12.7 \times 25.4 \text{ cm}^2$ cross section, viewed by two 5-inch PMTs, one at each end. Total target mass is 12 ton. The central detector was shielded by 1-m thick water buffer to moderate cosmogenic neutrons. Outside of the water tanks were 32 large liquid scintillator counters as the muon veto.

Due to the shallow overburden, Palo Verde suffered from large backgrounds. The energy averaged measured vs expected ratio is $1.01 \pm 2.4\%\text{(stat)} \pm 5.3\%\text{(syst)}$. The exclusion curves for $\sin^2 2\theta_{13}$ of both Chooz and Palo Verde are shown in Fig. [8][9].

One highlight of Palo Verde is that stabler Gd-LS is achieved. The Gd-LS use 2-ethyl-hexanoic acid as complex agent of GdCl$_3$. The complex is dissolved into a cocktail of 36% pseudocumene, 60% mineral oil, and 4% alcohol (use to increase the solubility of the Gd complex). The attenuation degradation is 12% in the first year and 3% in the second.

KamLAND experiment [3] locates in Japan, 500 m from Super-Kamiokande experiment. The rock overburden is 2700 m.w.e., provide an excellent shielding. It detects neutrinos from more than 60 reactors in Japan and Korea. The average baseline is $\sim 180 \text{ km}$. The experiment starts from 2002 and is running until now. The detector has also a two-layer structure. 1000 ton liquid scintillator (undoped) is suspended with a 135 $\mu$m-thick balloon in 1800 $\text{ m}^3$ mineral oil. They are contained in an 18-m diameter stainless steel tank. 1325 17-inch PMTs and 554 20-inch PMTs installed in mineral oil. Due to the large backgrounds from the radioactivity
accumulated on the balloon, a fiducial volume cut is applied for analysis, as well as a higher energy threshold. These two cuts bring 4.7% and 2.3% systematic uncertainties and result in a total systematic uncertainty of 6.5%.

KamLAND observed the first reactor anti-neutrino disappearance. The energy averaged measured vs expected ratio is $R = 0.658 \pm 0.044(\text{stat}) \pm 0.047(\text{syst})$. It confirmed antineutrino disappearance at 99.998% C.L. It verified the solar neutrino oscillation with man-made neutrino source and exhibited the oscillation pattern in terms of L/E, thus excluded other hypothesis such as neutrino decay and decoherence. It also provided the best $\Delta m^2_{21}$ measurement. Recently KamLAND updated the analysis with 2007 data [4]. With improved analysis, the fiducial volume uncertainty is reduced to 1.8% and energy threshold uncertainty to 1.5%, resulting in a total systematic uncertainty of 3.4%. With KamLAND data only, the oscillation parameter is determined to be

$$\tan^2 \theta_{12} = 0.56^{+0.14}_{-0.09},$$
$$\Delta m^2_{21} = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2,$$

3 Precision $\theta_{13}$ Experiments

There are six mixing parameters related with neutrino oscillation. We have measured $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ via atmospheric and accelerator experiments, $|\Delta m^2_{31}|$ and $\sin^2 2\theta_{12}$ via solar and reactor experiments. $\sin^2 2\theta_{13}$, CP violating phase $\delta_{\text{CP}}$, and the sign of $\Delta m^2_{32}$ are still unknown. The upper limit of $\sin^2 2\theta_{13}$ is set to be $< 0.17$ by Chooz, while the other two mixing angles are maximal or close to maximal.

Next generation of long baseline accelerator neutrino experiments, with a proton driver in the megawatt class or above, together with a detector of more than 100 kilotons mass, will have chance to measure all three unknowns, as long as $\sin^2 2\theta_{13}$ is larger than 0.01. However, since all three unknowns involve in the oscillation, it is hard to clearly determine any of them. A reactor experiment at medium baseline of around 2 km can determine the magnitude of $\theta_{13}$ independent of the influence of CP violation and the mass hierarchy. Meanwhile, $\theta_{13}$ modulate the effect of CP violation. If $\sin^2 2\theta_{13}$ is smaller than 0.01, a neutrino factory will...
be required. Given these reasons, it is recommended in APS Neutrino Study [10] in 2004 that "as a high priority, . . . An expeditiously deployed multi-detector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$.")

To improve the $\sin^2 2\theta_{13}$ sensitivity by an order, both systematic and statistical uncertainties must be greatly reduced from past reactor neutrino experiments. It is first proposed by Krasnoyarsk [11] to use near-far detectors to cancel systematic errors with relative measurement. Since 2002, eight experiments are proposed [12]. They are Angra in Brazil, Braidwood in US, Daya Bay in China, Diablo Canyon in US, Double Chooz in France, KASKA in Japan, Krasnoyarsk in Russia, and RENO in Korea. After several years’ R&D, four of them are cancelled. Angra is still under R&D. Daya Bay, Double Chooz, and RENO are heading to construction and all schedule the full operation in 2010.

Daya Bay aims at $\sin^2 2\theta_{13}$ sensitivity better than 0.01 while Double Chooz and RENO aim at 0.02 $\sim$ 0.03 at 90% C.L. in 3 years. There are many similarities in the detector design, based on past experiences.

- Identical detectors are put at the near site(s) and the far site to cancel out reactor-related uncertainties and part of detector-related uncertainties.

- Gadolinium-doped liquid scintillator (Gd-LS) is adopted as the neutrino target and extensive R&D is carried out to improve the quality of Gd-LS. The Daya Bay Gd-LS is based on Linear Alkylbenzene (LAB). Solid complex of GdCl$_3$ and TMHA is dissolved in pure LAB, as well as fluors. The Double Chooz uses $\beta$-diketonates to complex GdCl$_3$. Solid complex is dissolved in a mixture of 20% PXE and 80% dodecane. Both recipes show good long term stability with small or ton-level samples.

- Antineutrino detector is designed to be a cylinder with 3 layers, extended from a two-layer design of Chooz and KamLAND. The inner layer is Gd-LS, surrounded by a layer of undoped liquid scintillator (LS), called $\gamma$-catcher, to contain gamma energy. The outer layer is oil buffer to shield detector and ambient radioactivities. Three kinds of liquid are separated by optical transparent acrylic vessels. Scintillation light produced by neutrino reactions are viewed by PMTs installed in the oil buffer. Such a design will minimize the analysis cuts to reduce the detector related uncertainties, based on the experience of Chooz and KamLAND.

- Passive and active detector shielding, besides enough overburden, is improved comparing to past experiments, which allows a lower threshold to trigger reactor neutrinos in the full energy range to reduce the systematic uncertainties.

With these improvements, the reactor-related uncertainties could cancel out or be reduced to 0.1% level. The detector-related uncertainties could be lowered to 0.38% to 0.6%. And the background-related uncertainties could be suppressed to 0.4% to 1%.

3.1 Angra

Angra experiment [13] locates in the neighborhood of Rio de Janeiro, Brazil. Two reactors, Angra-I and Angra-II, have thermal power 1.8 GW and 4 GW, respectively. A initial design for Angra is to put a 50-ton near detector 300 m away from Angra-II, with 250 m.w.e overburden, and a 500-ton far detector at a distance of 1500 m, with 2000 m.w.e overburden. A statistical precision of $\sin^2 2\theta_{13} < 0.006$ at 90% C.L. could be obtained in three years.

Angra is planned to start in 2013. The collaboration is consisted of 30 researchers from 11 institutes. The Brazilian group also participates the Double Chooz experiment. In March 2007, a very near (prototype) detector for safeguards study was approved.
3.2 Daya Bay

Daya Bay experiment \cite{14} is the only one that is designed to measure $\sin^2 2\theta_{13}$ to better than 0.01 at 90% C.L. in near future.

Daya Bay Nuclear Power Plant (NPP) and LingAo NPP locate in the south of China, 55 km to the northeast of Hong Kong and 45 km to the east of Shen Zhen city. The two NPPs are about 1100 m apart. Each NPP has two cores running. Another two cores, called LingAo II, are expected to commission in 2010 and 2011, respectively. The thermal power of each core is 2.9 GW. Hence the existing total thermal power is 11.6 GW, and will be 17.4 GW starting from 2011. The NPPs are adjacent to high hills that can provide protection from cosmic rays. The rock is hard granite of density around 2.7 g/cm$^3$, ideal for tunnel construction. A horizontal tunnel will be built to connect the underground experimental halls, which makes the logistics much easier and large detectors could be built. The experiment layout is shown in Fig. 7. The experiment is consisted of three experimental sites, the Daya Bay near site (DYB), the LingAo near site (LA), and the far site. The baseline, overburden, and predicted muon rate for each site are also shown in the figure.

Figure 7: Layout of the Daya Bay experiment.

To measure $\sin^2 2\theta_{13}$ down to 0.01, systematic uncertainties should be $<0.5\%$. Cross check
with redundancy and extra handling on systematic uncertainties are necessary for such a high precision measurement. The experiment is designed to have multiple antineutrino detectors (ADs) at each site, two at each near site and four at the far site. The detector systematic errors can be cross checked to 0.1% level in 3 years via side-by-side calibration of two detectors at the same near sites. After the 1st 3 years’ data taking, ADs will be swapped between near and far sites to change systematics and further improve the experimental sensitivity. All ADs will be assembled in a cleaning room in Surface Assembly Building (SAB) and be filled in an underground Liquid Scintillator Hall with the same batch of Gd-LS and LS, and with a reference tank for precise target mass measuring.

The ADs will be submerged in a big water pool, with at least 2.5 m water shielding in any direction, to shield the cosmogenic neutrons produced in the rock, as well as radioactivities from the rock and the air. The pool is filled with high purity water. Around 300 8-in PMTs are instrumented in each pool to form a muon cherenkov detector. The pool is divided into an inner layer and an outer layer optically, thus muon efficiency can be cross checked and neutron rejection power can be studied. The water pool is covered with another muon detector, Resistive Plate Chambers (RPCs). 4 layers RPCs with alternating x and y strips are assembled in 2m×2m modules and supported by a steel frame on rails. The RPCs can be slided to aside for AD installation and maintenance. Combining the water cherenkov detectors and RPCs, muon efficiency will be determined to 99.5±0.25%. Together with the overburden of the Daya Bay sites, the uncertainties of two major backgrounds, fast neutron background and accidental coincidence background, will be kept below 0.1%. The scheme of the muon system is shown in Fig. 8.

Figure 8: Four antineutrino detectors in the water pool of the far hall of Daya Bay. Above the pool is the RPC detector on rails.

The AD design is studied with a φ2m×2m prototype at IHEP, starting running since Mar. 2006. The prototype has a two-layer structure. A φ1m×1m acrylic vessel filled with LS is viewed by 45 8-in PMTs in the outer mineral oil layer. Two reflective panels locate at the bottom and the top of the prototype. In Jan. 2007, the LS was replaced with 800 liter 0.1%
The Daya Bay antineutrino detector.

Gd-LS. The stability of Gd-LS is monitored in the prototype and no apparent degradation found, as shown in Fig. 10.

The Daya Bay collaboration is consisted of 34 institutes from China, Czech, Russia, and United States, about 180 collaborators. The bidding of civil construction was done recently and the tunnel construction will start in Oct. 2007. The civil construction will take 22 months. The SAB will be ready in Jun. 2008, when the detector assembly can be started. The first near site will start data taking in Jun. 2009 and full operation will be in Oct. 2010. The expected sensitivity of Daya Bay versus year is shown in Fig. 11.

3.3 Double Chooz

Double Chooz [15] locates in Ardennes, France. It uses the existing detector site of Chooz experiment as the far site. The baseline is 1050 m and overburden is 300 m.w.e. The size of the pit available for the detector is 7m×7m. A near site will be constructed ∼280 m away from the reactor cores, with ∼80 m.w.e. overburden. The layout is shown in Fig. 12.

Each site has a single neutrino detector of target mass 8.3 ton. The detector design is shown in Fig. 13 with dimensions of each volume. The γ-catcher thickness is 55 cm and the oil buffer thickness is 105 cm. The dimension of the neutrino detector is φ2.76m×5.67m.
Figure 11: Sensitivity of Daya Bay at 90% C.L. for $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2$.

Figure 12: Layout of Double Chooz.

Outside is a 50 cm veto layer filled with oil and a 15 cm shielding layer made of steel.

Figure 13: Detector of Double Chooz.

Double Chooz is consisted of $\sim 100$ scientists from 32 institutions. The experiment has been approved by most of the respective Scientific Councils. Detector construction and integration will start in 2007. Because the far site exists, it will take data with a single far site
starting from 2008. With the improved detector design, it will measure $\sin^2 2\theta_{13}$ to 0.06 at 90% C.L. in two years. The near site need civil construction and is expected to start in 2010. The goal $\sin^2 2\theta_{13}$ sensitivity is 0.02-0.03, shown in Fig. 14.

![Figure 14: Sensitivity of Double Chooz experiment](image)

3.4 RENO

RENO [16] is a Korean based experiment. The YongGwang NPP has equally spaced 6 cores with thermal power 16.4 GW. The distance between 2 cores is 256 m. The experiment layout is shown in Fig. 15. The near site will be located 150 m from the midpoint of 6 cores. The overburden is $\sim 93$ m.w.e. The far site is 1500 m from the midpoint, with $\sim 437$ m.w.e.

![Figure 15: Site and layout of RENO.](image)

Each site has a single neutrino detector of target mass 15 ton. The detector design is shown in Fig. 16. The target is a cylinder of $\phi 2.8 \text{m} \times 3.2 \text{m}$. The $\gamma$-catcher thickness is 60 cm and the oil buffer thickness is 70 cm. 573 8-inch PMTs are implemented in the oil buffer. The energy resolution is expected to be $7.7\%/\sqrt{E}$. Outside the neutrino detector is a water cherenkov detector of 1-m thickness.

The RENO collaboration is consisted of 43 collaborators from 11 institutes in Korea and 2 institutes in Russia. The project was approved in 2005. Geological survey was completed.
in May 2007. Detector construction will begin at the end of 2007. Data taking is expected to start in early 2010. The projected sensitivity of RENO is shown in Fig. 17 which is $\sim 0.02$ at 90% C.L. in 3 years.

Figure 17: Sensitivity of RENO.

\section{4 Neutrino Magnetic Moments}

The Minimal Standard Model predicts a tiny neutrino moment $\sim 3 \times 10^{-19} \mu_B \cdot m_{\nu}/1 \text{ eV}$. Many extensions beyond Standard Model give larger predictions, say, $10^{-10} - 10^{-12} \mu_B$ \cite{17}. Reactor neutrinos can be used for direct search of neutrino moments at very short baseline via neutrino-electron scattering. The contribution to the scattering cross section is

$$\left( \frac{d\sigma}{dT} \right)_\mu = \frac{\pi \alpha_{\text{em}}^2}{m_e^2} \frac{1 - T/E_\nu}{T} \mu_e^2,$$

which becomes larger as the recoil energy $T$ goes lower. Thus lowering the detection threshold to keV level or even lower is desirable. There were limits from DONUT, LSND, Borexino, Super-K, KamLAND, MUNU, and TEXONO experiments. The upper limit was $1.0 \times$
10^{-10} \mu_B$, established by MUNU, shown in Fig. 18. Recently TEXONO improved the upper limit to $\mu_\nu < 0.74 \times 10^{-10} \mu_B$ [18] and GEMMA announced their first result to be $\mu_\nu < 0.58 \times 10^{-10} \mu_B$ [19], both at 90% C.L. Both experiments use a single crystal HPGe detector of mass at 1 kg level at a distance 10-20 m from the reactor. The backgrounds are at 1 counts/kg/day/keV level with an energy threshold $\sim$10 keV. TEXONO is taking data with a 200 kg CsI(Tl) crystal array to first measure SM neutrino-electron scattering at MeV range. At the same time, it is developing an 1 kg Ultra-Low Energy Ge detector to lower the threshold to 100 eV. A $2.0 \times 10^{-11} \mu_B$ limit could be reached. GEMMA aims at the level of $1.5 \times 10^{-11} \mu_B$ with 4 times larger detector.

![Figure 18: Limit of neutrino magnetic moment.](image)

5 Summary

Precisely measuring $\theta_{13}$ is of high priority in neutrino oscillation study. Sensitivity to $\sin^2 2\theta_{13} < 0.01$ is achievable based on experiences of past reactor neutrino experiments. Four $\theta_{13}$ experiments are in progress. Three of them project similar timeline, full operation starting in 2010, as listed in table 1. Double Chooz will get to 0.06 before 2010 using a single far detector. Upper limit on neutrino magnetic moment is improved to $0.74 \times 10^{-10} \mu_B$ by TEXONO and $0.58 \times 10^{-10} \mu_B$ by GEMMA.

| Experiment     | Luminosity in 3 years (ton-GW·y) | Overburden near/far (mwe) | Projected Sensitivity | Projected full operation date  |
|----------------|----------------------------------|---------------------------|-----------------------|--------------------------------|
| Daya Bay       | 4200                             | 270/950                   | <0.01                 | End of 2010                    |
| Double Chooz   | 210                              | 80/300                    | 0.02-0.03             | 2010                           |
| RENO           | 740                              | 90/440                    | $\sim$ 0.02           | Early 2010                     |

Table 1: Summary of three $\theta_{13}$ experiments.
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