Reactor neutrino oscillation experiments: recent results and future prospects

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Abstract.

Reactor neutrino experiments have played a key role in the history of neutrino physics. From the first observation of the free antineutrino by Reines and Cowan to the observation of $\nu_e$ disappearance at KamLAND, reactors have been an invaluable tool in the study of neutrinos and helped shape our understanding of neutrinos and neutrino oscillation. Recent data from KamLAND unambiguously reveal the signature of neutrino oscillation in the observed $\nu_e$ spectrum and determine the $\nu_e$ oscillation parameter $\Delta m^2_{12}$ to 2.8%. A suite of next-generation reactor experiments are now under construction to determine the yet unknown neutrino mixing angle $\theta_{13}$ with a sensitivity of $\sin^2 2\theta_{13} < 0.01$. Stringent control of detector systematics and minimizing backgrounds will be key to the continued success of reactor neutrino oscillation experiments.

1. Neutrino Physics at Reactors

For more than five decades experiments have studied the flux and properties of antineutrinos emitted from reactors. From the first direct observation of the antineutrino by Reines and Cowan in 1956 [1] to the searches for neutrino oscillation at the ILL, Goesgen, Bugey, Krasnoyarsk, Palo Verde, and Chooz reactors [2], experiments at reactors have searched for neutrino oscillation, placed the best laboratory limit on the neutrino magnetic moment [3] and provide the best limit on the yet unknown neutrino mixing angle $\theta_{13}$ [4]. By measuring the time-dependent variation of the $\nu_e$ flux and spectrum reactor antineutrinos have also been used recently to remotely monitor the fuel composition of nuclear reactors for non-proliferation purposes [5].

Nuclear power plants emit copious amounts of $\nu_e$. They are produced in the decay of the fission products inside the reactor [6]. Fission products are generally neutron rich nuclei that can undergo successive $\beta$-decays each yielding one $\nu_e$. Each fission produces on average 6 $\nu_e$’s with an accompanying energy release of $\sim$200 MeV. From the energy release and the nuclear fuel composition of a reactor the total number of electron antineutrinos emitted from the nuclear reactor can be predicted. A typical nuclear power plant operating at 3 GW thermal output produces on average $7 \times 10^{20}$ $\nu_e$’s per second. The pure electron flavor content of the antineutrinos produced in the $\beta$-decay products of the fission isotopes make nuclear reactors a desirable source for neutrino studies. The Sun and nuclear reactors are two of the very few sources that provide pure flavor beams of neutrinos free of other contamination.

In the last 50 years a series of reactor experiments with increasing baseline have searched for electron antineutrino disappearance as a signature of neutrino oscillation. As early as 1969 Bruno Pontecorvo suggested that lepton flavor may not be conserved and neutrinos might change...
flavor [7]. Detectors filled with liquid scintillator were placed near nuclear plants at distances from tens of meters up to about one kilometer to measure the flux of $\nu_e$ emitted from the nuclear reactor. However, for all experiments up to a distance of 1 km from the reactor the observed reactor $\nu_e$ flux was found to be consistent with the expectation from no oscillation.

2. Precision Measurement of Antineutrino Oscillation with KamLAND

Following the observation of atmospheric neutrino oscillation in Super-Kamiokande and the discovery of solar neutrino flavor transformation at SNO the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) experiment has measured the reactor $\nu_e$ flux at a distance of $\mathcal{O}(100 \text{ km})$, two orders of magnitudes further away from the reactor source than any other experiment. KamLAND is a high-resolution liquid scintillator detector with 1 kton of ultrapure liquid scintillator [8, 9]. Antineutrinos interact with the protons in the scintillator through the inverse beta reaction $\nu_e + p \rightarrow e^+ + n$ with a 1.8 MeV energy threshold. With its long baseline KamLAND is uniquely positioned to confirm with terrestrial neutrinos the observed solar neutrino oscillation and provide the best possible measurement of $\Delta m^2_{12}$. The principal contribution to the reactor $\nu_e$ flux measured by KamLAND comes from 53 power reactors in Japan. Most reactors are located within a distance range of $L = 175 \pm 35 \text{ km}$ from KamLAND.

To a good approximation the survival probability for reactor electron antineutrinos is given by the following equation:

$$P(\nu_e \rightarrow \nu_e) \simeq \cos^4 \theta_{13} \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E_{\nu}}\right)$$

(1)

where $L$ is the distance of travel of the neutrinos and $E_{\nu}$ is the antineutrino energy. Reactor neutrinos typically have a mean energy of about $\sim 4 \text{ MeV}$. Matter effects that arise in the interaction of neutrinos with electrons inside matter [10] are usually negligible for reactor neutrinos.

The expected $\nu_e$ flux from the Japanese reactors and the resulting interaction rate at KamLAND are calculated from the reactor operation data including thermal power generation, fuel burn-up, exchange and enrichment records. The expected flux is calculated using the fission rates and $\nu_e$ spectra [6]. The $\nu_e$ contribution from Japanese research reactors and all reactors outside Japan is 4.5%. We assume that these reactors have the same average fuel composition as the Japanese power reactors.

In 2003 KamLAND reported the first observation of reactor $\nu_e$ disappearance [8]. With an exposure of 162 ton-yr corresponding to 145.1 days of data KamLAND found the ratio of the number of observed $\nu_e$ candidate events minus backgrounds to the expected number of $\nu_e$ events to be $N_{\text{observed}} - N_{\text{bkgd}} / N_{\text{expected}} = 0.611 \pm 0.085(\text{stat.}) \pm 0.041(\text{syst.})$. This result confirmed with terrestrial neutrinos the neutrino oscillation solution favored by a global analysis of all solar neutrino data [8]. With higher statistics KamLAND reported in 2005 evidence for distortion in the measured energy spectrum, a unique signature of the energy-dependent neutrino oscillation effect [9].

At this conference KamLAND presents a precision measurement of the $\nu_e$ oscillation parameters based on an analysis of data collected between March 2002 and May 2007. New features of this analysis include increased livetime, a lower analysis threshold, reduced uncertainty in the $^{13}$C($\alpha,n)^{16}$O backgrounds, reduced systematic in the fiducial volume, and a modified likelihood analysis procedure. To reduce the fiducial volume uncertainty, one of the dominant systematics in the previous analysis, the collaboration deployed a $4\pi$ calibration system that allows the calibration of the detector response with passive radioactive sources throughout the entire detector volume. The $4\pi$ system consists of a segmented calibration pole with multiple radioactive calibration sources that are used for the calibration of the energy response and vertex reconstruction throughout the detector. This provides a direct test of the vertex and energy.
reconstruction at radii out to $R=5.5$ m near the fiducial volume boundary. Figure 1 shows the conceptual design of the $4\pi$ calibration system in the KamLAND detector and the vertex distribution of $^{60}$Co/$^{68}$Ge composite source data collected in $4\pi$ calibration runs. A suite of radioactive sources including $^{60}$Co, $^{68}$Ge, and AmBe were used with the $4\pi$ system to map out the detector response in $\theta$, $\phi$, and $r$. Using the $4\pi$ system the fiducial volume is determined to 1.6% within 5.5 m from the center of the detector. Together with the $^{12}$B/$^{12}$N event ratio which is used to establish the uncertainty between 5.5 m and 6 m a combined 6-m-radius fiducial volume uncertainty of 1.8% is obtained. See Table 2.

With 1491 days of livetime and a fiducial volume of $(R_{\text{prompt}},R_{\text{delayed}}) < 6.0$ m which corresponds to an exposure of $2.44 \times 10^{32}$ proton-years KamLAND observed 1609 events over a background of $276 \pm 23.5$ events. The number of expected events for this time period is $2179 \pm 89$ events. Figure 2 shows the prompt energy spectrum, the no-oscillation expectation, and the best-fit oscillation scenario. The significance of $\nu_e$ disappearance above a 2.6 MeV analysis threshold is $8.5\sigma$ and the significance of spectral distortion is $>5\sigma$. An analysis of the measured prompt spectrum taking into account the $\nu_e$ rate, the shape of the spectrum, and the time variation of the reactor flux yields the best-fit oscillation parameters $\tan^2 \theta_{12} = 0.56^{+0.14}_{-0.09}$ and $\Delta m^2 = 7.58^{+0.22}_{-0.21} \times 10^{-5}$ eV$^2$ (Figure 3). The recent KamLAND data nicely reveal the oscillatory signature in the $L/E$ dependence of the neutrino survival probability. See Equation 1 and Figure 3. Given its effective, flux-weighted average baseline of $L_0 = 180$ km to the surrounding reactors KamLAND has little sensitivity to $\theta_{13}$ (Figure 3).

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Illustration of the KamLAND detector with $4\pi$ calibration system (left) and vertex distribution of $^{60}$Co/$^{68}$Ge composite source in $4\pi$ calibration runs (right).

**Figure 2.** Prompt energy spectrum of reactor $\nu_e$ measured in KamLAND.

### 3. A Precision Measurement of $\theta_{13}$ with Reactor Antineutrinos

Recent results from Super-Kamiokande, SNO, and KamLAND, have unambiguously demonstrated that neutrinos have mass and change flavor. Two of the three mixing angles in the $U_{\text{MNSP}}$ neutrino mixing matrix have been measured by the solar and atmospheric experiments and were found to be large and maximal respectively. The third neutrino mixing angle, $\theta_{13}$, has not been measured yet but is known to be small. The Chooz experiment has provided the best limit of $\sin^2 2\theta_{13} < 0.15$ [4]. The pattern of the neutrino mixing parameters revealed so far is strikingly different from that of quark mixing and places significant constraints and guidance on the construction of models involving new physics. The measurement of $\theta_{13}$ has sparked worldwide interest as it raises important questions about the phenomenology and theory of neutrino mixing.
Figure 3. Survival probability as a function of L/E (left) and oscillation parameter space allowed by KamLAND (center and right) for the two-neutrino and three-neutrino oscillation case.

and is key to the future of neutrino oscillation physics. The size of $\theta_{13}$ determines the electron component to the third neutrino mass eigenstate. If it turns out to be zero or very small, it would point to some $\mu$-$\tau$ symmetry in neutrino mixing. A non-zero $\theta_{13}$ is prerequisite to observable CP violation in the lepton sector. CP violation is a key ingredient to leptogenesis which can explain the observed baryon asymmetry in the Universe through out-of-equilibrium $L$-violating decays of heavy Majorana neutrinos. $\theta_{13}$ is also important for determining the nucleosynthesis yields in supernovae and the early Universe where neutrino mixing and neutrino interactions play a key role [12].

There are two approaches to measuring the neutrino mixing angle $\theta_{13}$. One involves the appearance measurement $\nu_\mu \rightarrow \nu_e$ with high-energy neutrinos at accelerators over long baselines. In this case the oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is dependent on the mixing angles as well the mass hierarchy and the mass splittings. $P$ is sensitive to matter effects which allow the determination of CP-violating phases. Such a measurement is rich in physics but the parameter degeneracy makes it challenging. On the other hand, the precise measurement of $\bar{\nu}_e$ disappearance with reactor antineutrinos is a clean measurement of the antineutrino oscillation in vacuum in the absence of matter effects. Since $\Delta m^2_{13} \ll \Delta m^2_{23}, \Delta m^2_{12} \approx \Delta m^2_{23}$ and we can predict the mass splitting and the wavelength of the unobserved $\theta_{13}$ oscillation. The relatively low energy of reactor $\bar{\nu}_e$ allows the observation of the oscillation effect over short distances of typically $O(1-2)$ km. Next-generation reactor experiments maximize their sensitivity to $\theta_{13}$ by optimizing detector baselines and using multiple detectors to cancel uncertainties in the reactor $\bar{\nu}_e$ flux prediction (see Table 1).

A relative measurement between two detectors placed near and far from the reactors largely eliminates reactor flux uncertainties and most of the detector-related systematics that have limited absolute $\bar{\nu}_e$ flux measurements in KamLAND and other past experiments. A change in the observed $\bar{\nu}_e$ interaction rate between these two detectors due to the decrease in the $\bar{\nu}_e$ survival probability as a function of distance would be an indication of sub-dominant $\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$ oscillation and allows the determination of $\sin^2 2\theta_{13}$. Uncertainties related to the absolute target mass and the absolute detection efficiency cancel in this relative measurement. Key to this concept is the use of “identical” detectors near and far to control relative systematic uncertainties. For the expected improvement in the uncertainties of the relative measurement over an absolute $\bar{\nu}_e$ flux measurement see Tables 1, 2, 3, and 4. The goal of next-generation neutrino oscillation experiments is to measure $\sin^2 2\theta_{13}$ to $< 0.01$ at 90% CL. This sets the limit for realistic studies of leptonic CP-violation in the near future. New technologies are needed if $\sin^2 2\theta_{13} \ll 0.01$. 

4
Several collaborations worldwide have undertaken the challenge to measure $\theta_{13}$ from the disappearance of reactor $\nu_e$. The Double Chooz, Reno, and Daya Bay experiments are currently in various phases of construction and will start taking data in 2009-2010. With a total of eight detectors of 20-ton target mass each installed in three underground experimental halls Daya Bay [13] is the largest experiment under construction and will reach the highest sensitivity of $\sin^2 2\theta_{13}$ to $< 0.01$ at 90% CL. The Daya Bay nuclear power plant presently operates 4 reactor cores with a total thermal power output of 11.6 GW$_{th}$. Two more cores are under construction and will increase the total power output to 17.4 GW$_{th}$ by 2011. The layout of the Daya Bay experiment is shown in Figure 4.

Common to all future reactor $\theta_{13}$ experiments is the design of the antineutrino detectors. Gd-liquid scintillator is used as the target for the $\nu_e$ interactions. With high proton density, good light yield, and a large neutron capture cross-section it provides an easily identifiable $\nu_e$ signal and good background discrimination. The inner target volume is surrounded by a liquid scintillator gamma catcher to eliminate the need for position reconstruction and fiducial volume cuts like in KamLAND. A mineral oil buffer region surrounds the target and provides shielding against radioactive backgrounds from the PMTs, the detector tank, and other detector elements. At Daya Bay all antineutrino detectors are placed in water pools instrumented with PMTs and RPCs. The pools act a muon veto and provide shielding against rock and environmental gamma background. All detectors will be located in underground halls to provide shielding against muons and cosmogenic backgrounds. See Figure 5.

Control of the relative detector systematics and the determination of backgrounds will be essential for the success of the upcoming reactor $\theta_{13}$ experiments. In the case of Daya Bay the $\bar{\nu}_e$ flux is measured in pairs of “identical” detectors deployed at the different sites. Tests have shown that the relative target mass in these detectors can be measured to $< 0.1\%$. We expect to calibrate and understand the relative antineutrino detection efficiency to $< 0.25\%$. See Table 4. With 4 (or 6) reactor cores Daya Bay will have an additional uncertainty from the multiple baselines between the detectors and reactor cores. This effect, however, is small in the relative measurement between detectors. See Table 3. The main challenge will be to understand cosmogenic backgrounds and in particular beta-delayed neutron emitters such as $^8$He/$^9$Li to better than 0.3%. This is likely to be the limiting uncertainty in the experiment. With these projected uncertainties a sensitivity of $\sin^2 2\theta_{13} < 0.01$ at 90% CL is achievable in three years of
Table 1. KamLAND: Reactor-related systematic uncertainties in a flux measurement with a single detector [11].

| Reactor related         | %  |
|-------------------------|----|
| p_e-spectra             | 2.4|
| reactor power           | 2.1|
| fuel composition        | <1.0|
| long-lived nuclei       | 0.3|
| time lag                | 0.01|
| total                   | 3.4|

Table 2. KamLAND: Detector-related uncertainties in a single detector [11].

| Detector related        | %  |
|-------------------------|----|
| fiducial volume         | 1.8|
| energy scale            | 1.5|
| efficiency              | 0.6|
| OD veto                 | 0.2|
| cross-section           | 0.2|
| livetime                | 0.03|
| total                   | 2.4%|

Figure 6. Signal and background event rates in the Daya Bay detectors in the three experimental halls Daya Bay (DYB), Ling Ao (LA), and the far site (Far). All numbers are rates in events/day/module unless stated otherwise [13].

| Event Rate            | DYB | LA | Far |
|-----------------------|-----|----|-----|
| antineutrino          | 930 | 760| 90  |
| natural radiation     | <50 | <50| <50 |
| single neutron        | 18  | 12 | 1.5 |
| β-emission isotopes   | 210 | 141| 14.6|
| accidental/signal     | <0.2%|<0.2%|<0.2%|
| fast neutron/signal   | 0.1%| 0.1%| 0.1%|
| ^8He-^9Li/signal      | 0.3%| 0.2%| 0.2%|

Table 3. Daya Bay: Net correlated errors from multiple reactors in a relative flux measurement between multiple detectors [13].

| Number of cores | σ(power) | σ(location) | σ(total) |
|-----------------|----------|-------------|----------|
| 4               | 0.035%   | 0.08%       | 0.087%   |
| 6               | 0.097%   | 0.08%       | 0.126%   |

Table 4. Daya Bay: Detector-related uncertainties in a relative measurement between two detectors [13].

| source             | baseline (%) | goal (%) |
|--------------------|--------------|----------|
| no. of protons     | 0.3          | 0.1      |
| energy cuts        | 0.2          | 0.1      |
| position cuts      | 0.0          | 0.0      |
| time cuts          | 0.1          | 0.03     |
| H/Gd ratio         | 0.1          | 0.1      |
| n multiplicity     | 0.05         | 0.05     |
| trigger            | 0.01         | 0.01     |
| live time          | <0.01        | <0.01    |
| total              | 0.38%        | 0.18%    |

Figure 7. Sensitivity of the Daya Bay experiment to sin^22θ_{13} [13].

Running. Tables 6 and Figure 7 show the expected signal event and background rates and the sensitivity of the Daya Bay experiment to sin^22θ_{13} as a function of running time.
4. Summary and Conclusions

KamLAND has played a key role in the history of reactor neutrino physics. Designed to observe antineutrinos from nuclear power plants in Japan, KamLAND made the first observation of reactor $\bar{\nu}_e$ disappearance at a flux-weighted average distance of about 180 km, found direct evidence for neutrino oscillation in spectral distortions, and has made a precision measurement of the reactor $\bar{\nu}_e$ oscillation parameters. With the help of the 4$\pi$ calibration system for the determination of the fiducial volume, reduced uncertainties in the $^{13}$C($\alpha$,n)$^{16}$O background, and improved analysis techniques a precision of 2.8% on $\Delta m^2_{12}$ was obtained. Together, solar neutrino experiments and KamLAND provide unambiguous evidence that neutrinos have mass and change flavor, and they provide the most precise determination of the neutrino oscillation parameters $\Delta m^2_{12}$ and $\theta_{12}$. Recent data from KamLAND illustrate clearly the oscillatory signature of neutrino mixing.

A suite of next-generation reactor antineutrino experiments including Daya Bay, Double Chooz, and Reno are now under construction to make a precision measurement of the reactor $\bar{\nu}_e$ flux over short distances of 0.2-2 km in order to measure the yet unknown mixing angle $\theta_{13}$. With the control of relative detector systematic uncertainties to $< 0.38\%$, Daya Bay will be able to reach a sensitivity of $0.01\%$ at 90% CL in three years of data taking. Fifty years after the discovery of the antineutrino, nuclear reactors still play an important role in understanding the mysteries of neutrinos, and the next reactor experiments may hold the clue to opening the path towards the study of leptonic CP violation with neutrinos.

Acknowledgments

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