REACTOR NEUTRINO EXPERIMENTS

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Previous searches for neutrino oscillations with reactor neutrinos have been done only with baselines less than 1 km. The observed neutrino flux was consistent with the expectation and only excluded regions were drawn on the neutrino-oscillation-parameter space. Thus, those experiments played important roles in understanding neutrinos from fission reactors. Based on the knowledge from those experiments, an experiment with about a 180 km baseline became possible. Results obtained from this baseline experiment showed evidence for reactor neutrino disappearance and finally provide a resolution for the long standing solar neutrino problem when combined with results from the solar neutrino experiments. Several possibilities to explore the last unmeasured mixing angle θ_{13} with reactor neutrinos have recently been proposed. They will provide complementary information to long baseline accelerator experiments when one tries to solve the degeneracy of oscillation parameters. Reactor neutrinos are also useful to study the neutrino magnetic moment and the most stringent limits from terrestrial experiments are obtained by measuring the elastic scattering cross section of reactor neutrinos.

1. Reactor Neutrinos

The first observation of neutrino existence was carried out by using a nuclear power reactor in 1956. The experiment led by Reines was called "Poltergeist" and located 11 m distance from a powerful reactor (700 MW) at Savannah River, 12 m underground. It used a large amount of proton target (200 liters of water), liquid scintillator (1400 liters of LS) and 55 photo-multiplier tubes for signal detection. The underground site was important to reduce cosmic ray induced backgrounds. A modern experiment in 2003 is still a simple extension of Poltergeist but uses a 70 GW (effective) power reactor, a proton target (1000 ton LS) and 1879 PMT's at a distance of about 180 km and 1000 m underground. This extension of many orders of magnitude became possible because of many important improvements in the knowledge of reactor neutrinos.

In the observation of reactor neutrinos, 4 fissile nuclei (^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu) are important and the others contribute only at the 0.1% level. Fission fragments from these nuclei sequentially beta-decay and emit antielectron-neutrinos. The purity of the "anti"neutrinos is very high and an electron-neutrino contamination is only at the 10 ppm level above 1.8 MeV. These four nuclei release similar energy when they undergo fission[1] (^{235}U 201.7$\pm$0.6, ^{239}Pu 210.0$\pm$0.9, ^{238}U 205.0$\pm$0.9 and ^{241}Pu 212.4$\pm$1.0 MeV). Thus the fission rate is strongly correlated with the thermal power output that is measurable at much better than 2% even without any special care. Then, one fission causes about 6 neutrino emissions on average and therefore, the neutrino intensity can be roughly estimated to be $\sim 2\times 10^{20}\,\bar{\nu}_e/\mathrm{GW}_{th}/\mathrm{sec}$. Fission spectra reach equilibrium within a day above $\sim$2 MeV. However, attention to the long-lived nuclei such as:

$$^{106}Ru \xrightarrow{T_{1/2}=372d} Rh \xrightarrow[E_{max}=3.541MeV]{} Pd$$

$$^{144}Ce \xrightarrow{T_{1/2}=285d} Pr \xrightarrow[E_{max}=2.996MeV]{} Nd$$

is necessary.[2] They affect the correlation between thermal power and neutrino flux.

The beta spectra from ^{235}U, ^{239}Pu and ^{241}Pu have been measured with a spectrometer irradiating thermal neutrons at ILL.[3] They fitted the observed beta spectra from 30 hypothetical beta branches and converted each branch to a neutrino spectrum.[4] In the case of ^{238}U, it doesn't undergo to fission with thermal neutrons and only a theoretical calculation[5] is available. This calculation traces 744 unstable fission products and obtains the corresponding neutrino spectrum. The error on the calculated spectrum is larger than the measurement, but it contributes only $\sim$8% on average for ordinary reactor cores. And knowing the time evolution of the fuel composition, the uncertainty of the neutrino event rate coming from the calculation of these spectra is only $\sim$2.3%.

The neutrino reaction used in "Poltergeist" and following experiments is the inverse beta decay:

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

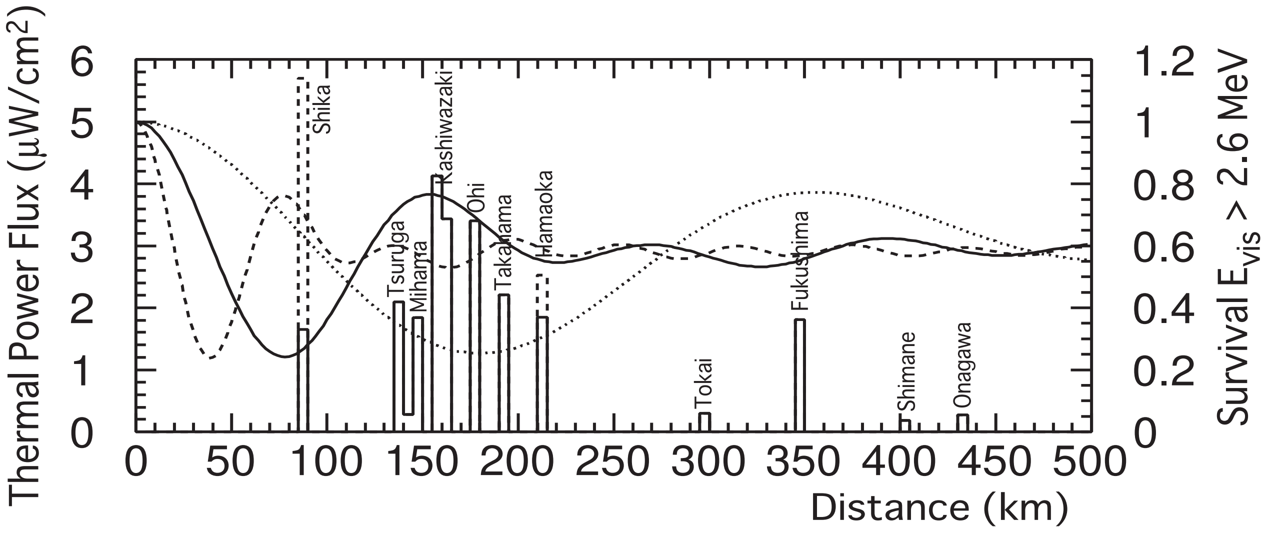

Figure 1. Distribution of nuclear power reactors as a function of distance from the KamLAND site. The solid histogram is the current operation and dashed histogram is an expected operation in 2006 (Shika at 88 km increases by a factor 3). Height of the histogram shows the thermal power flux contribution at Kamioka. Also shown as solid ($\Delta m^2 = 7 \times 10^{-5}$ eV^2), dashed (3×10^{-5}) and dotted (1.4×10^{-4}) lines are the survival probability of $\bar{\nu}_e$ as a function of distance (all for $\sin^2 2\theta = 0.84$). The probability is calculated for events above 2.6 MeV in visible energy.

Advantages of this reaction are the rich target number, low reaction threshold

$$E_{lab} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806 \text{ MeV},$$

very precisely known cross section and the delayed two-fold coincidence signal. The cross section is well related to the neutron life time ($n \to p + e^- + \bar{\nu}_e$) as follows.

$$\sigma_{tot}^{(0)} = \frac{2\pi^2/m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

Recent precise studies on neutrons provided the very accurate lifetime of $\tau_n = 885.7 \pm 0.8$ sec and as a result the precision of the neutrino cross section on proton is 0.2% with order 1/M corrections (Coulomb, weak magnetism, recoil, inner and outer radiative corrections).[6] The prompt signal is the positron and its annihilation gammas with a material electron, thus the prompt signal has energies always larger than 1 MeV (two electron masses). The delayed signal is the capture of the neutron on an environmental atom such as hydrogen, gadolinium, cadmium and ^{3}He. It provides clear tagging and very good background discrimination in timing, position and energy.

The validity of the neutrino spectra and cross section calculations have been experimentally tested. The most accurate measurement has been performed by the Bugey experiment.[7] It measured an overall reaction rate with 1.4% accuracy and the result ($\sigma_f = 5.750 \times 10^{-43}$ cm^2/fission $\pm$ 1.4%) was in very good agreement with the calculation ($\sigma_{V-A} = 5.824 \times 10^{-43}$ cm^2/fission $\pm$ 2.7%). The ratio of them is $\sigma_f/\sigma_{V-A} = 0.987 \pm 1.4\% \pm 2.7\%$. Also, Bugey-3 tested models of neutrino spectra and the ILL spectra showed an excellent agreement.[8] Finally, a few % precision became possible without a near detector for flux normalization with the above calculation models and procedures.

2. KamLAND

Reactor neutrino experiments before KamLAND had baselines only up to 1 km. All results from such short baselines were consistent with the calculation and oscillation parameters above 8×10^{-4} eV^2, and full mixing has been excluded with them. On the other hand, all solar neutrino experiments showed solar neutrino deficits and a combined neutrino oscillation analysis favored the large mixing angle solution below several $\times 10^{-4}$ eV^2. The only exception was the neutral current measurement at SNO and it was perfectly consistent with the standard solar model prediction. It resulted in a more than 5σ positive neutrino flux other than electron-neutrinos and is evidence for neutrino flavor transformation of solar electron-neutrinos to the other neutrino types. These results are well explained by the neutrino oscillation hypothesis but other models such as resonant spin flavor precession, neutrino decay, flavor-changing non-standard interactions and CPT violation models were still valid. Even assuming the neutrino oscillation, mass squared difference could vary from 10^{-10} to several $\times 10^{-4}$ eV^2. In order to explore these small mass difference region, baselines more than 100 km were required. For an experiment with such a baseline, much more powerful reactors, a bigger detector and a deeper underground site were necessary.

The total power generation with nuclear fission reactors in the world amounts to ~1.1 TW (thermal). It corresponds to $\sim 2 \times 10^{23}\,\bar{\nu}_e$ creations/sec. Surprisingly, 70 GW (7% of world total) is generated at 130-240 km distance from the Kamioka site where former Kamiokande and Super-Kamiokande exist. Reactor neutrino flux at the Kamioka site is $\sim 5 \times 10^6$ cm^{-2}s^{-1} and requires order kiloton underground detector for a practical experiment. KamLAND took over the cavity for the former Kamiokande experiment located 1000 m underground from the top of the mountain (2700 mwe (meters-of-water-equivalent)). Figure 1 shows the expected oscillatory pattern of neutrino survival probability for the LMA parameters. The effective distance of the reactors is ~180 km and it is very sensitive to the difference of Δm^2. A new Shika reactor is also planned to start at a distance of 88 km.

In order to estimate the expected neutrino spectrum at the Kamioka site, histories of thermal power output, new fuel volume ratios, fuel enrichments and burn-up information are obtained from 52 commercial reactor cores (~97% contribution) and histories of electric power output for 18 Korean reactors (~2.5% contribution) are also taken into account.

KamLAND is a monolithic liquid scintillator detector as shown in Fig. 2. It uses 1200 m^3 LS suspended with a 135 μm-thick balloon in 1800 m^3 of buffer oil. They are contained in an 18 m diameter stainless steel tank. The LS is a mixture of 80% do-

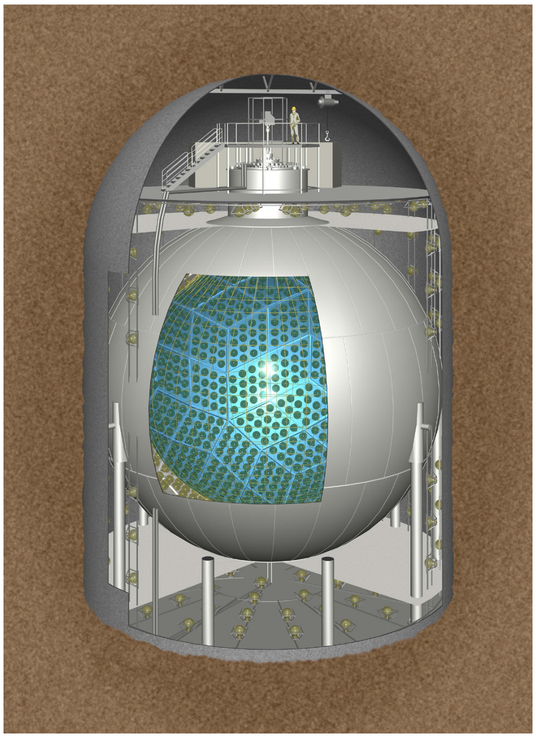

Figure 2. The KamLAND detector.

decane, 20% 1-2-4-trimethylbenzene and 1.5 g/liter PPO. The density of the LS is 0.78 g/cm^3. The buffer oil is a mixture of 50% dodecane and 50% isoparaffin and the density is controlled to be 0.04% lighter than the LS. The light output of the LS is ~ 8000 photons/MeV and its attenuation length is effectively ~10 m. These photons are monitored by the newly developed 1325 17″-tubes and 554 old 20″-tubes from the Kamiokande experiment. Total photo-coverage is 34% but only the 17″-tubes (22% coverage) are used for the first results.

The event trigger is set at 0.7 MeV (visible) providing a sufficiently low threshold for anti-neutrino reactions. Also a delayed trigger (0.4 MeV) is enabled for 1 msec after each prompt triggers to perform real-time impurity measurements of

$$^{214}Bi \xrightarrow{\beta,\gamma} {}^{214}Po(\tau = 237\mu sec) \xrightarrow[7.687MeV]{\alpha} {}^{210}Pb.$$

The latter alpha decay is observed with a quench of about a factor 14 and the delayed threshold is necessary to tag this delayed coincidence event. The measured impurity level at KamLAND is listed in Table 1 together with the requirements.

The achieved impurity level is much lower than

Table 1. Requirements and achievements of radioactive impurities.

Impurities	Achievements	Req.(reactor)	Req.(solar)
^{222}Rn	$0.03\ \mu$Bq/m^3		
^{238}U	$3.5 \pm 0.5 \times 10^{-18}$ g/g	10^{-13} g/g	10^{-16} g/g
^{232}Th	$5.2 \pm 0.8 \times 10^{-17}$ g/g	10^{-13} g/g	10^{-16} g/g
^{40}K	$< 2.7 \times 10^{-16}$ g/g	10^{-14} g/g	10^{-18} g/g
^{85}Kr	$\sim$1 Bq/m^3		$1\ \mu$Bq/m^3
^{210}Pb	$\sim$100 mBq/m^3		$1\ \mu$Bq/m^3
On the balloon		Equiv. mine dust	
^{222}Rn	4.0×10^{-4} Bq		
^{238}U	3.1×10^{-8} g	0.9 g	
^{232}Th	9.7×10^{-4} g	0.1 g	

the requirements for the reactor neutrino measurement and it is even cleaner than that for a solar neutrino observation. Thanks to this being the world's cleanest environment, accidental coincidence backgrounds are very low, 0.0086 ± 0.0006 events for a 2.6 MeV analysis threshold in a 162 ton-yr data sample and 1.81 ± 0.08 events for a 0.9 MeV threshold. The low energy accidental backgrounds are dominated by a combination of ^{210}Bi and ^{208}Tl. Cosmic ray muons are reduced by a factor 10^5 with 2700 mwe rock overburden, but this can cause correlated backgrounds and they are still the main source of backgrounds. One type of correlated backgrounds are fast neutrons from outside the detector. By tagging outer-detector-penetrating (OD) muons, the event rate of fast neutrons are measured. By considering the OD inefficiency and extrapolating contributions to rock-through-muons, total fast neutron backgrounds are estimated to be less than 0.5 events. Another type of correlated events is spallation products such as ^{8}He and ^{9}Li. They are beta-decay nuclei but they also emit neutrons at the same time and discrimination of them against the actual neutrino signal can be done only by looking at a space-time correlation of the parent muons. Considering a rejection efficiency of a spallation cut, the amounts of background from such spallation is estimated to be 0.94 ± 0.85 and 1.1 ± 1.0 events for the 2.6 and 0.9 MeV threshold, respectively. Finally, the amounts of total background are estimated to be 2.9 ± 1.1 and 1 ± 1 for the two thresholds.

There is also believed to be a neutrino background called "geo-neutrinos." Radioactivity contained in the earth is thought to be the major source (20 TW) of observed heat flow (44 TW) on the surface of the earth, and 16 TW out of it is coming from the ^{238}U and ^{232}Th decay series. In the series of their decay, anti-electron-neutrinos are also emitted. "A model guess" predicts about 9 and 0.04 events for 0.9 and 2.6 MeV analysis thresholds. If these neutrinos are eventually observed, it would be the important start of "Neutrino geophysics", but for the moment, the 2.6 MeV analysis threshold is employed to eliminate an uncertainty of geo-neutrino flux.

Table 2. Event selections.

(1)	fiducial cut	$R < 5m$, 3.46×10^{31} protons
(2)	timing correlation	$0.5 < \Delta T < 660\mu s$, $\tau = 212\ \mu$s
(3)	vertex correlation	$\lvert\vec{r}_{prompt} - \vec{r}_{delayed}\rvert < 1.6$ m
(4)	delayed energy	$1.8 < E < 2.6$ MeV
(5)	thermometer cut	$\sqrt{x^2 + y^2} > 1.2$ m
(6)	spallation cut	2 sec, all volume ($dQ > 10^6$ p.e.)
		2 sec, $L < 3$ m ($dQ < 10^6$ p.e.)
(7)	energy threshold	$E_{vis} > 2.6$ MeV

Event selections used for the first results are listed in Table 2. The detection efficiency up to number (5) is 78.3% and the dead time from the spallation cut is 11.4%.

Energy calibrations have been performed by suspending radioactive sources along the z-axis. Also uniformly distributing spallation products such as neutron capture and ^{12}B were used to monitor uniformity and time variation of the energy scale. The

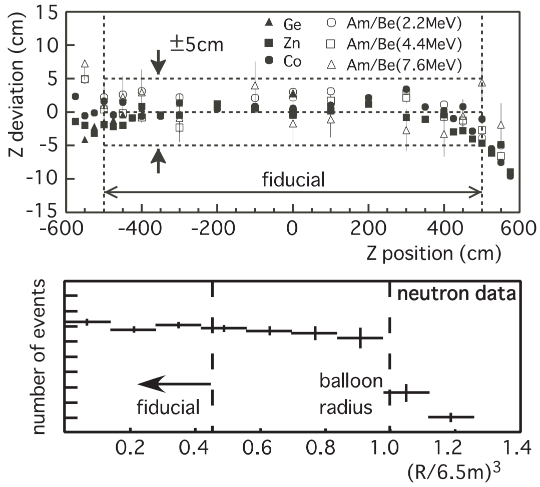

Figure 3. Vertex calibrations. The upper panel shows systematic biases of reconstructed positions along the z-axis. Biases are less than 5 cm within the fiducial region -500 cm to 500 cm for all energies. The lower panel is the R^3 distribution of uniformly distributed spallation neutron events. The uniform distribution appears as a flat distribution.

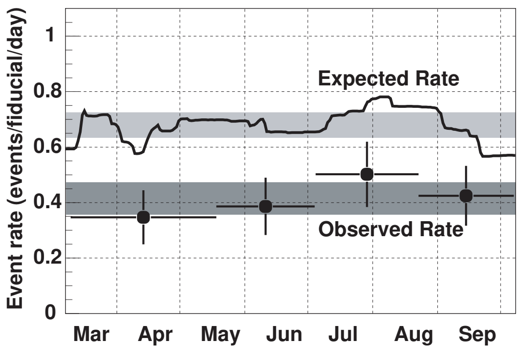

Figure 4. Reactor neutrino event rate. The plots and line are the observed and expected event rate, respectively, and the gray hatches are their averages. The structure in the expected rate reflects the change of reactor operations.

position dependence was smaller than 1.4% and the time variation was smaller than 0.6%. A quenching effect of the LS was also studied with alpha decays from ^{222}Rn, a wide range of gamma ray sources and beta decay of spallation products. The total uncertainty of the energy scale at the threshold energy 2.6 MeV is 1.91% which translates to a 2.1% systematic error in the neutrino event rate.

The largest systematic error comes from the determination of the fiducial volume. The vertex reconstruction was tuned with various radioactive sources along the z-axis and the systematic biases of vertices are smaller than 5 cm for the calibrated energy ranges from 1 MeV to 7.6 MeV as seen in the Fig. 3. A five cm bias corresponds to a 3% fiducial volume error. However, it is also calibrated by the vertex distribution of uniformly distributed spallation events. The ratio of number of events in the fiducial volume to the total volume was compared with the volume ratio. Distributions of neutron capture and ^{12}B events were consistent with the volume ratio at ±4.1% and ±3.5% accuracies, respectively. Those accuracies are dominated by the statistical uncertainty of the small number of spallation events. Currently, the fiducial volume error is conservatively estimated with the worst precision data. A breakdown of the systematic error is listed in Table 3.

From March 4 to October 6, 2002, KamLAND acquired 145.1 live days of data, equivalent to a 162 ton-yr exposure. Figure 4 shows the observed and the expected neutrino event rate above 2.6 MeV. The observed rate was always smaller than the expected. Combining the data from the entire period, the expected reactor neutrino signal is 86.8 ± 5.6 events and the estimated background rate is 1 ± 1 events. Only 54 events were observed. This shows clear evidence for reactor neutrino disappearance at the 99.95% confidence level. The ratio of observed to expected rate is:[9]

$$R = 0.611 \pm 0.085(stat) \pm 0.041(syst).$$

The expected signal for the 0.9 MeV threshold is 124.8±7.5 events and the background rate is 2.9±1.1 events without the uncertain geo-neutrino contribution of ~9 events. The observed number of signal events, 86, is consistent with neutrino disappearance. Figure 5 shows the observed ratios of reactor neutrino fluxes from KamLAND and previous experiments. The band shows the allowed range of the oscillatory pattern from various LMA parameters and the deficit at KamLAND is in good agreement with the LMA solution. The other oscillation solutions such as the SMA, LOW and VAC are shown as a dashed line and they are excluded at the 99.95% confidence level with the KamLAND result alone under the assumption of the CPT invariance. Similarly the other possibilities such as RSFP are also eliminated under the CPT hypothesis and the solar neutrino problem has been finally resolved as the LMA solution by this process of elimination.

Table 3. A breakdown of the KamLAND systematic error.

	0.9 MeV	2.6 MeV	
Thermal power	2.0	2.0	Japanese reactors contribute ∼90% of the neutrino flux.
Korean reactors	0.25	0.25	Only electric power is known but contribution is ∼2.5%
Other reactors	0.35	0.35	Contribution is only 0.7%
Burn-up effect	1.0	1.0	Fraction of $^{235}U/^{238}U/^{239}Pu/^{241}Pu$
Long-life nuclei	0.5	0.002	Contribution of ^{106}Ru and ^{144}Ce
Time-lag of beta decay	0.3	0.3	$<$ 1 day time lag for an equilibrium
Neutrino spectra	2.3	2.5	See the References[4,5]
Cross section	0.2	0.2	See the References[6]
Total LS mass	2.1	2.1	1171 ± 25 m^3
Fiducial volume ratio	4.1	4.1	Vertex distribution of spallation neutron
Energy threshold	-	2.1	Position 1.4%, time 0.6%, quench 1.02%, dark 0.4%
Efficiency of cuts	2.1	2.1	Capture time, space correlation, energy window
Live time	0.07	0.07	
Total	6.0	6.4	

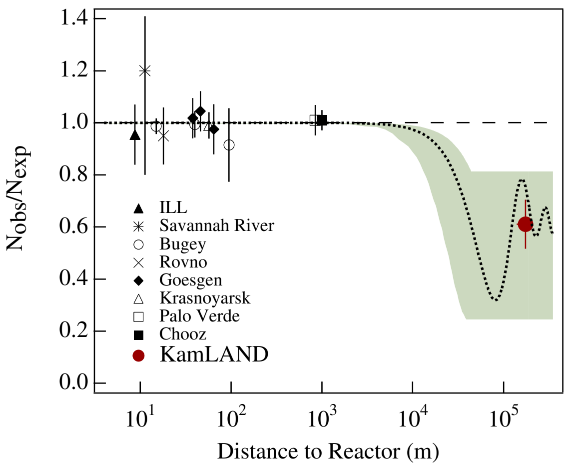

Figure 5. Observed neutrino rate at various baselines. The bands are for the various LMA parameters and the dotted line is for $(\sin^2 2\theta, \Delta m^2) = (0.833, 5.5 \times 10^{-5}$ eV$^2)$. The dashed lines are for no-oscillation, the SMA, LOW and VAC solutions.

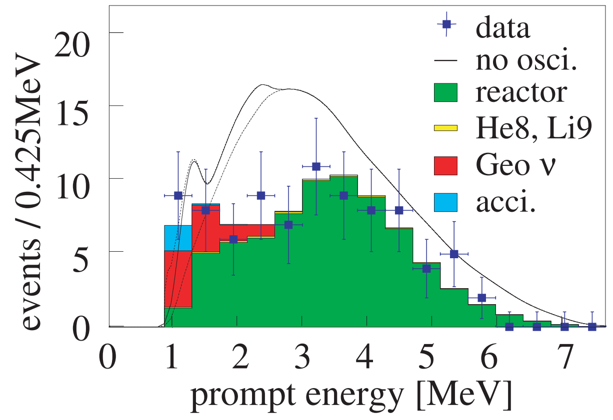

Figure 6. Energy spectrum at KamLAND. The curves are for no oscillation and the histograms are for the best-fit oscillation spectrum and the various background estimations.

The observed energy spectrum and the background estimations are shown in Fig. 6 with the best-fit oscillation spectrum at $(\sin^2 2\theta, \Delta m^2) = (1.0, 6.9 \times 10^{-5}$ eV$^2)$. If a 0.9 MeV threshold is used and treating the number of geo-neutrinos as a free parameter, the best fit for $\sin^2 2\theta$ becomes 0.91. The best-fit parameters for the number of geo-neutrinos are 4 for ^{238}U and 5 for ^{232}Th. However, they are consistent with 0 at 95% confidence level and it is still just a hint of geo-neutrinos. Using the spectrum shape information with the rate, the allowed oscillation parameter region has been obtained as shown in Fig. 7. The two bands overlap with the LMA solution from the solar neutrino experiments.

In order to claim neutrino oscillation with KamLAND alone, the oscillatory pattern should be found in the energy spectrum or distance dependence. The current spectrum is still consistent with constant suppression and thus the result is not evidence for neutrino oscillation, yet. In the future with more statistics, KamLAND can pin-point the Δm^2 with a greater precision (better than 5%). But, a precision measurement of $\sin^2 2\theta$ requires another measurement such as low energy solar neutrino observations or a precise measurement of NC/CC ratio at the SNO experiment. The new Shika reactor planned to start in 2006 may provide the first observation of an oscillation dip if LMA1 ($\Delta m^2 \sim 7 \times 10^{-5}$ eV^2) is the true solution. Three years of the new Shika ON data minus three years of OFF data (see Fig. 8)

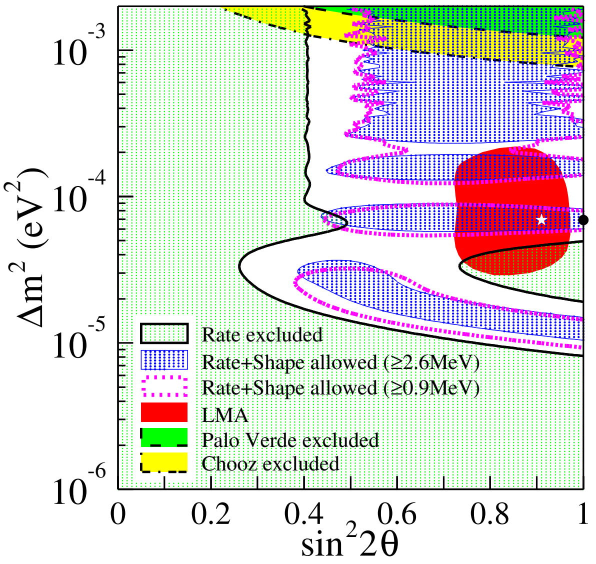

Figure 7. Allowed region of oscillation parameters. Region obtained from both 2.6 and 0.9 MeV analysis are shown.

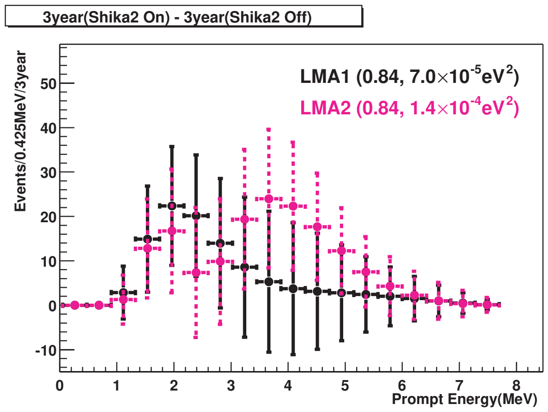

Figure 8. Expected spectrum from three years new Shika ON minus three years OFF with 5.5 m radius fiducial volume. Solids are for LMA1 $(0.84, 7\times10^{-5}\mathrm{eV}^2)$ and dots are for the LMA2 $(0.84, 1.4\times10^{-4}\mathrm{eV}^2)$ parameters.

will provide a new baseline measurement at 88 km. And the expected ratios from the LMA1 and LMA2 ($\Delta m^2 \sim 1.4\times10^{-4}$ eV^2) are $\frac{121\pm36}{173} \sim 0.70$ and $\frac{45\pm37}{173} \sim 0.26$, respectively.

3. θ_{13} Experiments

Neutrino mixing is commonly parameterized by the Maki-Nakagawa-Sakata matrix. The matrix contains 6 parameters (3 mixing, one Dirac CP phase and two Majorana CP phases) and 4 out of 6 (3 mixing and Dirac CP) are accessible with neutrino oscillation studies. The angle θ_{23} is measured by atmospheric neutrinos and a long baseline accelerator experiment to be almost maximal ($\theta_{23} \sim \pi/4$). The angle θ_{12} is measured by solar neutrino experiments and the KamLAND reactor neutrino experiment and it is known to be large ($\theta_{12} \sim \pi/6$). Only the third angle θ_{13} is unmeasured yet. The Dirac CP phase appears with θ_{13} and the size of the angle determines an accessibility to the CP phase in future experiments.

Accelerator experiments are aiming to observe a finite value of θ_{13} via an appearance reaction of $\nu_\mu \to \nu_e$. Its probability is related to the CP phase, the sign of $\theta_{23}-\pi/4$ and the mass hierarchy (the sign of Δm^2_{31}). This means there is a potential to measure those variables, but on the other hand, the θ_{13} measurement is affected by them. This is known as the "parameter degeneracy".

The reactor neutrino experiments observe disappearance of anti-electron-neutrinos and the probability doesn't depend on the CP phase nor the sign of $\theta_{23}-\pi/4$ and Δm^2_{31}. The neutrino survival probability for reactor neutrino experiments, for the normal hierarchy case, is given by the following expression.

$$\begin{aligned} P = 1 &- 4s^2_{13}c^2_{13}\sin^2\Delta_{31} \\ &-4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} \\ &+2s^2_{13}c^2_{13}s^2_{12}[\cos(2\Delta_{31}-2\Delta_{21})-\cos 2\Delta_{31}] \quad (1) \end{aligned}$$

For the inverted hierarchy case, s^2_{12} in the last term is replaced with c^2_{12}. The first and second terms are relevant to θ_{13} and θ_{12} measurements and valid at distances of order 1 km and 100 km, respectively. The third term is small but related to the mass hierarchy and is relevant for distances of the order of a few tens of km. Thus, the reactor experiment can be a pure θ_{13} measurement when a proper baseline (order 1 km) is chosen. Experiments with this baseline have already been performed by CHOOZ and Palo Verde, and the current best limit is obtained from the CHOOZ experiment.[10] Looking at the CHOOZ experiment, the systematic error is dominated by the understanding of reactor neutrinos (1.9% from reactor cross section, 0.7% from reactor power and 0.6% from energy release/fission out of a 2.9% total systematic error). In order to improve the situation, a Near/Far detector system is necessary to cancel these uncertainties. On the other hand, the Palo Verde experiment[11] is dominated by a background estimation error (3.3% out of a 5.3% total error). This is because the Palo Verde site is shallow (32 mwe) and the S/N ratio is only $0.5 \sim 1$. This implies that the site should be as deep as or deeper than the CHOOZ (300 mwe).

Several experiments are proposed to focus on the cancellation of the systematic error with a Near/Far system and reduction of backgrounds by going deeper. The first proposal was from Krasnoyarsk.[12] The site is 600 mwe underground and two 46-ton detectors are located at distances of 115 m and 1000 m from a 1.6 GW reactor. The design value of their systematic error is 0.8% for a rate analysis and 0.5% for a shape analysis. Using a shape analysis, the expected sensitivity is one order of magnitude better than the CHOOZ result.

Another proposal is from Kashiwazaki.[13] Kashiwazaki is the most powerful reactor complex (24.3 GW) in the world. It consists of two clusters of reactor cores. One has 4 cores and another has 3 cores. It plans to have two near detectors for two clusters at $300 \sim 350$ m and one far detector at a distance of about 1300 m. The overburdens are 200 mwe for the near detectors and 400 mwe for the far detector, requiring digging 6 m diameter shafts for each detector. The size of the detector is 8.5 tons. The design value of the systematic error is $0.5 \sim 1\%$ and the expected sensitivity to $\sin^2 2\theta$ is about a factor 7-10 better than the CHOOZ result ($0.15 \rightarrow 0.016 \sim 0.025$ @$\Delta m^2 = 2.6 \times 10^{-3}$eV^2) with 2 years of data taking as shown in Fig. 9. The site use is already permitted and a possible fastest schedule is for data-taking to start in 2007.

The US activities can be found in the References.[14] Site selection is under way and one candidate is "Diablo Canyon Nuclear Power Plant." The key point of their study is a movable far detector to calibrate near/far detectors head to head. The planned start time is the year 2008.

Activities in Europe can be found in the References.[15] Site selection is under way. One different type of experiment is also proposed.[16] It uses a 20-30 km baseline with a big detector (112 tons). An outstanding feature of this experiment appears if the LMA2 is the right solution, $\Delta m^2_{31} < 2.5 \times 10^{-3} eV^2$ and $\sin^2 \theta_{13} > 0.03$. In such a case, the experiment can determine the mass hierarchy with a 125 GW-kt-yr data set.

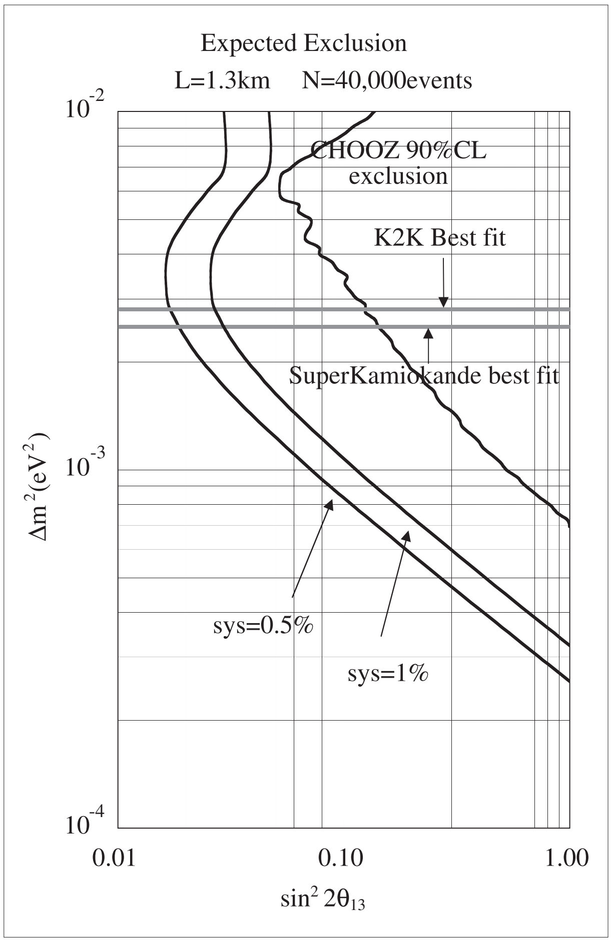

Figure 9. Expected sensitivity of Kashiwazaki experiment with 2 years of data.

4. Search for Neutrino Magnetic Moment

If neutrinos have magnetic moments, their elastic scattering cross section with electrons can be written as follows:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_V + g_A)^2 + (g_V - g_A)^2(1 - \frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{1 - T/E_\nu}{T}. \quad (2)$$

The last term comes from the magnetic moment interaction. The effect of the magnetic moment becomes larger as the recoil energy goes lower. In order to investigate the neutrino magnetic moment, experiments looked for an excess in the low energy recoil. Figure 10 shows the expected differential cross section for the Standard Model weak interaction and for a magnetic moment interaction in the case of

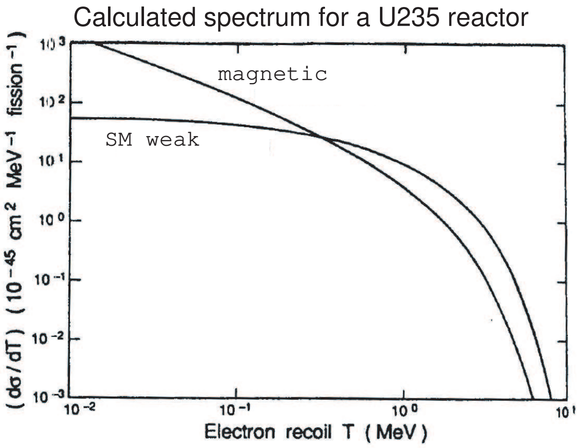

Figure 10. Differential cross section for the Standard Model weak interaction and a magnetic moment interaction with $\mu_\nu = 10^{-10}\mu_B$.

$\mu_\nu = 10^{-10}\mu_B$.

The TEXONO experiment in Taiwan measured the recoil energy spectrum above 5 keV at 28 m from one of the Kuo-Sheng reactors (2×2.9 GW). They used an ultra-low-background high-purity Germanium detector (1.06 kg) with NaI(Tl) and CsI(Tl) anti-Compton detectors. By fitting reactor ON spectra to $\phi_{OFF} + \phi_{SM} + \kappa^2\phi_{MM}[10^{-10}\mu_B]$, they obtained $\kappa^2 = -0.4\pm1.3(stat)\pm0.4(sys)$ and translated the result to a limit on the neutrino magnetic moment of less than $1.3\times10^{-10}\mu_B$ at the 90% confidence level.[17] The sensitivity of the experiment is limited by an uncertainty of the fission neutrino spectra below 1.8 MeV where various long-lived nuclei become significant and no precise estimation is available now.

The MuNu experiment[18] set their analysis threshold at 900 keV which corresponds to a well-understood neutrino energy of $E_\nu > 1.8$ MeV. The effect of the magnetic moment is smaller at this energy and the experiment must have high statistics and be very precise to see the effect. The MuNu experiment uses a 2.75 GW reactor in Bugey and a CF_4 time projection chamber with target mass of 11.4 kg. The experiment can measure the recoil direction and a subtraction of uniform background from the forward direction signal (uniform BG + signal) can be done. They obtained a limit of $\mu_\nu < 1.0 \times 10^{-10}\mu_B$ at the 90% confidence level from 66.6 days of reactor ON data.

5. Summary

KamLAND has observed evidence for reactor neutrino disappearance at a distance of ~180 km at the 99.95% confidence level. Assuming CPT invariance, the result is only compatible with the LMA solution of the neutrino oscillation hypothesis. In a process of elimination, the long-standing solar neutrino problem has been finally solved.

The last unmeasured mixing angle can be explored with reactor experiments down to $\sin^2 2\theta_{13} \sim 0.02$ which is comparable to accelerator long baseline experiments. Reactor experiments are relatively low cost and quicker and are complementary to accelerator experiments when solving the parameter degeneracy. Various possibilities are being discussed and international collaborations are being formed.

Direct searches for the neutrino magnetic moment are extensively performed with reactor neutrinos and the best limit, so far, is $\mu_\nu < 1.0 \times \mu_B$ from MuNu experiment at the 90% confidence level.

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DISCUSSION

Carlos Wagner (Argonne): You mentioned the bound on θ_{13} of 10 degrees. Does the bound include the new Super-Kamiokande result?

Kunio Inoue: No, it does not include the new result.

Hugh Montgomery (Fermilab): This is about the third talk in the last 6 months where the picture is being painted that the next reactor experiment can be built rather quickly. Would you like to comment on the associated running time to get to results.

Kunio Inoue: For Kashiwazaki it is about 2 years. In 2 years, they can accumulate about 40,000 neutrinos in the far detector that corresponds to a 0.5% statistical error and that is good enough to improve the θ_{13} region down to 0.02.

Hugh Montgomery (Fermilab): So that's down to $\sin^2 2\theta$ of 0.02?

Kunio Inoue: Yes.

Luc Declais (IPNL, France): When you compare in an experiment with two or three detector positions like in Japan, you still have to compare detectors that need to be identical but cannot be completely identical. So, it is not as easy to reduce the systematics as it has been quoted in some papers. For example, what is the energy calibration difference needed between two detectors in order to avoid wriggles when you compare spectra?

Kunio Inoue: For the energy calibration you don't set an energy threshold, so it's just the reaction rate and there's no error from the energy calibration. We set the threshold at 1 MeV so we take all data. And for the fiducial volume errors, we don't set a fiducial volume, actually, it is defined by the volume of the scintillating detector. So gadolinium is loaded only in the inner detector and all events that come from that gadolinium are measured, but of course we can't measure like in a far- and near-detector head-to-head comparison, so the largest error comes from their difference and it is about 0.5% as quoted in the proposal.

Luc Declais (IPNL, France): But this is only related to the total number of events. But in order to achieve such low sensitivity for θ_{13}, you need to compare the shape of the energy spectrum you measure, to do so you need to have a very good comparison between the energy calibrations of the detector to another detector.

Kunio Inoue: That's right. In the Krasnoyarsk case, they are going to use the shape but in the Kashiwazaki case, it assumes only systematic errors and if we can use the energy spectrum it will improve. Currently it's probably better to consider this to be a 1% systematic error for a conservative case.

Louis William (LANL): What is the possibility that KamLAND will be able to make a solar neutrino measurement?

Kunio Inoue: Currently we are putting the biggest effort in reducing Krypton-85 and Lead-210. We can reduce Krypton by bubbling it, it is very easy. We know Lead-210 can be reduced by distillation, but it costs a lot. We're still looking at water extraction methods to remove Lead-210. And we think we can eventually detect solar neutrinos.