Reactor neutrino oscillation studies with KamLAND

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Abstract. KamLAND, the 1000 t liquid scintillator detector utilizing nuclear power reactors distributing effectively \( \sim 180 \text{ km} \) from the experimental site, has performed a search for reactor neutrino oscillations. Results obtained from the baseline show evidence for reactor neutrino disappearance, while previous searches at less than 1 km showed consistent flux, as expected. This provides a resolution for the long-standing solar neutrino problem if combined with results from solar neutrino experiments. KamLAND with increased statistics also provided evidence of spectral distortion as expected from the neutrino oscillation and, if converted to the \( L/E \) distribution, it shows clear oscillatory behaviour of neutrino propagation. Consequently, the results have a good sensitivity on neutrino oscillation parameters and a precise determination of \( \Delta m^2 \) has been realized.
1. Introduction

KamLAND has obtained evidence for reactor anti-neutrino disappearance [1] and of its spectral distortion [2]. This paper describes the KamLAND detector and reviews these important breakthroughs in neutrino physics.

Nuclear power reactors are intense $\bar{\nu}_e$ sources and useful for neutrino studies. In fact, the first discovery of neutrino existence was carried out with reactor neutrinos. Since then, vigorous efforts have been made to investigate neutrino properties with nuclear reactors. Knowledge of the intensity of neutrinos and neutrino spectra from nuclear fission has accumulated with various experiments. Theoretical calculations on neutrino cross-section and non-thermal fission neutrino spectra have also been improved along with the experimental progress. Finally, the interaction rate of reactor $\bar{\nu}_e$ has become predictable at a few % level without a near detector for normalization. The baseline of reactor neutrino experiments has then extended [3, 4] to $\sim 1000$ m to look for neutrino oscillations. However, no significant deficit from neutrino oscillations has been observed so far.

In parallel with the progress in reactor neutrino study, the observation of solar neutrinos was started in 1968. The unexpected new problem—that the observed neutrino flux was much smaller than predicted by standard solar models [5]—has not been resolved for more than 30 years. Several experiments followed the solar neutrino observation with various neutrino reactions. In addition to the first radiochemical $^{37}$Cl experiment [6], neutrino–electron elastic scattering in real-time water Cherenkov detectors [7, 8], low reaction threshold $^{71}$Ga radiochemical experiments [9]–[11], and a real-time heavy water Cherenkov detector [12]. All the experiments except for the neutral current measurement of the heavy water experiment have obtained a clear deficit of
neutrino flux. These experiments are purely or mainly sensitive to the $\nu_e$ component while the neutral current measurement is equally sensitive to all neutrino flavours, $\nu_e$, $\nu_\mu$ and $\nu_\tau$. Before the neutral current measurement, the possibility of some deficiency in standard solar model calculations or of unknown neutrino properties have both been forceful arguments. The obtained agreement of the neutral current result with the prediction of standard solar models established flavour transition of neutrinos during their travel from the Sun to the Earth and thus it was found that the deficits were caused by a neutrino property not included in the standard model of elementary particle physics. The most popular hypothesis to explain the deficit was a neutrino oscillation, but other models such as resonant spin flavour precession [13], neutrino decay [14], flavour changing neutral current and so on also remained possibilities at that time. Even assuming the neutrino oscillation hypothesis, one of the oscillation parameters, mass squared difference, could vary by many orders of magnitude from $10^{-10}$ to several $\times 10^{-4}$ eV$^2$. In order to conclude that neutrino oscillation was the right solution and to restrict the allowed oscillation parameter region, a terrestrial neutrino experiment with a well-understood artificial neutrino source was required.

The common important feature of those solar experiments are that the sites are deep underground in order to avoid cosmogenic backgrounds and that detectors are very large to overcome the very small interaction probability of neutrinos. These features are also relevant for reactor neutrino measurements when one wants to extend its baseline. In order to explore the small mass difference region allowed by solar neutrino results, baselines of more than 100 km are necessary. For an experiment with such a baseline, much more powerful reactors, a bigger detector and a deeper underground site were necessary. A new experiment, KamLAND, occupied the location where the former Kamiokande experiment existed. KamLAND is an abbreviation of Kamioka Liquid-scintillator Anti-Neutrino Detector. It holds about 1200 m$^3$ of liquid scintillator and is located 1000 m underground; 80% of reactor neutrino contribution $\sim 5 \times 10^6$ cm$^{-2}$ s$^{-1}$ is coming from reactors distributing 130–220 km away from the detector. Total thermal power output generated over that distance range amounts to 70 GW. It corresponds to 7% of the world total nuclear power generation. Compared with the pioneering ‘Poltergeist’ experiment which first established neutrino existence, LS amount is scaled up from 1400 l to 1200 m$^3$ (1000 times), effective reactor power from 700 MW to 70 GW (100 times), depth from 12 to 1000 m (100 times) and effective distance from 11 m to $\sim 180$ km (more than 10000 times!). These many orders of magnitude extensions became possible by various important improvements on the knowledge of reactor neutrinos by previous experiments. And most importantly, this baseline is the right distance to explore the LMA solution which was the most favourable oscillation parameter with solar neutrino results (see figure 1).

Now, the terrestrial KamLAND experiment using a well-understood artificial neutrino source can explore the oscillation parameters relevant for the phenomena found in the $1.5 \times 10^{11}$ m astronomical-scale distance.

2. Reactor neutrinos

2.1. Neutrino spectra and cross-section

The total power generation of world-wide reactors amounts to $\sim 1.1$ TW and it corresponds to one-third mole $\bar{\nu}_e$ creation per second. These very intense neutrinos are freely available and are really useful if one could find a good location for their measurement.
In the observation of reactor neutrinos, four 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 anti-electron–neutrinos. The purity of the ‘anti’ neutrinos is very high and electron–neutrino contamination is only at the 10 ppm level above an inverse $\beta$ decay threshold, 1.8 MeV. These four nuclei release similar energy when they undergo fission \cite{15} ($^{235}$U $^{201.8 \pm 0.5}$, $^{239}$Pu $^{210.3 \pm 0.6}$, $^{238}$U $^{205.0 \pm 0.7}$ and $^{241}$Pu $^{212.6 \pm 0.7}$ 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 six neutrino emissions on average and, therefore, the neutrino intensity can be roughly estimated to be $\sim 2 \times 10^{20} \bar{\nu}_e \text{GW}^{-1} \text{s}^{-1}$. Fission spectra reach equilibrium within a day above $\sim 2$ MeV. This delay is a possible cause of systematic error. Also, attention to the long-lived nuclei such as

\[
^{106}\text{Ru} \quad ^{T_{1/2}=372 \text{d}} \rightarrow ^{\text{Rh}} \quad ^{E_{\text{max}}=3.541 \text{MeV}} \rightarrow ^{\text{Pd}},
\]

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

is necessary \cite{16}. They affect the correlation between thermal power and neutrino flux at low-energy region by <1% level.

The beta spectra from $^{235}$U, $^{239}$Pu and $^{241}$Pu have been measured with a spectrometer irradiating thermal neutrons at ILL \cite{17}. They fitted the observed beta spectra from 30 hypothetical beta branches and converted each branch to a neutrino spectrum \cite{18}. In the case of $^{238}$U, it does not undergo fission with thermal neutrons and only a theoretical calculation \cite{19} 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 commonly used since ‘Poltergeist’ and subsequent experiments is the inverse \( \beta \) decay:

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

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

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

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

\[
\sigma^{(0)}_{\text{tot}} = \frac{2\pi^2}{f_{\text{p.s.}}^R} \frac{E^{(n)}_e}{\tau_n} P^{(0)}_e.
\]

Recent precise studies on neutrons provided a very accurate lifetime of \( \tau_n = 885.7 \pm 0.8 \text{ s} \) 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) [20]. 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 or \( ^3\text{He} \). It provides clear tagging and very good background discrimination in timing, position and energy. Effective neutrino energy of reactor neutrinos via the inverse decay is about 4 MeV.

The validity of the neutrino spectra and cross-sectional calculations have been experimentally tested. The most accurate measurement has been performed by the Bugey experiment [15]. It measured an overall reaction rate with \( 1.4\% \) accuracy and the result \( \sigma_f = 5.750 \times 10^{-43} \text{ cm}^2 \text{ fission}^{-1} \pm 1.4\% \) was in very good agreement with the calculation \( \sigma_{V-A} = 5.824 \times 10^{-43} \text{ cm}^2 \text{ fission}^{-1} \pm 2.7\% \). The ratio \( \sigma_f/\sigma_{V-A} = 0.987 \pm 1.4\% \pm 2.7\% \). Also, Bugey-3 tested models of neutrino spectra and the ILL ones showed an excellent agreement [21]. Finally, a few % precision became possible without a near detector for flux normalization with the above calculation models and procedures.

2.2. Reactors around the Kamioka site

There are 52 commercial power reactor cores distributed in 16 sites in Japan and the nominal thermal power output 152 GW is 15% of the world total. The reactor complex located at about 160 km from Kamioka site, Kashiwazaki Kariwa, is the world’s strongest reactor and its full thermal power generation is 24.3 GW. A fortunate characteristic of the Kamioka site is that 80% of neutrino contribution comes from 130 to 220 km, the distance relevant for the solar LMA solution.

As described above, the thermal power output has a direct relation with neutrino flux and the accuracy of the thermal power output is currently taken as 2%. Thermal power is measured by temperature change and flow rate of cooling water and the error is dominated by the precision
of the flow meter. While the error is very conservatively taken now, it may be improved in future by investigating properties of flow meters in detail.

In addition, the composition of four fissile nuclei is also important to predict the reactor neutrino spectrum. On burning the fuel, the contribution of four nuclei changes in time, the so-called burn-up effect. This effect is calculable knowing the initial $^{235}\text{U}$ enrichment, fraction of new fuel and history of thermal power output for each reactor core. The systematic error of the neutrino event rate coming from this calculation is much smaller than 1%.

Detailed thermal power history and enrichment information for all the Japanese commercial reactor cores and one of the research cores have been obtained from the companies for the analysis periods, the first result from 4 March to 6 October 2002 and the second result from 9 March 2002 to 11 January 2004. Also histories of electric power output from Korean reactors were obtained (http://www.insc.anl.gov/). Since many reactor cores were inspected in 2003, the expected neutrino signal rate has decreased to $\sim 40\%$ level of 2002 as shown in figure 2. Contribution of Korean and rest-of-the-world reactors over the live time has changed between the analysis periods from 2.5 to 3.4% (Korean) and from 0.7 to 1.1% (rest). But the average fuel composition $^{235}\text{U}$ : $^{238}\text{U}$ : $^{239}\text{Pu}$ : $^{241}\text{Pu}$ changed only slightly from 0.568 : 0.078 : 0.297 : 0.057 to 0.563 : 0.079 : 0.301 : 0.057. These average compositions are used to estimate neutrino spectra from Korean and rest-of-the-world reactors. As the operation pattern changes, the average distance weighted by the expected no-oscillation event rate for reactors up to 400 km is also changed, as shown in figure 2.

Some of the systematic errors discussed in the previous subsection depend on experiment. Considering the observation periods and analysis threshold, KamLAND specific errors are calculated as follows. In addition to 2% thermal power error of Japanese reactor cores, we assigned 10% error for cores with only the electric power history is available (Korean reactors) and 50% error for cores for which only nominal power is known (rest-of-the-world and research reactors) and the combined error from thermal power was estimated to be 2.1%. The effect of time lag from the slow $\beta$ decay component was estimated by sliding the operation time window up to 1 day and was obtained as 0.01% and the effect of $^{106}\text{Ru}$ and $^{144}\text{Ce}$ is less than 0.02% above 2.6 MeV visible energy.

Figure 2. Time variation of expected reactor neutrino event rate at KamLAND and of average distance weighted by event rate for reactors up to 400 km are shown for the data period from March 2002 to January 2004.
The analysis threshold of 2.6 MeV for visible energy increases the error from anti-neutrino spectra from 2.3 to 2.5%. Then, the total systematic error of the anti-neutrino signal rate except for a detector part was obtained as 3.4%.

3. KamLAND detector

3.1. Apparatus

KamLAND is a monolithic liquid-scintillator detector located at longitude $137^\circ18'43.495''$, latitude $36^\circ25'35.562''$ in the Japanese geodetic system 2000 based on international terrestrial reference frame and geodetic reference system 1980. Its altitude is 358 m and it is covered by 2700 m water-equivalent mountain rock under Mt. Ikenoyama (1368 m). As shown in figure 3, the detector contains 1200 m$^3$ liquid scintillator (LS: 1,2,4-trimethylbenzene, 20%; dodecane, 80% and PPO, 1.52 g l$^{-1}$ as a fluor) and 1800 m$^3$ buffer oil (BO: dodecane, 50% and isoparaffin, 50%)
in an 18-m-diameter stainless-steel tank. Free protons in the LS are the $\bar{\nu}_e$ targets. A positron from the inverse $\beta$ decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$) and a 2.2 MeV $\gamma$ ray from the neutron capture on a proton (mean capture time is $\sim 210 \mu s$) make clear a two-fold-delayed-coincidence signal. The LS is suspended by a Kevlar rope network in the BO with a 13-m-diameter spherical balloon made of 135-$\mu$m-thick transparent film (EVOH–Nylon–Nylon–Nylon–EVOH). The buoyancy of the BO is controlled to be slightly (0.04%) lighter than LS to keep the balloon shape. Photons emitted in the detector are monitored by 1325 newly developed 17” tubes and 554 old Kamiokande 20” tubes. While the total photocoverage is 34%, only the 17” tubes corresponding to 22% were used until 27 February 2003. The photon yield of the LS is about 8000 photons MeV$^{-1}$ and the photoelectron yield is $\sim 300$ and $\sim 470$ p.e. MeV$^{-1}$ without and with 20” tubes, respectively. All these PMTs are isolated from the inner region by a 3-mm-thick acrylic sphere at 16.6 m diameter for preventing radon emanation from these materials. The outer detector (OD) is a water Cherenkov detector with 3.2 kt pure water and 225 old Kamiokande 20” tubes for purposes of external background absorption and cosmic-ray muon tag.

3.2. Event trigger

Each phototube is connected to two sets of three range analogue-transient-waveform-digitizers recording whole pulse shape from one to thousands of photoelectrons for about 200 ns. The global event trigger is issued based on the number of hit channels (each channels has about 0.3 p.e. threshold) and currently set at 200 hits corresponding to $\sim 700$ keV. Also a delayed trigger (120 hits, $\sim 400$ keV) is enabled for 1 ms after each global event trigger to perform real-time impurity measurements of uranium and thorium using delayed coincidence events such as

$$\begin{align*}
^{214}\text{Bi} & \rightarrow^{214}\text{Po} (\tau = 237 \mu s) \rightarrow^{210}\text{Pb}. 
\end{align*}$$

The latter $\alpha$ decay is observed with a quench of about a factor 14 and the low threshold delayed trigger is necessary to tag this $\alpha$ decay. The lowest trigger threshold is limited by data size but is sufficiently low for the reactor neutrino analysis (all phenomena have visible energies of more than two electron masses). The OD trigger threshold is set to provide more than 99% muon tagging efficiency.

3.3. Impurity level

The primary target, in reactor neutrino measurements, requires a radioactive impurity level of lower than $10^{-13}$ g g$^{-1}$ for uranium and thorium. The measured impurity level is listed in table 1 together with the requirements. The achieved impurity levels of uranium ($3.5 \pm 0.5 \times 10^{-18}$ g g$^{-1}$) and thorium ($5.2 \pm 0.8 \times 10^{-17}$ g g$^{-1}$), assuming radioactive equilibrium, are much better than the initial requirement and even better than that of the future $^7\text{Be}$ solar neutrino measurement. However, an extra purification of $^{85}\text{Kr}$ and $^{210}\text{Pb}$ (daughter of $^{222}\text{Rn}$) contamination is necessary to start solar neutrino observation in the second stage. Vigorous efforts are being made to develop an efficient purification method and ways to measure their concentration.

3.4. Energy calibrations

Energy calibrations are performed suspending radioactive sources ($^{68}\text{Ge}$: two 511 keV $\gamma$, $^{65}\text{Zn}$: 1.11 MeV $\gamma$, $^{60}\text{Co}$: 1.17 + 1.33 MeV $\gamma$) along the z-axis. Spallation products (neutron,
Table 1. Requirements and achievements of radioactive impurities.

| Impurities | Achievements       | Requirements (reactor) | Requirements (solar) |
|------------|--------------------|------------------------|----------------------|
| 222Rn      | 0.03 µBq m⁻³      | 10⁻¹³ g g⁻¹            | 10⁻¹⁶ g g⁻¹          |
| 238U       | 3.5 ± 0.5 × 10⁻¹⁸ g g⁻¹ | 10⁻¹⁰ g g⁻¹            | 10⁻¹⁸ g g⁻¹          |
| 232Th      | 5.2 ± 0.8 × 10⁻¹⁷ g g⁻¹ | 10⁻¹² g g⁻¹            | 10⁻¹⁷ g g⁻¹          |
| 40K        | <2.7 × 10⁻¹⁶ g g⁻¹ | 10⁻¹⁴ g g⁻¹            | 10⁻¹⁶ g g⁻¹          |
| 85Kr       | ∼1 Bq m⁻³         | 10⁻¹ⁱ g g⁻¹            | 10⁻¹⁷ g g⁻¹          |
| 210Pb      | ∼100 mBq m⁻³      | 10⁻¹⁰ g g⁻¹            | 10⁻¹⁷ g g⁻¹          |

On the balloon

| Impurities | Achievements       | Equiv. mine dust |
|------------|--------------------|------------------|
| 222Rn      | 4.0 × 10⁻⁴ Bq      |                  |
| 238U       | 3.1 × 10⁻⁸ g       | 0.9 g            |
| 232Th      | 9.7 × 10⁻⁴ g       | 0.1 g            |

12B/12N are also utilized to know the behaviour at off z-axis. Neutrons are created at the rate of ∼3000 events (kt-day)⁻¹ and are captured on proton or on 12C (∼0.5%) and provide 2.22 or 4.95 MeV γ. 12B (Q = 13.4 MeV, T₁/₂ = 20.2 ms) and 12N (Q = 17.3 MeV, T₁/₂ = 11.0 ms) are β decays and are produced at the rate of 80 events (kt-day)⁻¹. Fits to the energy distribution and decay time result in the relative contribution of 12N being only ∼1%. These wide range energy calibrations cover up to ∼13 MeV well above the relevant energies of reactor neutrino measurement, 1.0–8.5 MeV as shown in figure 4. Spallation events distribute uniformly both in time and space and are thus very useful to monitor space uniformity and time variation. γ rays (40K and 208Tl) from external material also provides a good monitor of time variations.

The energy resolution achieved so far is 7.3%/√E(MeV) and 6.2%/√E(MeV) with only 17” tubes and with both 17” and 20” tubes, respectively. The observed uniformity of the energy scale with the latest energy estimator is better than 0.3% in 5.5-m-radius fiducial volume and time variation of the scale was controlled within 1.3%. In addition to these wide energy range calibrations, α decays in the Bi–Po chain provide a wide variety of dE/dx and this helped in a detailed study of the quenching effect of LS (thus a linearity study of the energy scale). Extracting dE/dx dependence of photon yield and Cherenkov contribution from these calibrations, a positron energy scale relevant for the reactor neutrino analysis has been made. Finally, the systematic error of the energy scale at the 2.6 MeV threshold was estimated to be 2.0% and the systematic error on the neutrino event rate above 2.6 MeV was then obtained as 2.33%.

3.5. Vertex calibrations

The fiducial cut is applied based on the reconstructed vertices from the relative times of PMT hits. The vertex resolution is ∼23 cm/√E(MeV) and ∼20 cm/√E(MeV) for a point source before and after the 20” PMT inclusion. The vertex reconstruction tool has been tuned using γ ray sources along the z-axis and vertex biases are less than 5 cm in the region −5.5 < z < 5.5 m as shown in figure 5. It corresponds to less than 3% fiducial volume error if one assumes spherical symmetry of the detector. This uniform performance of the vertex fitter together with the energy estimator made it possible to expand the fiducial volume from 5 m radius in the first results [1] to 5.5 m radius in the second results [2] and resulted 33% increase in the number of free target

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protons in the fiducial volume from $3.46 \times 10^{31}$ (408.5 t LS) to $4.61 \times 10^{31}$ (543.7 t LS) taking into account the LS density of 0.780 g cm$^{-3}$ at 11.5° and chemical composition of the LS listed in table 2.

This systematic error was verified with uniformly distributing cosmogenic nuclei ($^{12}$B $\beta$ decays). The number of events observed in the fiducial volume was compared with the total number of events observed in the whole LS volume. The total LS volume has been measured at three independent places during detector filling and resulted in $1171 \pm 25$ m$^3$. The ‘nominal’ 5.5 m radius fiducial volume corresponds to $0.595 \pm 0.013$ of the total LS volume. The number of $^{12}$B events observed in the fiducial volume compared to the whole volume was $0.607 \pm 0.006$ (stat) $\pm 0.006$ (syst), where the systematic error arises from events near the balloon edge that deposit a fraction of their energy outside the LS. Similarly, spallation neutron events were counted for a consistency check and the consistent ratio of $0.587 \pm 0.013$ (stat) was obtained. Since $^{12}$B provides calibration for energy more than 4 MeV, $^8$He/$^9$Li delayed coincidence events ($\beta$ + neutron) were used to relatively extend vertex calibration down to 2.2 MeV. Comparing the radius of each pair of high energy prompt event and 2.2 MeV delayed event, the energy dependence of a possible vertex bias was found to be less than 5 cm in the fiducial volume. The bias corresponds to 2.7% systematic error. Combining errors from the LS volume measurement, $^{12}$B and $^8$He/$^9$Li calibrations, total fiducial volume error was estimated as 4.7%.

Figure 4. Energy calibrations with discrete $\gamma$ rays and $\beta$ decays of $^{12}$B/$^{12}$N are shown. Average energies for multiple $\gamma$ are used for $^{68}$Ge and $^{60}$Co and the horizontal bar for $^{12}$B/$^{12}$N in the bottom panel is the energy range used for the calibration.
Figure 5. Vertex calibrations: (a) vertex biases of source calibrations along the $z$-axis; (b) the $R^3$ distribution of cosmogenic $^{12}$B/$^{12}$N events; (c) the vertex correlation of high-energy prompt and 2.2 MeV $\gamma$ events from $^{8}$He/$^{9}$Li data sample; (d) the $R^3$ distribution of spallation neutron events.

Table 2. Chemical composition of the LS.

| Atoms | Number (kt) | Nuclei | Natural abundance | Number (kt) |
|-------|-------------|--------|-------------------|-------------|
| H     | $8.470 \times 10^{31}$ | $^1$H   | 0.99985           | $8.469 \times 10^{31}$ |
|       | $2H$        | 0.00015 |                   | $1.271 \times 10^{28}$ |
| C     | $4.302 \times 10^{31}$ | $^{12}$C | 0.989             | $4.255 \times 10^{31}$ |
|       | $^{13}$C    | 0.011   |                   | $4.732 \times 10^{29}$ |
| N     | $1.593 \times 10^{28}$ | $^{14}$N | 0.99634           | $1.587 \times 10^{28}$ |
| O     | $7.064 \times 10^{27}$ | $^{16}$O | 0.99762           | $7.074 \times 10^{27}$ |
3.6. Analysis and systematic errors

Detection and tagging efficiencies of delayed coincidence signals are measured by a LED pulser, intensity measurements of radioactive sources, AmBe delayed coincidence signals, and so on. For the specific selection criteria applied in this analysis: (i) a 5.5 m radius fiducial cut for both prompt and delayed, (ii) a time correlation cut (0.5–1000 µs), (iii) a vertex correlation cut (2.0 m), (iv) a delayed energy cut (1.8–2.6 MeV) and (v) a prompt energy cut (2.6–8.5 MeV visible energy), the total efficiency for the reactor neutrino signals was obtained as 89.8 ± 1.5%. A major inefficiency comes from the space correlation at the fiducial edge events (91.3%) because the 5.5 m radius cut is applied for both the prompt and the delayed events. Cuts for the delayed coincidence signal have been extracted from the first results (0.5–660 µs and 1.6 m) to increase the detection efficiency and it reduced the systematic error at the same time, and an 1.2 m radius cylinder cut around z-axis for delayed events applied in the first result is not used in the new analysis. By extracting cuts and extending fiducial volume, accidental background increases rapidly and the selection is not applicable below 2.6 MeV where geo-neutrino signals are expected. The main sources of error are from 210Bi as prompt and 208Tl as delayed events.

The earth has 44 TW heat flow at the surface: 20 TW of it is thought to come from radioactivity in the earth, 16 TW from uranium and thorium and 4 TW from 40K. In U and Th decay chains, there are β decays emitting observable $\bar{\nu}_e$ with inverse decay (1.806 MeV threshold). Their sharp edges at the end-points and their constant flux, independent of thermal power variation of reactors, will be useful to distinguish them if there are enough statistics. Subtraction of geo-neutrino contributions cannot be done blindly using inaccurate predictions. Therefore, the analysis threshold of visible energy, 2.6 MeV, is for now set above the geo-neutrino end-point energy, 2.49 MeV. On the other hand, U and Th contributions can be separately obtained from their characteristic energy spectra when sufficient statistics is acquired. Subtraction of nearby contributions with a radioactivity map will make it possible to investigate the interior of the earth with neutrinos. This is the start of the new field of ‘neutrino geophysics’. The lower threshold covering all $\bar{\nu}_e$ events (0.9 MeV) was also used for a consistency check and for a geo-neutrino search in the first paper. An updated analysis below 2.6 MeV will be presented elsewhere.

There are also two types of correlated backgrounds associating with showering cosmic-ray muons. One is fast neutrons from outside and another is long-lived β-decay-nuclei accompanied by neutron emission in the detector. Fast neutrons from outside are strongly suppressed by multiple layers of absorbers: the OD itself, the 2.5 m of non-scintillating oil surrounding the LS and the 1–1.5 m LS layer outside the fiducial volume. The contribution of fast neutrons is estimated by tagging muons in the OD and looking for a delayed coincidence signal in the ID. Vertices of such events are concentrated close to the wall, and there are very few events entering the fiducial volume. Therefore, the upper limit of the fast neutron background is obtained by considering 8% inefficiency of the OD tagging (number of good OD hits larger than 5), and also estimating contribution of rock penetrating muons by simulation with restriction of the measurement. Long-lived neutron emitter candidates are $^8$He and $^9$Li. Their half-lives are 0.12 and 0.18 s and 16 and 50% of their β decays emit neutrons. The production rate of these nuclei with neutron emission mode was obtained as $\sim$1.5 events (kt-day)$^{-1}$ looking at correlations with preceding muons. From fits to the decay time and β decay spectra of those events, mostly $^9$Li decays (more than 85 at 90% CL) are observed. In order to eliminate these backgrounds, spallation cuts are employed. We apply a 2 ms veto after any muons. For muons with extra energy losses from minimum ionization larger than 10⁶ p.e. on 17" PMTs (∼3 GeV) and for
Table 3. Background summary (number of events).

| Background     | First result, 0.9 MeV       | First result, 2.6 MeV       | Second result, 2.6 MeV     |
|----------------|----------------------------|----------------------------|----------------------------|
| Accidental     | $1.81 \pm 0.08$            | $0.0086 \pm 0.00005$       | $2.69 \pm 0.02$            |
| $^9\text{Li}^9\!	ext{He}$ | $1.1 \pm 1.0$            | $0.94 \pm 0.85$            | $4.8 \pm 0.9$              |
| Fast neutron   | $<0.5$                     | $<0.5$                     | $<0.89$                    |
| Total          | $2.9 \pm 1.1$              | $1 \pm 1$                  | $7.5 \pm 1.3$              |

Table 4. Estimated systematic uncertainties (%) of the new analysis.

| Source              | Uncertainty (%) |
|---------------------|-----------------|
| Fiducial volume     | 4.7             |
| Energy threshold    | 2.3             |
| Cut efficiency      | 1.6             |
| Live time           | 0.06            |
| Total               | 6.5             |

muons tracked with poor reliability, a 2 s veto is additionally applied. For smaller energy losses, the 2 s veto is applied only in the 3 m radius cylinder around the muon track. These spallation cuts caused 11.4% (5 m radius fiducial volume) and 9.7% (5.5 m radius) dead time.

Considering dead time from the spallation cuts, the total live time used for the reactor neutrino analysis became 145.1 days for the first result and 515.1 days for the second result. The total exposures are 162 and 766.3 t-year, respectively. Estimated non-neutrino backgrounds during the periods are summarized in table 3. Accidental backgrounds are estimated by an off-timing window, 10 ms to 20 s, and by swapping the prompt and the delayed selection criteria [4]. Known neutrino backgrounds are small enough except for geoneutrinos in the 0.9 MeV analysis. An earth model with 16 TW heat from uranium and thorium predicts 9 events in the 0.9 MeV threshold sample of the first result.

The estimated systematic uncertainties of the new analysis for the rate analysis above 2.6 MeV are listed in table 4. The total systematic error becomes slightly larger than the previous analysis from 6.4 to 6.5%. The largest systematic error is still the fiducial volume error and it will be improved by future full-volume source calibrations.

4. Results

4.1. Evidence for reactor neutrino disappearance

The expected reactor anti-neutrino event rate for no oscillation and the observed rate during the first result period, from 4 March to 6 October 2002 (162 t-year exposure) are plotted in figure 6. The observed rates are always smaller than the no-oscillation expectation. While the expected number of neutrino events above 2.6 MeV is $86.8 \pm 5.6$ signal events and $1 \pm 1$ background events, only 54 events were observed. The significance of neutrino disappearance calculated with the following formula

$$P = \frac{1}{\sqrt{2\pi\sigma}} \int_0^\infty dx \exp \left( -\frac{(N_{\text{no-osc}} + N_{\text{BG}} - x)^2}{2\sigma^2} \right) \sum_{n=0}^{N_{\text{obs}}} \frac{x^n e^{-x}}{n!}$$

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Figure 6. Reactor neutrino event rate in 2002. The plots and line are the observed and expected event rate, respectively, and the grey hatches are their average. The structure in the expected rate reflects the change in the reactor operations.

is 99.95%, where $N_{\text{no-osc}}$ and $N_{\text{BG}}$ are the mean number of expected signal and background (86.8 and 1, respectively) and $x$ run possibilities constrained by the Gaussian term, $\sigma$ is the systematic and background total error $\sqrt{(86.8 \times 0.064)^2 + 1^2} = 5.66$ and $N_{\text{obs}} (= 54)$ is the observed number of events. The possibility of observing less than 54 events with $x$ expected is integrated for all possible $x$; it gives 0.05% in this case. The ratio of observed to expected number of events is

$$R = \frac{N_{\text{obs}} - N_{\text{BG}}}{N_{\text{no-osc}}} = 0.611 \pm 0.085 \text{ (stat)} \pm 0.041 \text{ (syst)}.$$

The expected signal for the 0.9 MeV threshold is $124.8 \pm 7.5$ events and the background rate is $2.9 \pm 1.1$ events without the uncertain geo-neutrino contribution of $\sim 9$ events. The observed number of signal events (= 86), is consistent with the neutrino disappearance observed above 2.6 MeV. Figure 7 shows the observed ratios of reactor neutrino flux 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. This evidence of neutrino disappearance supports the LMA solution of the solar neutrino problem and all the other oscillation solutions are excluded at 99.95% CL under the CPT invariance. Also the other exotic models (RSFP, neutrino decay, etc) cannot be the leading phenomena of the solar neutrino problem. Adding the KamLAND results to the solar neutrino observations, the solar neutrino problem has been finally solved and the LMA solution is found to be the right one.

The spectrum information in figure 8 helps to shrink the allowed region of the oscillation parameters. An unbinned maximum likelihood method was applied using the following $\chi^2$:

$$\chi^2_{\text{rate+shape}} = \chi^2_{\text{rate}}(\theta, \Delta m^2, N_{\text{BG1\sim2}}, \alpha_{1\sim4}) - 2 \log L_{\text{shape}}(\theta, \Delta m^2, N_{\text{BG1\sim2}}, \alpha_{1\sim4})$$

$$+ \chi^2_{\text{BG}}(N_{\text{BG1\sim2}}) + \chi^2_{\text{distortion}}(\alpha_{1\sim4}),$$

$$\chi^2_{\text{rate}} = \frac{(N_{\text{obs}} - N_{\text{osc}}(\theta, \Delta m^2, \alpha_{1\sim4}) - N_{\text{BG1\sim2}})^2}{\sigma^2_{\text{stat}} + \sigma^2_{\text{syst}}},$$
Figure 7. Observed neutrino rate at various baselines. The bands are for the various LMA parameters and the dotted line is for \((\sin^2 2\theta, \Delta m^2) = \left(0.833, 5.5 \times 10^{-5} \text{eV}^2\right)\). The dashed lines are for no oscillation, the SMA, LOW and VAC solutions and the other hypothesis.

Figure 8. 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.

where \(\theta\) and \(\Delta m^2\) are the oscillation parameters, \(N_{\text{BG1-2}}\) the number of \(^9\text{Li}/^8\text{He}\) backgrounds floated with an constraint of \(\chi^2_{\text{BG}}(N_{\text{BG1-2}})\) term, \(\alpha_{1-4}\) floating parameters to account for the spectral effects of energy scale uncertainty, finite resolution, \(\bar{\nu}_e\) spectrum uncertainty, and fiducial volume error, respectively also constrained by the \(\chi^2_{\text{distortion}}(\alpha_{1-4})\) term. Figure 9 shows the excluded region from the rate analysis and the allowed region from rate + shape analysis with two different threshold data. Only two bands overlap with the LMA region [22] from solar
Figure 9. Excluded region by rate analysis and allowed region by rate + shape analysis from the first result. All regions are shown for a 95% confidence level. The black dot is the best-fit parameter from the rate + shape analysis above 2.6 MeV and the star is from the 0.9 MeV threshold.

observations. Two different thresholds give similar allowed region and it means data below and above 2.6 MeV are consistent with each other. When using data below 2.6 MeV, both uranium and thorium geo-neutrino contributions are treated as free parameters. This is the reason that the allowed region does not shrink with larger statistics in the 0.9 MeV threshold. The best-fit parameters are met at \( (\sin^2 2\theta, \Delta m^2) = (1.0, 6.9 \times 10^{-5} \text{eV}^2) \) with the 2.6 MeV threshold and \( (0.91, 6.9 \times 10^{-5}) \) with the 0.9 MeV threshold. The mass difference is stable but the mixing angle changes easily. There is an excess from the expected reactor spectrum below 2.6 MeV but the statistics is yet insufficient to discuss geo-neutrinos and a thorough background study is necessary.

4.2. Evidence of spectral distortion

The first results shrank the allowed region of oscillation parameters to two bands, LMA1 \( (\Delta m^2 \sim 7 \times 10^{-5} \text{eV}^2) \) and LMA2 \( (\Delta m^2 \sim 1.4 \times 10^{-4} \text{eV}^2) \), but the spectral distortion was not yet significant.

The second result increased the exposure by factor 4.7 \((\times 3.55 \text{ from live time and } \times 1.33 \text{ from expanded fiducial volume})\) from 162 to 766.3 t-year. Also the unusually low reactor operation in 2003 is used to see a correlation between the thermal power flux and neutrino event rate.

The expected number of signals without oscillation above 2.6 MeV \( (E_{\bar{\nu}} = 3.4 \text{ MeV}) \) is 365.2 \( \pm \) 23.7 (syst) and the estimated number of backgrounds is 7.5 \( \pm \) 1.3 while 258 events are
observed. It confirms reactor neutrino disappearance at the 99.995% CL, and the average survival probability during the live time is

$$R = 0.686 \pm 0.044 \text{ (stat)} \pm 0.045 \text{ (syst)}.$$  

The statistical error is already comparable with the systematic error. If the new analysis is applied for the period covered by the first result, the ratio $0.582 \pm 0.069 \text{ (stat)} \pm 0.039 \text{ (syst)}$ is obtained and is in good agreement with the first result.

The data set was divided into five bins according to the expected signal rate without oscillation and the observed number of events was compared with that expected for each set as shown in figure 10. The statistics is not enough to extract the uncorrelated component of $\bar{\nu}_e$ flux to reactor operation and the intercept is consistent with the estimated background rate.

The reactor neutrino spectra obtained with the updated data set is shown in figure 11 together with the lego plot of delayed energy versus prompt energy after all the selections except for the delayed energy cut. Events observed at delayed energy $\sim 5$ MeV are consistent with the probability of neutron capture on $^{12}$C ($\sim 0.5\%$). Three events are observed where $\sim 1.5$ events are expected.

The observed spectrum does not agree with the no-oscillation spectrum at all. The goodness-of-fit was tested by binning the data into 20 equal-probability bins and by calculating the Pearson-$\chi^2$ statistic for the data. The method helps to avoid the difficulty of treating small statistics bins. The $\chi^2_P$ was calculated for the scaled no-oscillation spectrum to see the statistical significance of

**Figure 10.** A plot of the observed $\bar{\nu}_e$ event rate versus no-oscillation expectation. The dashed line is the best linear fit, the grey region is the associated 90% CL. The solid line shows a fit constrained to the expected background at zero reactor anti-neutrino flux. The inset shows a division of the data set into five bins.
the spectral distortion. Then, the probability of exceeding the observed $\chi^2_P$, the goodness-of-fit was estimated by MC simulation. The $\chi^2$ of the scaled no-oscillation is 43.4 with 19 d.o.f. and the goodness-of-fit is only 0.1%. This means the no-oscillation is excluded at 99.9% CL with only spectral shape information. This is evidence of spectral distortion. Considering the significance of deficit of 99.995%, no-oscillation is excluded at a great confidence level.

The obtained spectral distortion can be well reproduced by a neutrino oscillation. The best-fit oscillation parameter was surveyed using the unbinned method, the same way as with the first result but adding new background term for non-negligible accidental events. The best-fit values for $\Delta m^2$ and $\tan^2 \theta$ are $8.3 \times 10^{-5}$ eV$^2$ and 0.41, respectively. If the flux is scaled freely, the best-fit parameter of a shape-only analysis gives $\Delta m^2 = 8.3 \times 10^{-5}$ eV$^2$ and $\tan^2 \theta = 0.78$. The allowed region of the oscillation parameter is mostly determined by the shape information and an addition of rate information does not change the sensitivity very much. The best-fit oscillation spectrum is also shown in figure 11, and the $\chi^2_P$ and the goodness-of-fit of the best-fit spectrum are 18.3 with 18 d.o.f. and 42%. The oscillation spectrum explains the observed spectral distortion very well.

The goodness of the oscillation hypothesis can be seen more easily with a $L/E$ plot as shown in figure 12. The energy spectrum is rebinned according to $L_0$ over $E_{\bar{\nu}_e} \sim E_{\text{prompt}} + 0.8$ MeV where the constant $L_0$ is chosen at 180 km as a relevant distance. The observed oscillatory behaviour agrees very well with the expected pattern from the best-fit oscillation parameters.
Figure 12. The ratio of observed event rate to no-oscillation expectation is plotted as a function of $L_0/E_{\bar{\nu}_e}$. The energy spectrum is rebinned according to $L_0$ over $E_{\bar{\nu}_e}$ and the constant $L_0$ is chosen at 180 km as a relevant distance. Histograms are for the best-fit-oscillation, decay and decoherence considering real distance distribution of reactors and detector responses. Only the dashed sine curve represents oscillatory behaviour for the best-fit oscillation parameter as if only one reactor existed at a 180 km distance. Results from previous short baseline experiments are also plotted.

as shown by the green solid histogram in the figure. It clearly shows about one full phase of the oscillation. The oscillatory behaviour is compared with a neutrino decay model [23] and a decoherence model [24]. Surveys of parameter spaces resulted in the best-fit parameters of decay and decoherence as $(\sin^2\theta, m/c\tau) = (1.0, 0.011 \text{ MeV km}^{-1})$ and $(\sin^2 2\theta, \gamma^0) = (1.0, 0.028 \text{ MeV km}^{-1})$, respectively. The expected $L/E$ dependences of these parameters are also plotted in figure 12. Their monotonically decreasing ratio does not agree with the observed oscillatory pattern, and the goodness-of-fit for these parameters using the Pearson-$\chi^2$ are only 5% ($\chi^2_\text{d.o.f.} = 30.1/18$) for decay and 6% ($\chi^2_\text{d.o.f.} = 28.6/18$) for decoherence. Naively considering $\Delta \chi^2$ from the oscillation ($\chi^2_\text{d.o.f.} = 18.3/18$), the oscillation is favoured over decay and decoherence more than 99% level. Now, KamLAND alone can conclude the observation of neutrino oscillation without a help of solar neutrino results and an assumption of CPT invariance.

4.3. Measurement of neutrino oscillation parameters

The allowed region of two neutrino oscillation parameters from the updated data set is shown in figure 13. Comparing with the first result, the precision of the parameter determination has been significantly improved. The allowed region from solar neutrino results shown in the figure uses the neutrino flux from BP2004 [5]. The best-fit point from KamLAND is $(\sin^2 2\theta, \Delta m^2) = (0.83, 8.3 \times 10^{-5} \text{ eV}^2)$ and sits in the LMA1 region. Maximal mixing of the LMA1 region is allowed at the 79% CL. The LMA2 region barely appears at the 99.73% CL (allowed at the 99.6% CL) while the LMA0 is allowed at the 94% CL.
In order to see the dark side of the oscillation parameters, the allowed region is plotted on the $\Delta m^2$ versus $\tan^2 \theta$ space in figure 14. A small asymmetry seen between the light side and the dark side in the figure comes from the matter effect during a neutrino propagation. A constant matter density 2.7 of g cm$^{-3}$ was used in the analysis. The best-fit has been obtained in the light side but the difference with the local minimum in the dark side is very small.

Assuming the CPT invariance, KamLAND result and the solar global analysis can be combined. Figure 15 shows the allowed region from the solar + KamLAND global analysis. There is only one region allowed at 99.73% CL and the parameter space is very much scaled up in the figure. The measured value of the two neutrino oscillation parameters are $\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}$ eV$^2$ and $\tan^2 \theta = 0.40^{+0.07}$. The sensitivity in $\Delta m^2$ is dominated by the observed spectral distortion in KamLAND while the mixing angle is mainly constrained by the solar neutrino results. Further improvement of the precision of the neutrino oscillation parameters will require an improvement of the systematic error already larger than the statistical error in KamLAND.

5. Overlooked background

In a survey of possible background sources, various neutron-producing reactions such as photon-neutron production, spontaneous fission, neutral current interaction of atmospheric neutrinos,
Figure 14. Allowed region of neutrino oscillation parameters from the second result. Horizontal axis is now $\tan^2 \theta$ and the dark side ($\tan^2 \theta > 1$) is also shown.

Figure 15. Allowed region of neutrino oscillation parameters from the solar + KamLAND global analysis. The global best-fit point with 1σ error is $(\tan^2 \theta, \Delta m^2) = (0.40^{+0.09}_{-0.07}, 8.2^{+0.6}_{-0.5} \times 10^{-5} \text{eV}^2)$. 
deuteron disintegration by solar neutrinos and \((\alpha, n)\) interactions were additionally investigated. And it turned out that the previously unnoticed background from \(^{13}\text{C}(\alpha, n)^{16}\text{O}(*)\) is not negligible \([25]\).

A number of \(^{222}\text{Rn}\) have decayed in the liquid scintillator before the experiment starts and long-lived \(^{210}\text{Pb}\) (\(T_{1/2} = 22.3\ \text{yr}\)) have accumulated in the detector. Daughter nuclei, \(^{210}\text{Po}\) (\(T_{1/2} = 138.4\ \text{d}\)), are almost in equilibrium with \(^{210}\text{Pb}\) and they emit 5.3 MeV \(\alpha\)-rays. The natural abundance of \(^{13}\text{C}\) is only 1.1\% but neutrons are created with \(Q = 2.2\ \text{MeV}\) at a probability of about one per 10 million \(\alpha\) decays. Neutron energy ranges from 0 to 7.5 MeV depending on the final states of \(^{16}\text{O}\). Hard recoil of a proton by neutron elastic scattering has the possibility of faking a prompt event of the neutrino signal although the quenching effect of the liquid scintillator makes the visible energy very low and mostly subthreshold. A \(^{12}\text{C}(n, n')^{12}\text{C}^*(4.44\ \text{MeV}, 2^+)\) reaction, if it took place successively, could make a 4.4 MeV \(\gamma\) ray as a prompt signal from the decay of the excited state. Also internal pair conversion of \(^{16}\text{O}^*(6.05\ \text{MeV}, 0^+)\) and \(\gamma\) ray emission from \(^{16}\text{O}^*(6.13\ \text{MeV}, 3^-)\) effectively mimic the prompt signal. Considering these reactions, a preliminary background estimation of about 10 events in the 5.5 m radius fiducial volume has been obtained. Their effect on the oscillation parameter determination was tested with the global analysis and the result did not change much as shown in figure 16. The allowed region slightly shifted to smaller \(\Delta m^2\).

\section*{Figure 16.} Preliminary allowed region of neutrino oscillation parameters from the solar + KamLAND global analysis. A preliminary estimation of previously unnoticed background \(^{13}\text{C}(\alpha, n)\) is included. The result does not change much but the best fit \(\Delta m^2\) moves a little downward.

\[\Delta m^2 \times 10^{-5} \quad \Delta m^2 \text{ (eV}^2) \]

\[\tan^2 \theta \quad \text{tan}^2 \theta \]

\[\text{KamLAND + Solar} \]

\[\text{95\% C.L.} \]

\[\text{99\% C.L.} \]

\[\text{99.73\% C.L.} \]

\[\text{global best fit} \]

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### 6. Summary

KamLAND first observed evidence of reactor neutrino disappearance at $\sim 180$ km baseline. It excluded all but the LMA solution of the solar neutrino problem, which has lasted for more than 30 years. Improved analysis and increased run time provided 4.7 times larger exposure and the significance of the reactor neutrino disappearance was strengthened to 99.995% CL. In addition, the scaled no-oscillation spectrum was excluded at the 99.9% CL and the observed $L/E$ distribution matches very well with the expected oscillatory behaviour of the neutrino oscillation. This evidence of spectral distortion can conclude the observation of neutrino oscillation by KamLAND alone. Combining the great sensitivity of KamLAND in $\Delta m^2$ with the solar neutrino results, the neutrino oscillation parameters have been determined to drastically improved value $(\tan^2 \theta, \Delta m^2) = (0.40^{+0.09}_{-0.07}, 8.2^{+6.6}_{-3.5} \times 10^{-5}$ eV$^2$). A terrestrial experiment using a well-understood artificial neutrino source has finally confirmed the neutrino oscillations suggested by the solar neutrino experiments and provided a resolution of the long-standing solar neutrino problem, and it has now entered a precision measurement of the neutrino oscillation parameters.

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