Precision Measurement of Neutrino Oscillation Parameters with KamLAND


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The KamLAND experiment has determined a precise value for the neutrino oscillation parameter \( \Delta m^2_{12} \) and stringent constraints on \( \theta_{12} \). The exposure to nuclear reactor antineutrinos is increased almost fourfold over previous results to \( 2.44 \times 10^{32} \) proton yr due to longer livetime and an enlarged fiducial volume. An undistorted reactor \( \bar{\nu}_e \) energy spectrum is now rejected at >5\sigma. Analysis of the reactor spectrum above the inverse beta decay energy threshold, and including geoneutrinos, gives a best fit at \( 7.58^{+0.14}_{-0.13}(\text{stat})^{+0.17}_{-0.15}(\text{syst}) \times 10^{-5} \) eV\(^2\) and \( \tan^2 \theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat})^{+0.08}_{-0.10}(\text{syst}) \). Local \( \Delta \chi^2 \) minima at higher and lower \( \Delta m^2_{12} \) are disfavored at >4\sigma. Combining with solar neutrino data, we obtain \( \Delta m^2_{12} = 7.59^{+0.21}_{-0.21} \times 10^{-5} \) eV\(^2\) and \( \tan^2 \theta_{12} = 0.47^{+0.06}_{-0.05} \).

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Experiments studying atmospheric, solar, reactor, and accelerator neutrinos provide compelling evidence for neutrino mass and oscillation. The Kamioka Liquid scintillator Antineutrino Detector (KamLAND) investigates neutrino oscillation parameters by observing electron antineutrinos (\( \bar{\nu}_e \)) emitted from distant nuclear reactors. Previously, KamLAND announced the first evidence of \( \bar{\nu}_e \) disappearance [1], followed by direct evidence for neutrino oscillation by observing distortion of the reactor \( \bar{\nu}_e \) energy spectrum [2]. More recently, KamLAND showed the first indication of geologically produced antineutrinos (geoneutrinos) from radioactive decay in the Earth [3], possibly a unique tool for geology.

This Letter presents a precise measurement of \( \Delta m^2_{12} \) and new constraints on \( \theta_{12} \) based on data collected from March 9, 2002 to May 12, 2007, including data used earlier [1,2]. We have enlarged the fiducial volume radius from 5.5 to 6 m and collected significantly more data; the total exposure is \( 2.44 \times 10^{32} \) proton yr (2881 ton yr). We have expanded the analysis to the full reactor energy spectrum and reduced the systematic uncertainties in the number of target protons and the background. We now observe almost

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two complete oscillation cycles in the $\bar{\nu}_e$ spectrum and extract more precise values of the oscillation parameters.

KamLAND is at the site of the former Kamiokande experiment at a depth of $\sim$2700 m water equivalent. The heart of the detector is 1 kton of highly purified liquid scintillator (LS) enclosed in an EVOH/nylon balloon suspended in purified mineral oil. The LS consists of 80% dodecane, 20% pseudocumene, and 1.36 ± 0.03 g/l of PPO [4]. The antineutrino detector is inside an 18-m-diameter stainless steel sphere. An array of 1879 50-cm-diameter photomultiplier tubes (PMTs) is mounted on the inner surface of the sphere. A subset of 554 PMTs are used from the Kamiokande experiment, while the remaining 1325 PMTs are a faster version masked to 17 inches. A 3.2-kton cylindrical water-Cherenkov outer detector (OD), surrounding the containment sphere, provides shielding and operates as an active cosmic-ray veto detector.

Electron antineutrinos are detected via inverse $\beta$-decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, with a 1.8 MeV threshold. The prompt scintillation light from the $e^+$ gives a measure of the $\bar{\nu}_e$ energy, $E_{e^+} \approx E_p + E_n + 0.8$ MeV, where $E_p$ is the prompt event energy including the positron kinetic and annihilation energy, and $E_n$ is the average neutron recoil energy, $O(10$ keV). The mean neutron capture time is 207.5 ± 2.8 $\mu$s. More than 99% capture on free protons, producing a 2.2 MeV $\gamma$ ray.

KamLAND is surrounded by 55 Japanese nuclear power reactor units, each an isotropic $\bar{\nu}_e$ source. The reactor operation records, including thermal power generation, fuel burnup, and exchange and enrichment logs, are provided by a consortium of Japanese electric power companies. This information, combined with publicly available world reactor data, is used to calculate the instantaneous fission rates using a reactor model [5]. Only four isotopes contribute significantly to the $\bar{\nu}_e$ spectra; the ratios of the fission yields averaged over the entire data taking period are: $^{235}$U:$^{238}$U:$^{239}$Pu:$^{241}$Pu = 0.570:0.078:0.295:0.057. The emitted $\bar{\nu}_e$ energy spectrum is calculated using the $\bar{\nu}_e$ spectra inferred from Ref. [6], while the spectral uncertainty is evaluated from Ref. [7]. We also include contributions from the long-lived fission daughters $^{90}$Sr, $^{106}$Ru, and $^{144}$Ce [8].

We recently commissioned an “off-axis” calibration system capable of positioning radioactive sources away from the central vertical axis of the detector. The measurements indicate that the vertex reconstruction systematic deviations are radius- and zenith-angle-dependent, but smaller than 3 cm and independent of azimuthal angle. The fiducial volume (FV) is known to 1.6% uncertainty up to 5.5 m using the off-axis calibration system. The position distribution of the $\beta$-decays of muon-induced $^{12}$B/$^{12}$N confirms this with 4.0% uncertainty by comparing the number of events inside 5.5 m to the number produced in the full LS volume. The $^{12}$B/$^{12}$N event ratio is used to establish the uncertainty between 5.5 and 6 m, resulting in a combined 6-m-radius FV uncertainty of 1.8%.

Off-axis calibration measurements and numerous central-axis deployments of $^{60}$Co, $^{68}$Ge, $^{203}$Hg, $^{65}$Zn, $^{241}$Am$^\text{m}$Be, $^{137}$Cs, and $^{210}$Po$^{137}$C radioactive sources established the event reconstruction performance. The vertex reconstruction resolution is $\sim 12$ cm/$\sqrt{E(\text{MeV})}$, and the energy resolution is 6.5%/$\sqrt{E(\text{MeV})}$. The scintillator response is corrected for the nonlinear effects from quenching and Cherenkov light production. The systematic variation of the energy reconstruction over the data set give an absolute energy-scale uncertainty of 1.4%; the distortion of the energy scale results in a 1.9% uncertainty on $\Delta m^2_{21}$, while the uncertainty at the analysis threshold gives a 1.5% uncertainty on the event rate. Table I summarizes the systematic uncertainties. The total uncertainty on $\Delta m^2_{21}$ is 2.0%, while the uncertainty on the expected event rate, which primarily affects $\theta_{12}$, is 4.1%.

For the analysis, we require 0.9 MeV $< E_d < 8.5$ MeV. The delayed energy, $E_d$, must satisfy 1.8 MeV $< E_d < 2.6$ MeV or 4.0 MeV $< E_d < 5.8$ MeV, corresponding to the neutron-capture $\gamma$ energies for $p$ and $^{137}$Cs, respectively. The time difference ($\Delta T$) and distance ($\Delta R$) between the prompt event and delayed neutron capture are selected to be 0.5 $\mu$s $< \Delta T < 1000$ $\mu$s and $\Delta R < 2$ m. The prompt and delayed radial distance from the detector center ($R_p$, $R_d$) must be $< 6$ m.

Accidental coincidences increase near the balloon surface ($R = 6.5$ m), reducing the signal-to-background ratio. We use constraints on event characteristics to suppress accidental backgrounds while maintaining high efficiency. We construct a probability density function (PDF) for accidental coincidence events, $f_{acc}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$, by pairing events in a 10- to 20-s delayed-coincidence window. A PDF for the $\bar{\nu}_e$ signal, $f_{\bar{\nu}_e}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$, is constructed from a Monte Carlo simulation of the prompt and delayed events using the measured neutron capture time and detector response. For the $E_p$ distribution in $f_{\bar{\nu}_e}$, we choose an oscillation-free reactor spectrum including a contribution from geoneutrinos estimated from Ref. [9]. A discriminator value, $L = \sum_{i=1}^{n} \frac{f_{\bar{\nu}_e}}{f_{\nu} + f_{acc}}$, is calculated for each candidate pair that passes the earlier cuts. We establish a selection value $L^{\text{cut}}_i$ in $E_p$ bins of 0.1 MeV, where $L^{\text{cut}}_i$ is the value of $L$ at which the figure-of-merit, $\frac{1}{\sqrt{S_i + R_i}}$, is maximal. $S_i$ is the

| Table I. Estimated systematic uncertainties relevant for the neutrino oscillation parameters $\Delta m^2_{21}$ and $\theta_{12}$. |
|-----------------|-----------------|-----------------|
| Detector-related (%) | Reactor-related (%) |
| $\Delta m^2_{21}$ | Energy scale | 1.9 | $\bar{\nu}_e$-spectra [7] | 0.6 |
| Event rate | Fiducial volume | 1.8 | $\bar{\nu}_e$-spectra | 2.4 |
| | Energy threshold | 1.5 | Reactor power | 2.1 |
| | Efficiency | 0.6 | Fuel composition | 1.0 |
| | Cross section | 0.2 | Long-lived nuclei | 0.3 |

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that there are /0.0133 introduced into the LS during construction. We estimate /0.0015 state and 20% for the excited states. Accounting for decay-rate, we assign an uncertainty of 11% for the ground

number of Monte Carlo signal events in the i'th energy bin with $L > L_{\text{cut}}^i$, $B_i$ is calculated similarly using the accidental coincidence event pairs. The choice of the $E_p$ distribution in $f_{\nu_e}$ affects only the discrimination power of the procedure; substituting the oscillation-free reactor spectrum by an oscillated spectrum with the parameters from Ref. [2] changes our oscillation parameter results by less than 0.2σ. The selection efficiency $\epsilon(E_p)$ is estimated from the fraction of selected coincidence events relative to the total generated in $R < 6$ m in the simulation, see Fig. 1 (top).

The dominant background is caused by $^{13}$C$(\alpha, n)^{16}$O reactions from $\alpha$-decay of $^{210}$Po, a daughter of $^{222}$Rn introduced into the LS during construction. We estimate that there are $(5.56 \pm 0.22) \times 10^9$ $^{210}$Po $\alpha$-decays. The $^{13}$C$(\alpha, n)^{16}$O reaction results in neutrons with energies up to 7.3 MeV, but most of the scintillation energy spectrum is quenched below 2.7 MeV. In addition, $^{12}$C$(n, n')^{12}$C$_s^*$, and the 1st and 2nd excited states of $^{16}$O produce signals in coincidence with the scattered neutron but the cross sections are not known precisely. A $^{210}$Po$^{13}$C source was employed to study the $^{13}$C$(\alpha, n)^{16}$O reaction and tune a simulation using the cross sections from Refs. [10,11]. We find that the cross sections for the excited $^{16}$O states from Ref. [10] agree with the $^{210}$Po$^{13}$C data after scaling the 1st excited state by 0.6; the 2nd excited state requires no scaling. For the ground state, we use the cross section from Ref. [11] and scale by 1.05. Including the $^{210}$Po decay-rate, we assign an uncertainty of 11% for the ground state and 20% for the excited states. Accounting for $\epsilon(E_p)$, there should be 182.0 ± 21.7 $^{13}$C$(\alpha, n)^{16}$O events in the data.

To mitigate background arising from the cosmogenic beta delayed-neutron emitters $^9$Li and $^8$He, we apply a 2 s veto within a 3-m-radius cylinder around well-identified muon tracks passing through the LS. For muons that deposit a large amount of energy or cannot be tracked, we apply a 2 s veto of the full detector. We estimate that 13.6 ± 1.0 events from $^9$Li/$^8$He decays remain by fitting the time distribution of identified $^9$Li/$^8$He since the prior muons. Spallation-produced neutrons are suppressed with a 2 ms full-volume veto after a detected muon. Some neutrons are produced by muons that are not detected by the OD or miss the OD but interact in the nearby rock. These neutrons can scatter and capture in the LS, mimicking the $\bar{\nu}_e$ signal. We also expect background events from atmospheric neutrinos. The energy spectrum

![FIG. 1 (color). Prompt event energy spectrum of $\bar{\nu}_e$ candidate events. All histograms corresponding to reactor spectra and expected backgrounds incorporate the energy-dependent selection efficiency (top panel). The shaded background and geo-neutrino histograms are cumulative. Statistical uncertainties are shown for the data; the band on the blue histogram indicates the event rate systematic uncertainty.](image1)

![FIG. 2 (color). Allowed region for neutrino oscillation parameters from KamLAND and solar neutrino experiments. The side-panels show the $\Delta \chi^2$-profiles for KamLAND (dashed line) and solar experiments (dotted line) individually, as well as the combination of the two (solid line).](image2)

<table>
<thead>
<tr>
<th>TABLE II. Estimated backgrounds after selection efficiencies.</th>
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<tbody>
<tr>
<td><strong>Background</strong></td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Accidentals</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
</tr>
<tr>
<td>Fast neutron &amp; Atmospheric $\nu$</td>
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<tr>
<td>$^{13}$C$(\alpha, n)^{16}$O$_s, np \rightarrow np$</td>
</tr>
<tr>
<td>$^{13}$C$(\alpha, n)^{16}$O$_s,^{12}$C$(n, n')^{12}$C$_s^*$ (4.4 MeV $\gamma$)</td>
</tr>
<tr>
<td>$^{13}$C$(\alpha, n)^{16}$O 1st exc. state (6.05 MeV e$^+ e^-$)</td>
</tr>
<tr>
<td>$^{13}$C$(\alpha, n)^{16}$O 2nd exc. state (6.13 MeV $\gamma$)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
We observe 1609 events. The histogram and curve show the expectation account-
probability bins of the best fit including all backgrounds (see Fig. 1). The accidental coincidence background above 0.9 MeV are assessed with a maximum likelihood fit to two-flavor neutrino oscillation (with \( \theta_{13} = 0 \)), simultaneously fitting

The calculated \( \frac{L_0}{E} \) fluxes for U and Th-decay, including neutrino oscillation is excluded at more than 5\( \sigma \). An independent analysis using cuts similar to Ref. [2] gives \( \Delta m^2_{21} = 7.66^{+0.22}_{-0.20} \times 10^{-5} \text{ eV}^2 \) and \( \tan^2 \theta_{12} = 0.52^{+0.16}_{-0.06} \) for \( \tan^2 \theta_{12} < 1 \). A scaled reactor spectrum with no distortion from neutrino oscillation is excluded at more than 4\( \sigma \). For three-neutrino oscillation, the data give the same result for \( \Delta m^2_{21} \), but a slightly larger uncertainty on \( \theta_{12} \). Incorporating the results of SNO [16] and solar flux experiments [17] in a two-neutrino analysis with KamLAND assuming CPT invariance, gives \( \Delta m^2_{21} = 7.59^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2 \) and \( \tan^2 \theta_{12} = 0.47^{+0.06}_{-0.05} \).

The allowed contours in the neutrino oscillation parameter space, including \( \Delta \chi^2 \)-profiles, are shown in Fig. 2. Only the so-called LMA-I region remains, while other regions previously allowed by KamLAND at \( \sim 2.2 \sigma \) are disfavored at more than 4\( \sigma \).

The KamLAND data, together with the solar \( \nu \) data, set an upper limit of 6.2 TW (90% C.L.) for a \( \bar{\nu}_e \) reactor source at the Earth’s center [19], assuming that the reactor produces a spectrum identical to that of a slow neutron artificial reactor.

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![FIG. 3 (color). Ratio of the background and geoneutrino-subtracted \( \bar{\nu}_e \) spectrum to the expectation for no-oscillation as a function of \( \frac{L_0}{E} \). \( L_0 \) is the effective baseline taken as a flux-weighted average (\( L_0 = 180 \text{ km} \)). The energy bins are equal probability bins of the best fit including all backgrounds (see Fig. 1). The histogram and curve show the expectation accounting for the distances to the individual reactors, time-dependent flux variations, and efficiencies. The error bars are statistical only and do not include, for example, correlated systematic uncertainties in the energy scale.](221803-4)
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[4] Previous publications incorrectly indicated 1.52 g/l of PPO.