KamLAND (Anti-Neutrino Status)

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Abstract. The KamLAND experiment is a long baseline experiment, designed to explore the neutrino oscillation of $\bar{\nu}_e$’s from reactors, at a flux-weighted average distance of 180 km. The sensitivities to oscillation parameters are much improved with enhanced statistics of 2881 ton-yr data set, added data lowering the energy threshold, and suppressed systematic uncertainties. As a result, we firmly established the spectral distortion of reactor $\bar{\nu}_e$’s at $>5\sigma$, and other hypotheses for neutrino disappearance, neutrino decay and decoherence, are strongly disfavored.

1. Introduction

The KamLAND experiment searched for the neutrino oscillation of $\bar{\nu}_e$’s emitted from distant power reactors. Previously, KamLAND revealed a significant deficit of $\bar{\nu}_e$’s and excluded all solar neutrino solutions but the LMA solution assuming CPT invariance [1], followed by direct evidence of spectral distortion of the reactor $\bar{\nu}_e$’s above the neutrino energy 3.4 MeV [2]. In this report, we have extended the analysis down to the energy threshold of inverse $\beta$-decay ($\bar{\nu}_e + p \rightarrow e^+ + n$), and suppressed the systematic and background uncertainties. The exposure to reactor $\bar{\nu}_e$’s is almost 4 times over previous results owe to the more data collection and the enlarged fiducial volume radius from 5.5 m to 6 m. These improvements contributed the precise measurement of neutrino oscillation parameters.

2. Efficiency and systematic uncertainties

Electron anti-neutrino events are selected by the delayed coincidence. Prompt scintillation light from the $e^+$ gives information on the incident $\bar{\nu}_e$ energy, $E_{\bar{\nu}_e} \simeq E_p + E_n + 0.8$ MeV, where $E_p$ is the prompt event energy including the positron kinetic energy and the annihilation energy, and $E_n$ is the average neutron recoil energy. Neutron capture on hydrogen emits a 2.2 MeV $\gamma$-ray with $\sim 200$ $\mu$s delay and is a powerful tool for reducing backgrounds.

The detection efficiency and its uncertainties are evaluated with MC simulations. The anti-neutrino selection is based on the discriminator $L = \frac{f_{\bar{\nu}_e}}{f_{\bar{\nu}_e} + f_{\text{acc}}}$, where $f_{\bar{\nu}_e}$ and $f_{\text{acc}}$ are probability density function (PDF) for $\bar{\nu}_e$ signals and accidental backgrounds, as a function of prompt and delayed energies, space and time correlation, radial distances from the detector center ($E_p$, $E_d$, $\Delta R$, $\Delta T$, $R_p$, $R_d$). For the discrimination of accidental backgrounds, we determined a selection value $L_{\text{cut}}(E_p)$ to get the maximal figure of merit $\frac{S}{\sqrt{S+B_{\text{acc}}}}$ for each prompt energy interval of 0.1 MeV. We evaluated the efficiency uncertainties by comparing MC simulations with the $^{68}\text{Ge}$ and $^{241}\text{Am}^{9}\text{Be}$ calibration data. Table 1 summarizes the systematic uncertainties on the expected event rate of reactor $\bar{\nu}_e$’s, and the overall uncertainty is 4.1%. The fiducial volume uncertainty
Figure 1. Energy spectrum of the observed prompt events, along with the expected no oscillation spectrum and best-fit including neutrino oscillations. The detection efficiency has an energy dependence as shown in the top panel.

1.8% was significantly improved over the previous result [2], because we confirmed the vertex reconstruction bias was less than 3 cm established by a new ”off-axis” calibration system.

Table 1. Estimated systematic uncertainties on the expected event rate of reactor $\bar{\nu}_e$'s.

| Detector-related (%) | Reactor-related (%) |
|---------------------|---------------------|
| Fiducial volume     | $\bar{\nu}_e$-spectra | 2.4 |
| Energy scale        | Reactor power        | 2.1 |
| L-selection eff.    | Fuel composition     | 1.0 |
| Cross section       | Long-lived nuclei    | 0.3 |
| total               | total               | 3.3 |

3. Results

3.1. Oscillation analysis

The data presented in this report were collected from March 9, 2002 through May 12, 2007, including the reanalysis of the data used in earlier results [1, 2]. In the absence of anti-neutrino disappearance, we expect $2179 \pm 89$ (syst) events from all reactors and $276.1 \pm 23.5$ events from backgrounds [3], and we observed 1609 events. The oscillatory energy spectrum of the data is inconsistent with the expected no oscillation shape. From the $\chi^2$ test in $0 < E_p < 8.5$ MeV, the no spectral distortion is excluded at more than $5\sigma$ considering the background and systematic uncertainties.

The expected no oscillation spectrum and the best fit of oscillation spectrum are shown in Figure 1. The oscillation evaluation is based on the maximum likelihood method considering background and systematic uncertainties. The geo neutrino contributions from U and Th-decays are treated as free parameters to avoid uncertainties from geology. The best-fit for $\Delta m_{21}^2$ and $\tan^2 \theta_{12}$ are $7.58^{+0.21}_{-0.20} \times 10^{-5}$ eV$^2$ and $0.56^{+0.14}_{-0.09}$ if $\tan^2 \theta_{12} < 1$. To illustrate oscillatory behavior of the data, the $L_0/E$ distribution is shown in Figure 2. The two alternate hypotheses for neutrino disappearance, neutrino decay [4] and neutrino decoherence [5], give different $L_0/E$ dependence. The minimum $\chi^2$ of decay and decoherence are 34.5 and 45.1 larger than neutrino
oscillation, strongly indicating the neutrino oscillation is the most favored hypothesis. The data covers 2 cycles of oscillatory shape expected from neutrino oscillation.

The allowed region of neutrino oscillation parameters are shown in Figure 3, including the $\Delta \chi^2$ profiles projected onto each parameter. From the KamLAND data, the most favored solution is the so-called LMA I ($\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV$^2$), and other solutions at higher or lower $\Delta m^2_{21}$ are disfavored at more than 4$\sigma$. Assuming CPT invariance, the allowed region, especially for $\tan^2 \theta_{12}$, is more constrained by combining the solar data [6, 7] as shown in Figure 4.

Figure 3. Allowed region for neutrino oscillation parameters from KamLAND and Solar. The side-panels show the marginalized $\Delta \chi^2$-projections for KamLAND (dashed), Solar (dotted), and KamLAND + Solar (solid).

Figure 4. Result of a combined two-neutrino oscillation analysis of KamLAND and Solar under the assumption of CPT invariance. The best-fit gives $\Delta m^2_{21} = 7.59^{+0.21}_{-0.23} \times 10^{-5}$ eV$^2$ and $\tan^2 \theta_{12} = 0.47^{+0.06}_{-0.05}$ with marginalized errors.

3.2. Geo neutrino analysis

The calculated neutrino fluxes from a reference earth model [8] for U and Th are 29 TNU and 8 TNU, corresponding to 57 events and 13 events after considering the detection efficiencies and neutrino oscillation. From the anti-neutrino analysis including the oscillation constraint on reactor $\bar{\nu}_e$’s by the solar data, the measured geo neutrino flux is $39 \pm 14$ TNU fixing the Th/U mass ratio to 3.9. The obtained result is consistent with a earth model prediction.

References

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