MEASUREMENT OF ANTI-NEUTRINO SPECTRAL DISTORTION BY KAMLAND

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Received (1 November 2004)
Revised (Day Month Year)

The KamLAND experiment uses reactor anti-neutrinos to study the solar neutrino oscillation parameters. KamLAND recently updated the reactor neutrino measurement, with almost a factor 5 more statistics than previously reported. The measured spectral distortion in the anti-neutrino spectrum favors neutrino oscillation as the explanation for neutrino disappearance and gives the best value of Δm^2_{12} to date.

Keywords: Neutrino-oscillation; Spectral distortion; Reactor spectrum; Anti-neutrinos.

1. Introduction

Many reactor anti-neutrino experiments have been conducted in the past 50 years. In 1955, the first such experiment, Poltergeist, measured first evidence of the anti-neutrino and measured its proton cross section. The original Poltergeist experiment was located only a few meters from the reactor core, the source of anti-neutrinos. In the years since that first experiment, reactor neutrino experiments have steadily increased their baselines, with the goal to ultimately find neutrino disappearance. That goal was reached in 2002, when KamLAND reported first observation of reactor anti-neutrino disappearance at an average baseline of $\sim$180 km [1].

Nuclear reactors emit electron anti-neutrinos isotropically during the decay of fission products in the fission process. Without a disappearance mechanism, one expects to measure a $1/R^2$ neutrino flux decrease with distance R. If however, neutrinos are massive, they may oscillate into flavors undetectable to the detector, leading to an apparent disappearance of electron anti-neutrinos.

The $\overline{\nu}_e$ spectrum emitted by commercial reactors can be calculated with $\sim$2% uncertainty from $\overline{\nu}_e$ spectra and the reactor fission rates provided by power companies operating the reactors. The average reactor $\overline{\nu}_e$ energy is 4 MeV. The low energy of reactor anti-neutrinos make the experiments especially sensitive to low values of Δm^2. In addition, since the oscillation probability function depends on L/E_ν, any oscillatory behavior should also manifest itself in a distortion of the neutrino energy spectrum.

2. The KamLAND Experiment

The most recent large reactor neutrino experiment is KamLAND. The experiment searches for neutrino oscillation using a baseline that is two orders of magnitude larger than previous experiments. Due to the long baseline, the $\overline{\nu}_e$ flux is significantly decreased relative to earlier experiments, necessitating a much larger detector volume to compensate for the loss in flux. The KamLAND experiment therefore uses a 1 kton fiducial mass. However, the increased volume of the detector also demands more shielding from cosmic backgrounds to avoid dead time, this effectively means that the detector has to be placed deep underground.

KamLAND is situated in the old Kamiokande cavity in a horizontal shaft mine in the Japanese Alps. The site is surrounded by 53 Japanese commercial power reactors, at a flux weighted average distance of 180 km from the reactors. This baseline makes KamLAND sensitive to the neutrino mixing angle associated with the solar neutrino problem and in particular to the large mixing angle (LMA) solution.

KamLAND consists of a stainless steel sphere of 18 m diameter with 1879 photomultiplier tubes mounted to the inner surface. Inside the sphere is a 13 m diameter nylon balloon filled with liquid scintillator. Outside of the balloon, non-scintillating, highly purified oil provides buoyancy for the balloon and acts as a shield against external radiation. Surrounding the detector outside of the stainless steel sphere is a water Cherenkov detector which provides a muon veto counter and acts as shielding from radioactivity in the rock. The energy resolution of the detector is $6.2\%/\sqrt{E(MeV)}$.

Electron anti-neutrinos are detected via inverse β-decay, $\overline{\nu}_e + p \rightarrow e^+ + n$, with a 1.8 MeV $\overline{\nu}_e$ energy threshold. The prompt scintillation light from the e^+ gives an estimate of the incident $\overline{\nu}_e$ energy, $E_{\overline{\nu}_e} = E_{prompt} + \overline{E}_n + 0.8\,\mathrm{MeV}$, where E_{prompt} is the prompt event energy including the positron kinetic energy and the annihilation energy, and $\overline{E}_n$ is the average neutron recoil energy, which is a few tens of keV. The neutron captures on hydrogen $\sim 200\,\mu s$ later, giving off a characteristic 2.2 MeV γ ray. This delayed coincidence is a powerful tool for reducing background.

The analysis presented here utilizes the following event selection cuts: (a) a radial fiducial volume cut of 5.5 m; (b) a time difference between the positron and delayed neutron of $0.5\,\mu\mathrm{s} < \Delta T < 1000\,\mu\mathrm{s}$; (c) a position difference of $\Delta R < 2\,\mathrm{m}$ between the two; (d) a prompt event energy of $2.6\,\mathrm{MeV} < E_{prompt} < 8.5\,\mathrm{MeV}$ and (e) a delayed event energy of $1.8\,\mathrm{MeV} < E_{delayed} < 2.6\,\mathrm{MeV}$. The lower prompt energy limit of 2.6 MeV lowers backgrounds significantly and avoids the effect of anti-neutrinos from uranium and thorium decaying in the Earth (geo-neutrinos). The efficiency of all cuts is $(89.8 \pm 1.5)\%$. The total systematic uncertainty is 6.5%, where the largest contribution is due to the systematic uncertainty of the fiducial volume. The total livetime of the data presented here is 515 days [2].

Understanding backgrounds is vital in KamLAND. The background from accidental correlations of radioactive decays in KamLAND is estimated by employing an off-time coincidence window; it is 2.69 ± 0.02 events in the data sample. Fast

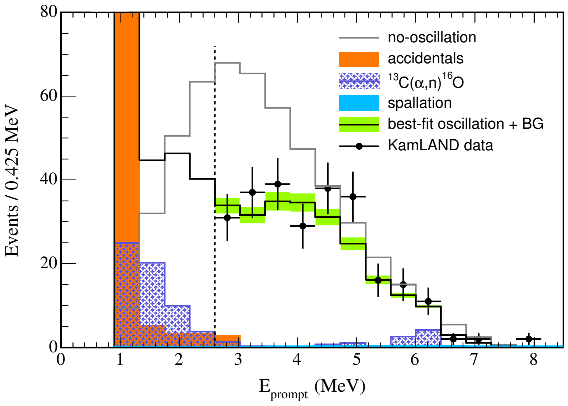

Fig. 1. Prompt event energy spectrum of $\overline{\nu}_e$ candidate events with associated background spectra. The shaded band indicates the systematic error in the best-fit reactor spectrum above 2.6 MeV. Events from the ^{13}C(α,n)^{16}O reaction are the main background to the measurement.

neutrons coming from muon spallation interactions in the rock outside of KamLAND contribute 0.89 background events. Other cosmogenically produced background comes from the beta delayed-neutron emitter ^{9}Li. This background is suppressed by either tracking the preceding muon and vetoing a detector volume in a 3 m radius around the muon track for 2 s or vetoing the entire detector for the same amount of time in case of particularly energetic muon events or when the muon could not be tracked reliably. We estimate that the ^{9}Li background contributes 4.8 ± 0.9 events to the data sample.

Finally, a fourth background is an indirect background triggered by α-decay in ^{210}Po. The 5.3 MeV α has a small probability of interacting with ^{13}C in the scintillator (^{13}C has a 1.1% natural abundance in carbon). The subsequent neutron from the ^{13}C(α,n)^{16}O reaction has a few MeV kinetic energy and will predominantly loose energy through elastic scattering on protons in the scintillator. The quenched proton energy will mostly be below the 2.6 MeV analysis threshold, however the neutron also has a small probability of inelastically interacting with ^{12}C in the scintillator, emitting a 4.4 MeV γ or exciting the ^{16}O to the 6 MeV state. The prompt neutron energy loss and the subsequent capture of the neutron makes the signature of these events similar to the $\overline{\nu}_e$ signature. These events contribute 10.3 ± 7.1 events to the total background of 17.8 ± 7.3 events. The observed prompt energy of the (α,n) background is shown in fig. 1.

3. Recent Results

In an exposure of 766 ton-year to reactor $\overline{\nu}_e$ and in the absence of $\overline{\nu}_e$ disappearance, KamLAND expects to observe 365.2 ± 23.7(syst) events above 2.6 MeV. KamLAND observes only 258 $\overline{\nu}_e$ events, confirming $\overline{\nu}_e$ disappearance at the 99.998% significance level. The spectrum of the 258 $\overline{\nu}_e$ candidates, including all backgrounds is

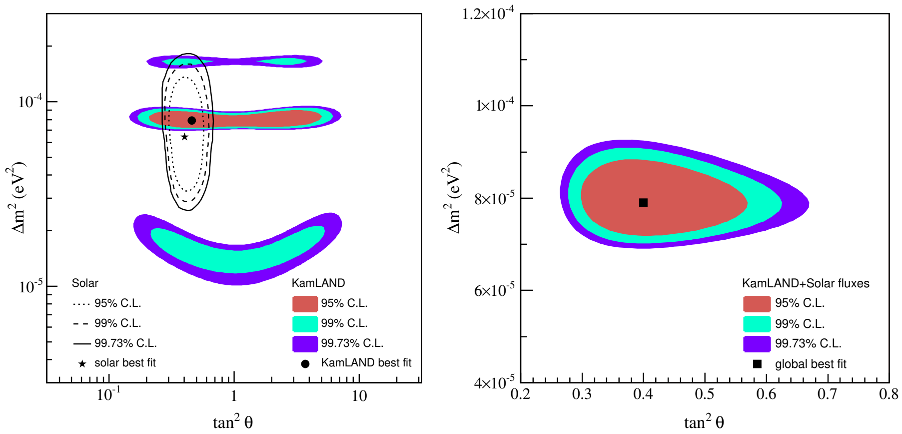

Fig. 2. (left) Neutrino oscillation parameter allowed region from KamLAND anti-neutrino data (shaded regions) and solar neutrino experiments (lines)[3]. (right) Result of a combined two-neutrino oscillation analysis of KamLAND and the observed solar neutrino fluxes under the assumption of CPT invariance.

shown in fig. 1. Performing a two neutrino oscillation analysis, we find a best-fit of $\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\text{eV}^2$ and $\tan^2\theta = 0.46$, with a large uncertainty on $\tan^2\theta$. A statistical analysis of the data [2] finds that the best-fit oscillation parameters have a goodness-of-fit of 11.1%, while the goodness-of-fit of the scaled no-oscillation spectrum where the normalization was fit to the data is only 0.4%.

A two neutrino oscillation analysis of a combination of KamLAND data and observed solar neutrino fluxes [3] yields $\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\text{eV}^2$ and $\tan^2\theta = 0.40^{+0.10}_{-0.07}$, the best determination of the solar oscillation parameters to date. Fig. 2 shows the allowed regions for the KamLAND-only and the global analysis.

4. Conclusion

KamLAND has reconfirmed reactor disappearance at 99.998% statistical significance. The observed energy spectrum disagrees with the expected spectral shape in the absence of neutrino oscillation at 99.6% significance and prefers the distortion expected from neutrino oscillation. The statistical and systematic uncertainties of the neutrino rate measurement are now comparable. The KamLAND collaboration is currently working to reduce the systematic uncertainty.

References

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