A High Sensitivity Search for $\bar{\nu}_e$'s from the Sun and Other Sources at KamLAND

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Data corresponding to a KamLAND detector exposure of 0.28 kton-year has been used to search for $\bar{\nu}_e$'s in the energy range 8.3 MeV < $E_{\bar{\nu}_e}$ < 14.8 MeV. No candidates were found for an expected background of 1.1±0.4 events. This result can be used to obtain a limit on $\bar{\nu}_e$ fluxes of any origin. Assuming that all $\bar{\nu}_e$ flux has its origin in the Sun and has the characteristic ^{8}B solar ν_e energy spectrum, we obtain an upper limit of 3.7×10^2 cm^{-2} s^{-1} (90% C.L.) on the $\bar{\nu}_e$ flux. We interpret this limit, corresponding to 2.8×10^{-4} of the Standard Solar Model ^{8}B ν_e flux, in the framework of spin–flavor precession and neutrino decay models.

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Of the many mechanisms that have been suggested to explain the solar neutrino problem [1], neutrino oscillations are strongly favored by the data. Assuming CPT invariance, the recent observation of reactor $\bar{\nu}_e$ disappearance by the Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) [2], combined with direct measurements of the solar neutrino flux [3], indicates that the oscillation parameters lie in the Mikheyev-Smirnov-Wolfenstein (MSW) [4] Large Mixing Angle (LMA) region [5]. However, the limited precision of current measurements still allows for the possibility that other mechanisms play a sub-dominant role. Since further study of the nature of neutrinos and the properties of the Sun is vital, we report in this *Letter* on a search for solar $\bar{\nu}_e$'s.

There are several conceivable mechanisms which would lead to a $\bar{\nu}_e$ component in the solar flux incident on Earth. Electron neutrinos with a non-zero transition magnetic moment can evolve into $\bar{\nu}_\mu$'s or $\bar{\nu}_\tau$'s while propagating through intense magnetic fields in the solar core. These neutrinos can, in turn, evolve into $\overline{\nu}_e$'s via flavor oscillations. There is also neutrino decay, in which a heavy neutrino mass eigenstate decays into a lighter anti-neutrino mass eigenstate [6, 7].

The analysis presented in this *Letter* concerns a search for $\bar{\nu}_e$'s regardless of origin. Possible non-solar sources of $\bar{\nu}_e$'s at KamLAND include Weakly Interacting Massive Particle (WIMP) annihilation in the Sun and Earth [8] and relic supernova neutrinos [9, 10], either of which could contribute to a continuous $\bar{\nu}_e$ flux. The event rates from these [11] and other non-solar sources are expected to be small, however, and we choose to focus on models that predict a flux of $\bar{\nu}_e$'s descendant from solar neutrinos.

KamLAND was designed to study the flux of reactor $\bar{\nu}_e$'s. While the reactor $\bar{\nu}_e$ flux spectrum has an endpoint of $\sim$ 8.5 MeV, the ^{8}B solar neutrino flux spectrum extends well beyond this energy to $\sim$ 15 MeV. As a result, KamLAND data may be used to search for $\bar{\nu}_e$'s in the solar neutrino flux over an energy range largely free of reactor $\bar{\nu}_e$ events.

The detector consisted of a thin plastic–walled balloon, 13 m in diameter, filled with about 1 kton of liquid scintillator (7.6×10^{31} free protons). The balloon was surrounded by an 18–meter-diameter stainless steel sphere instrumented with 1325 17–inch and 554 20–inch Hamamatsu photomultiplier tubes (PMTs), which provided 34% photo-coverage. For the search presented here, only the data from the 17–inch PMTs were analyzed, lowering the photo-coverage to 22%. The space between the stainless steel sphere and the balloon contained a mixture of dodecane and isoparaffin oils to act as a buffer against external backgrounds. The stainless steel sphere and its contents (hereafter referred to as the inner detector (ID)) was itself contained within a cylindrical water Cerenkov outer detector (OD) equipped with 225 20–inch PMTs. The OD was used to tag events due to cosmic ray induced particles. The entire detector was shielded by a rock overburden of about 1000 m (2700 m.w.e.), which reduced the cosmic muon flux by a factor of 10^5 relative to that at the surface.

The signature of a $\bar{\nu}_e$ interacting in the KamLAND detector is the inverse β–decay reaction

$$\bar{\nu}_e + p \;\rightarrow\; e^+ + n, \tag{1}$$

consisting of a prompt energy deposit from the positron and two annihilation γ's followed $\sim$210 μs later by neutron capture on hydrogen, producing a 2.2 MeV γ. The $\bar{\nu}_e$ energy was deduced from the prompt energy E$_{prompt}$ using the relationship E$_{\bar{\nu}_e}$ = E$_{prompt}$ +E$_{recoil}$+ 0.8 MeV, where the small quantity E$_{recoil}$ refers to the neutron kinetic energy in the final state and was neglected.

Event reconstruction for high energy inverse β–decay events in this analysis was similar to that described in [2] and was found to be accurate to within 2% from comparison with the observed energy distribution of the β decay of cosmogenically produced ^{12}B and ^{12}N (Figure 1). The measured energy resolution of KamLAND for this data set was $7.5\%/\sqrt{E_{prompt}(\mathrm{MeV})}$. Events with 8.3 MeV $< E_{\bar{\nu}_e} <$ 14.8 MeV, followed $0.5\,\mu\mathrm{s} - 660\,\mu$s later by a delayed event depositing between 1.8 MeV and 2.6 MeV of energy, were selected. The distance between the prompt and delayed vertices was constrained to be less than 160 cm and both vertices were required to be within 550 cm of the detector center in order to suppress backgrounds due to natural radioactivity and muon spallation. Backgrounds were further reduced by using ID PMTs to reconstruct a muon track for all events containing OD data. Anti-neutrino candidates associated with

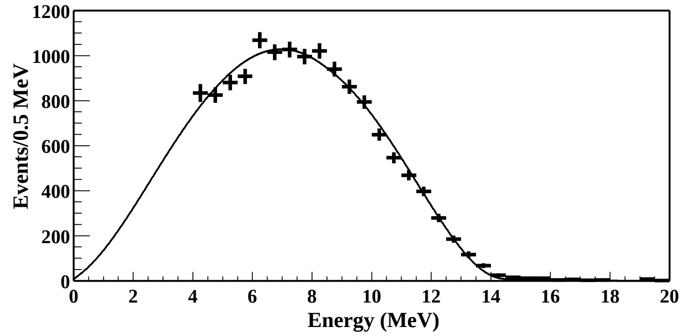

FIG. 1: Prompt energy spectrum of ^{12}B decay. Points are KamLAND data and the curve is the expected β decay spectrum convolved with the detector response.

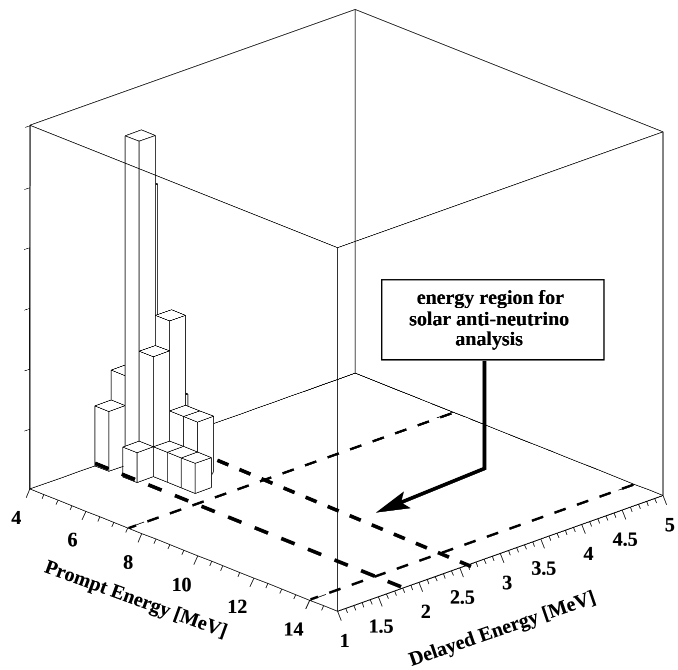

FIG. 2: Energy distribution of the final event candidates. The tail from reactor $\bar{\nu}_e$ events is visible below 8 MeV.

detected muons were discarded if they occurred within 2 s after un-reconstructed muons, within 2 s after muons depositing at least 3 GeV, or within 2 s and less than 3 m from a reconstructed muon track. Spallation neutrons associated with tagged muons were also removed and did not contribute to the background.

Figure 2 shows the delayed versus prompt energy distribution for events after all selection cuts, except those on the prompt and delayed energies themselves. Taking into account the 12% deadtime associated with muon rejection, the total sample livetime, corresponding to the period March 4 - December 1, 2002, was 185.5 days.

The detection efficiency for inverse β–decay events was estimated from Monte Carlo simulation and calibration data to be $84.2 \pm 1.5\%$. The main contributions to the detection inefficiency were the cuts on the distance between the prompt and delayed vertices ($89.8 \pm 1.6\%$), the time between the prompt and delayed vertices ($95.3 \pm 0.3\%$), neutron capture on protons (99.5%), and the energy of the delayed event (98.9 ± 0.1 %). The efficiency of the vertex-separation cut was determined by a Monte Carlo simulation checked against AmBe neutron source data. The neutron capture time distribution with mean $210{\pm}5\,\mu$s and the delayed energy cut efficiency were measured using both AmBe neutron and spallation neutron data.

No events were observed in the signal region over the 0.28 kton-year sample. A separate analysis of the KamLAND data was carried out as a cross-check using a subset of the 0.28 kton-year sample presented here. The results of both analyses were consistent.

The energy spectrum of reactor $\bar{\nu}_e$'s extends to about 8.5 MeV and may have constituted a small background in the solar $\bar{\nu}_e$ energy region due to the detector's finite energy resolution. The number of background events was estimated to be 0.2 ± 0.2 and uncertainties in the detector energy scale and neutrino oscillation parameters were the dominant sources of error. The background from atmospheric neutrinos was estimated, using the Barr-Gaisser-Stanev flux [12], to be 0.001 events.

Cosmic ray muons interact in and near the detector producing spallation neutrons with an energy spectrum extending up to several hundred MeV. These neutrons constituted a source of background for the inverse β–decay measurement as the prompt deposit of the neutron's kinetic energy followed $\sim$210 μs later by the capture of the thermal neutron was indistinguishable from the inverse β–decay event signature. As outlined below, we estimated the spallation neutron contribution to the background using a sample of neutrons selected from the data.

Spallation neutron cuts were the same as for $\bar{\nu}_e$ candidates except that the fiducial volume cut was dropped and the muon-related cuts were replaced by the requirement that at least 5 PMTs in the OD fired. The radial distribution of the remaining candidates was fitted in order to obtain a smooth extrapolation of the fast neutrons into the fiducial volume. The resulting fitted function was integrated inside the volume to estimate the expected number of fast neutron events N_{fn} meeting the selection criteria. We used this quantity to estimate the two components of the fast neutron background by multiplying N_{fn} by a factor of 0.11, determined from Monte Carlo calculations, to obtain the contribution from fast neutrons due to muons passing through the rock near the detector and by scaling N_{fn} by the OD detector inefficiency to obtain the contribution from fast neutrons produced by muons passing through the OD but missing the ID. Summed, these two components contributed 0.3 ± 0.2 events to the background.

We estimated the background due to accidental coincidences using data events falling within an off-time delayed coincidence window of 1–10 s. Two hundred and seventeen such coincidences were found, corresponding to a background contribution of 0.02 events after normalization to the width of the $\bar{\nu}_e$ delayed coincidence window.

The residual backgrounds from cosmogenic ^{8}He ($t_{1/2} = 0.12$ s) and ^{9}Li ($t_{1/2} = 0.18$ s) decays were estimated by determining the total number of these events in the data sample and extrapolating into the $\bar{\nu}_e$ signal region using known decay times and vertex distributions. Above 8.3 MeV, the ^{9}Li contribution dominated and, accordingly, analyses in that energy region dealt exclusively with ^{9}Li. The residual contribution to the background was calculated to be 0.6 ± 0.2 events.

Table I summarizes the background estimates for this data set.

Background Source	Expected Events
Reactor $\bar{\nu}_e$	0.2 ± 0.2
Atmospheric neutrinos	0.001
Fast neutrons (N_{fn})	0.3 ± 0.2
Accidental coincidences	0.02
^{8}He & ^{9}Li	0.6 ± 0.2
Total	1.1 ± 0.4

TABLE I: Estimated backgrounds for the inverse β–decay signal in the energy range of 8.3 MeV $< E_{\bar{\nu}_e} <$ 14.8 MeV for 185.5 live-days.

The $\bar{\nu}_e$ flux integrated over the energy range 8.3– 14.8 MeV is obtained from:

$$\Phi_{\bar{\nu}_e} = \frac{N_{signal}}{\bar{\sigma} \times \bar{\epsilon} \times T \times \rho_p \times f_v}, \quad (2)$$

where N_{signal} is the number of detected $\bar{\nu}_e$'s, $\bar{\sigma} = 6.88 \times 10^{-42}\,\mathrm{cm}^2$ and $\bar{\epsilon} = 0.841$ are the average cross section and detection efficiency respectively, $\mathrm{T} = 1.60 \times 10^{7}\,\mathrm{s}$ is the livetime, and $\rho_p \times f_v = 4.61 \times 10^{31}$ is the number of target protons in the fiducial volume f_v (radius 550 cm). For calculating the average cross section and detection efficiency, the shape of the Standard Solar Model ^{8}B flux without oscillations [13] was used.

Systematic uncertainties in the quantities in Equation 2 are tabulated in Table II. The systematic uncertainty in the number of target protons ($\rho_p \times f_v$) was obtained by adding in quadrature the 2.1% uncertainty in the amount of scintillator in the balloon and the estimated 3.7% uncertainty in the fiducial volume. This latter estimate is based on the difference between the measured number of spallation products in the fiducial volume and the expected number assuming that the spallation products were uniformly distributed. The contribution from the energy threshold was calculated using the uncertainties in the energy scale (2%) and the slope of the neutrino flux at the threshold of 8.3 MeV.

Quantity	Systematic Uncertainty (%)
Detection efficiency ($\bar{\epsilon}$)	1.6
Cross section ($\bar{\sigma}$)	0.2
Number of target protons	4.3
Energy threshold	4.3
Livetime (T)	0.07
Total	6.3

TABLE II: Systematic uncertainties in quantities used to determine the flux of solar $\bar{\nu}_e$.

We derived an upper limit on $\Phi_{\bar{\nu}_e}$ using the Feldman-Cousins unified approach [14] supplemented with Bayesian modifications to account for the errors on nuisance [15] and background parameters [16, 17, 18]. For no observed events, the upper limit of the $\bar{\nu}_e$ flux was 3.7×10^2 cm^{-2}s^{-1} at 90% CL. Using the prescription described in [14], the sensitivity of this measurement was 7.9×10^2 cm^{-2}s^{-1} (90% C.L.). Normalizing to the solar ^{8}B ν_e flux [19] in the analysis energy window ($8.3\,\mathrm{MeV} < \mathrm{E}_{\nu_e} < 14.8\,\mathrm{MeV}$, containing 29.5% of the total flux of $5.05^{+1.01}_{-0.81}\times10^6$ cm^{-2}s^{-1} [19]), this flux limit corresponds to an upper limit on the neutrino conversion probability of 2.8×10^{-4} at the 90% C.L. and represents a factor of 30 improvement over the best previous measurement [20].

We have assumed a non-oscillatory solar $\bar{\nu_e}$ flux up to now in order to retain as much generality as possible but, in the following, we have interpreted the KamLAND upper limit on the solar $\overline{\nu}_e$ flux in the framework of two models: spin-flavor precession combined with neutrino oscillations and neutrino decay.

Assuming that the solution to the solar neutrino problem lies within the LMA region of parameter space and that the MSW effect is a dominant mechanism affecting the solar neutrino flux, we followed the treatment of [21, 22] (taking the value of 34 degrees for the mixing angle) and obtained the following limit on the product of the neutrino transition magnetic moment μ and the transverse component of the magnetic field B_T in the Sun at a radius of $0.05R_s$:

$$\frac{\mu}{10^{-12}\mu_B}\frac{B_T(0.05R_s)}{10\ \mathrm{kG}} < 1.3 \times 10^3 \qquad (3)$$

The current best limit on the neutrino magnetic moment is from the MUNU experiment [23]: $\mu_{\overline{\nu}_e} < 1.0\times10^{-10}\ \mu_B$ (90% C.L.).

Similarly, for quasi-degenerate neutrino masses, we were able to constrain the lifetime [6, 7] for ν_2, the heavier neutrino, to $\tau_2/m_2 > 0.067$ s/eV. If the neutrino mass spectrum is hierarchical, the limit is weaker and for an m_2 of about 0.01 eV ($\sim \sqrt{\Delta m^2_{12}}$), $\tau_2 > 11\ \mu$s. This limit represents an improvement over the current bound of $\tau/m > 10^{-4}$ s/eV calculated in [6].

To summarize, we have described a search for $\bar{\nu}_e$'s in the energy range ($8.3\ \mathrm{MeV} < E_{\bar{\nu}_e} < 14.8\ \mathrm{MeV}$) with KamLAND. The KamLAND detector's source-independent sensitivity allows for the measurement of $\bar{\nu}_e$ fluxes independent of origin. No events were found in the 185.5 live-day data set, allowing for an upper limit to be set on the flux from any source producing $\bar{\nu}_e$'s in the appropriate energy range. We have obtained a flux limit of $\Phi_{\bar{\nu}_e} < 3.7 \times 10^2$ cm^{-2} s^{-1} (90% C.L.), assuming a solar origin and an un-oscillated ^{8}B neutrino energy spectrum. This limit has been used to constrain models of neutrino spin–flavor precession and neutrino decay.

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