KamLAND: A Reactor Neutrino Experiment Testing the Solar Neutrino Anomaly

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Abstract

KamLAND is a 1000 ton liquid scintillation detector currently under construction in the Kamioka mine in Japan. This underground site, with its large overburden of 2700 mw.e., is conveniently located at a distance of 150-210 km to several Japanese nuclear power stations. A measurement of the flux and energy spectrum of the electron anti-neutrinos, emitted by those reactors, will allow us to test the Large Mixing Angle Solution of the solar neutrino anomaly by performing a disappearance search for anti-neutrino oscillations. We will hence, for the first time, provide a completely solar model independent test of this particle physics solution of the solar neutrino problem. Data taking is expected to commence in 2001.

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1 Introduction

The neutrino flux deficit, experimentally demonstrated for atmospheric and solar neutrinos, constitutes strong evidence for the existence of neutrino oscillations, and hence finite neutrino masses and mixing. The appearance of an anomalous anti-neutrino flux component, reported by the LSND collaboration can, at this time, only be explained by neutrino oscillations. However, this result has not yet been independently confirmed. These intriguing findings are discussed in detail elsewhere in these proceedings. A review of the state of affairs in this field shall not be repeated here.

The task at hand is to convincingly *prove* the existence of neutrino oscillations and perform accurate measurements of the relevant mass and mixing parameters. New experiments are in a situation to tune their sensitivity to cover the allowed parameter ranges in the Δm^2- mixing parameter space. These are the so-called atmospheric neutrino range (maximal mixing, $\Delta m^2 \sim 10^{-3}$ eV^2

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probably due to dominantly $\nu_\mu \leftrightarrow \nu_\tau$) [1], the solar neutrino range (large or small mixing, $\Delta m^2 \sim 10^{-11} - 10^{-4}$ eV^2, due to $\nu_e \leftrightarrow \nu_x$) [2–6] and the LSND allowed area (small mixing, $\Delta m^2 \sim 0.2 - 2$ eV^2, $\overline{\nu}_\mu \leftrightarrow \overline{\nu}_e$) [7].

The US-Japanese KamLAND collaboration is building a large liquid scintillation detector in the Kamioka mine in Japan to test the Large Mixing Angle Solution (LMAS) of the solar neutrino anomaly using electron anti-neutrinos emitted by Japanese nuclear power plants. This will be done by performing a disappearance search for neutrino[1] oscillations. A comparison of measured and calculated $\overline{\nu}_e$-flux and spectrum will serve as oscillation signature. Previous reactor neutrino experiments, performed at much shorter distances, have shown that the theoretical neutrino flux predictions are reliable to within 2% [8]. Such test is hence independent of the solar model.

The low average energy of reactor neutrinos of about 4 MeV (weighted by cross section) allows us to perform this measurement at 100-200 km distance to the neutrino sources. This is easily seen by substituting the neutrino mixing parameters and average energy into the well known distance dependence of the oscillation probability P. Here a massive mixed neutrino with energy E$_\nu$ (MeV) is emitted in the flavor eigenstate $|\nu_\ell\rangle$ will be detected as $|\nu_{\ell'}\rangle$ after traveling the distance L (m):

$$P(\nu_\ell \to \nu_{\ell'}) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu}$$

with Δm^2 (eV^2) denoting the mass splitting of the relevant mass eigenstates. The oscillation amplitude $\sin^2 2\theta$ corresponds to the neutrino mixing angle (two flavor mixing) or an appropriate combination of neutrino mixing matrix elements.

The current generation of reactor experiments, performed at about 1 km baseline, have reached $\Delta m^2 < 10^{-3}$ eV^2 [9] and demonstrated that the atmospheric neutrino anomaly is not due to $\nu_\mu \leftrightarrow \nu_e$ oscillations.

In KamLAND this proven concept will be implemented at an unprecedented baseline. The 16 commercial nuclear power stations, generating about 30% of Japan's electrical power, deliver a $\overline{\nu}_e$-flux of $1.3 \cdot 10^6$ cm^{-2}s^{-1} (for E$_\nu$ > 1.8 MeV) at the Kamioka mine. About 78% of this flux comes from 6 reactor stations forming a well defined baseline of 139-214 km. This "arrangement" of power stations around Kamioka makes KamLAND possible.

In KamLAND we will make use of the inverse beta decay reaction $\overline{\nu}_e + p \to e^+ + n$ which offers a relatively "high" cross section ($\sim 6 \cdot 10^{-43}$ cm^2/fission), low threshold (1.8 MeV) and a correlated event signature. The 1000 ton active liquid scintillation target of KamLAND offers a large number of protons and allows a convenient calorimetric measurement of the positron energy together with the possibility to detect the reaction neutrons by delayed capture on protons through $n+p \to d+\gamma(2.2MeV)$ ($\tau \approx 180\mu s$). The chosen reaction allows

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[1] From here on neutrinos and anti-neutrinos will not be distinguished

a measurement of the neutrino energy. At full reactor power and no neutrino oscillations we expect a reaction yield of about 3 per day.

Figure 1 shows expected positron spectra calculated for KamLAND. The mass-mixing parameters used fall into the LMAS. They would result in (a) distorted spectrum and (b) a suppressed event rate. The positron yield suppression can reach up to a factor 2 for oscillation parameters in the LMAS. A precise knowledge of the expected neutrino flux and spectrum is needed to compute an expectation value for the reaction rate. To do this we will monitor the power and fuel composition of all 51 Japanese power reactors on a daily basis. An agreement has been reached with all Japanese power producers which will give us access to this information.

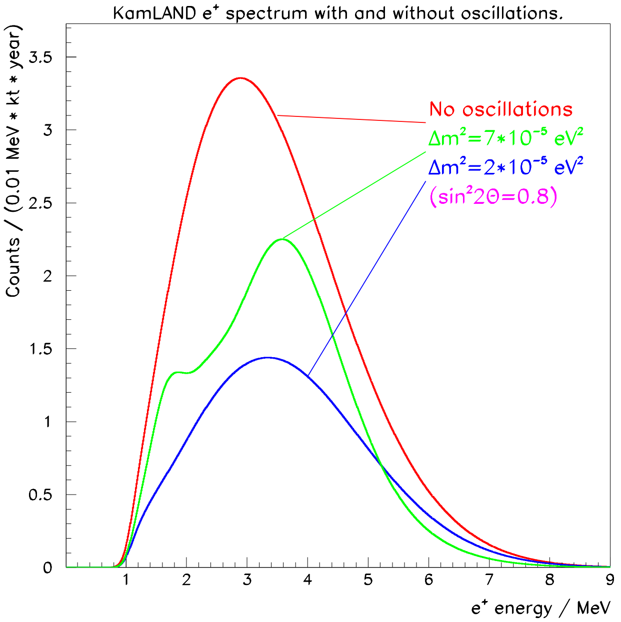

Fig. 1. Calculated positron spectra for KamLAND. The two mass-mixing parameter combinations corresponding to the LMAS are resulting in strong spectral deformation compared to the no-oscillation spectrum.

2 The Detector

Figure 2 sketches a cross sectional view of the KamLAND detector. The active 1000 ton liquid scintillation target, contained in a thin plastic balloon, is suspended by a system of ropes in a mineral oil buffer. The scintillator is a mixture of 80% paraffin and 20% pseudocumene using 1.5 g/l PPO as fluor. The buffer oil is contained in a spherical vessel made from stainless steel. The hole assembly is viewed by 1280 17” and 652 20” PMTs, which are attached

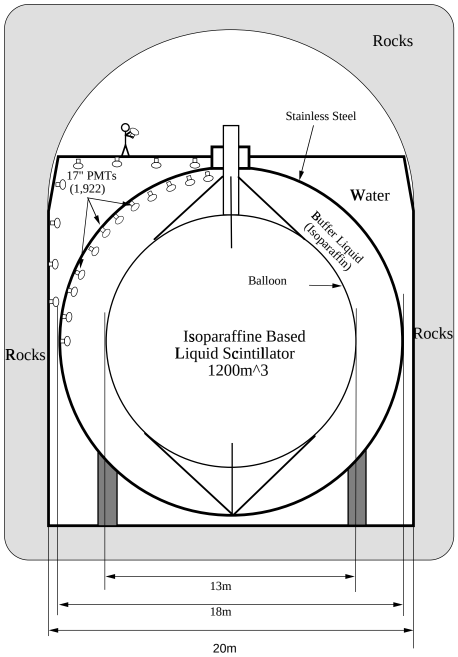

Fig. 2. Schematic view of the KamLAND detector.

to the steel container. The PMTs are separated by 3 mm thick acrylic sheets from the rest of the mineral oil buffer to limit liquid convection and hence Radon transport. Scintillator formulation and PMT coverage have been chosen to allow positron-proton particle identification by pulse shape analysis. The outside cylindrical volume is filled by water, acting as passive shield and water Cherenkov muon-veto detector.

The large detector size puts stringent requirements on the optical transparency of the scintillator. Due to the low energy of the neutrino signal the scintillator has to have a high light yield as well. Based on laboratory tests we are expecting a resolution of about 150 photo-electrons/MeV. The event vertex will be reconstructed using PMT timing information. As of the writing of this article the detector tank had been installed, fully instrumented with PMTs and installation of the acrylic sheets had been concluded. Test containment balloons of various size (including a full size one) have been successfully deployed. A scintillator purification plant is in an advanced stage of construction.

The data taking electronics will consist of buffered waveform digitizers for each PMT channel which will allow for dead-timeless data taking to up to a kHz rate. Correlated events will be reconstructed off-line. The event trigger will be provided by a field programmable gate array. This adds flexibility as the trigger can be reconfigured according to the needs.

3 Expected Background

The expected event yield of 2-3 neutrino interactions per day and kton of detector, combined with the low energy of the events, which are with 1-8 MeV within the range of natural and artificial radioactivity, requires vigorous background control. However, the correlated signature of the chosen neutrino detection reaction, resulting in a delayed coincidence within several hundred μs, makes this a manageable problem. We distinguish two classes of background: (a) random coincidences and (b) correlated background. To estimate these backgrounds we performed a detailed Monte Carlo study.

Random coincidence background is mainly caused by radioactivity. It is minimized by selecting all construction materials for their content of radioactivity by means of low background gamma spectroscopy, neutron activation analysis and mass spectroscopy. Major background components are due to the PMT glass, the balloon holding ropes and the liquid scintillator. While the former ones can be countered by a more or less restrictive fiducial volume cut off-line we estimate that the liquid scintillator should not contain more than 10^{-14} g/g of U/Th and 10^{-10} g/g K. KamLAND's large size allows a 1 m fiducial volume cut from the containment balloon, still leaving 600 tons of active detector.

Radioactive Rn gas, constantly released from all surfaces, is well soluble in organic solvents. Convection of the liquid can hence transport it near the detector. To limit its contribution to the background the buffer is divided into two sections by thin acrylic sheets. They separate the PMTs from the fiducial volume. The scintillator containment balloon has been engineered from a novel composite film which has a low Rn permeability and high resistance to the aggressive liquid scintillator. It will act as the main Rn barrier. We estimate that we will be able to reduce the Rn activity of the liquid scintillator to 1 μBq/m^3 by these measures. The massive passive shielding of 2-3 meters of oil and water effectively suppresses leakage of external gamma radiation.

To achieve the required scintillator purity the liquid scintillator and buffer will be constantly purified by water extraction and Nitrogen degassing. The better solubility of actinides in water compared to organic solvents will improve the radio purity of the liquid scintillator while the Nitrogen purging will remove dissolved Rn gas.

At above purity level we expect to detect 0.15 random delayed coincidences (using appropriate neutrino selection cuts) per day and kt. While taking data we are intending to study improved liquid purification techniques with the goal to improve the scintillator purity by a factor 100.

Correlated background is dominantly caused by cosmic ray muons and neutrons. At the large overburden of KamLAND (2700 mw.e.) we expect only about 0.21 s^{-1} of cosmic muons going through the scintillator. KamLAND's depth is the main tool to suppress those backgrounds. Our outer water filled veto detector will tag muon events.

The prompt part of an neutrino event may be simulated by fast neutron recoil on protons where the neutron was created by either muon spallation or muon capture on nuclei inside or outside the muon veto detector. A fast neutron or muon may create radioactivity inside the scintillator through neutron spallation or exchange of a virtual photon between a μ and a C nucleus, respectively. The following radioactive decay can then simulate the prompt part of a neutrino capture. The delayed coincidence is supplied by the capture of the same neutron. The leading component of the correlated background is due to neutrons created in the rock outside the veto detector with the muon not registered. Energetic spallation neutrons can penetrate the passive shield and cause background. The neutron associated backgrounds are hard to estimate as neither production yields nor neutron energy spectra are well understood. However, background estimates done for previous experiments showed satisfactory agreement with the data. By Monte Carlo we estimate a correlated background of 0.05 events per day and kt. A fiducial volume cut will reduce it even further if necessary.

Our background estimates hence indicate a very favorable neutrino signal to background ratio of 10 to 15 depending on the power status of the Japanese reactors.

The detector background can be directly measured by unfolding the time dependent neutrino signal rate from a constant background. To do this we will exploit the fact that the reactor neutrino flux in Kamioka varies by typically 20% during the year due to reactor maintenance mainly in spring and fall. This is the most conservative data-oriented approach. Its statistical uncertainty is limited by the smallness of the overall flux variation. Should the background be mainly caused by components which are invariant under reversal of the selection criteria applied to the prompt and delayed signal a novel ("swap") method of background determination, discussed in [10], could greatly improve the statistical uncertainty. However, such treatment introduces a greater dependence on Monte Carlo simulation.

The random background can be measured together with the signal by requiring a time correlation between prompt and delayed signal which is beyond the known neutron capture time. Should the positron/proton particle identification by pulse shape analysis be efficient then the major correlated background of fast neutron recoils can be tagged and its spectrum be measured.

4 Anticipated Results

Figure 3 depicts the estimated sensitivity of KamLAND after 3 years of data taking. Different background determinations, as discussed above, are influencing the achievable sensitivity. Even for the most conservative scenario in which the background has to be determined from the reactor power fluctu-

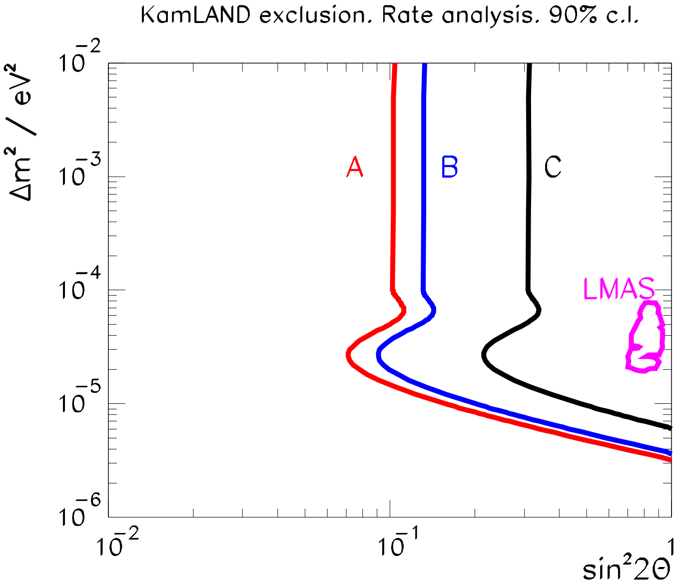

Fig. 3. Estimated sensitivity at 90% c.l. of KamLAND's disappearance search for reactor neutrinos after 3 years of data taking with no fiducial volume cut. Curve (A) was calculated for zero background. Exclusion (B) corresponds to a signal-to-background ratio of 10. It was further assumed that that the background can be determined to ±25% independently of the reactor power information e.g. by using the swap method described in the text. Curve (C) corresponds to the same signal-to-background ratio. Here the power fluctuations of the reactors is used to determine the background.

ations the LMAS (contour obtained from N. Hata) is completely covered. KamLAND is thus the first terrestrial experiment to cover this neutrino parameter range and is, as stated before, completely independent of the solar model. A *measurement* of neutrino oscillations by KamLAND would hence constitute convincing evidence for the particle physics nature of the solar neutrino problem. We estimate that in such case KamLAND would be able (for neutrino mixing parameters within the LMAS) to determine the mixing angle and mass-difference to within 20% accuracy at 99% c.l..

Due to its large size KamLAND can be used for a variety of secondary tasks. Beyond the reactor neutrino measurement we are planning to perform the first measurement of the anti-neutrino flux emitted by the radioactivity contained in the earth's crust. KamLAND's electronics and data acquisition is build to digest the neutrino burst of a galactic supernova. Should an improvement of the scintillator purification system, as discussed above, be feasible KamLAND would be in a position to measure the flux of low energy solar ^{7}Be neutrinos using neutrino-electron elastic scattering.

5 Conclusion

The KamLAND collaboration is currently constructing a large underground liquid scintillation neutrino detector. The detector is designed to test the Large Mixing Angle Solution of the solar neutrino anomaly by searching for reactor neutrino oscillations at a baseline of 150-210 km to commercial nuclear power stations. The projected sensitivity will allow a conclusive test of the LMAS. Data taking is expected to begin in 2001. The project is funded by the Japanese Ministry for Science and Education and the US Department of Energy.

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