An overview of the KamLAND experiment

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Abstract. KamLAND, a nuclear reactor $\bar{\nu}$ detector, is uniquely situated and designed to be maximally sensitive to the Large Mixing Angle parameters of the MSW theory of ν oscillations. The KamLAND detector began to acquire data on January 22, 2002. This paper presents an overview of the detector, of the very low backgrounds and of the status of the detector performance as of September 2002. A discussion of the plan for a solar neutrino experiment is included.

1. Introduction

While exciting results are being reported from solar based ν experiments, independent measurements of the flavor oscillation parameters increase in importance. The solar neutrino data from Super Kamiokande and the Sudbury Neutrino Observatory definitively show that ν_e's oscillate in flavor while traveling between the sun and the earth, with a preferred mixing angle that is large[1, 2]. KamLAND[3], a Japanese-American collaborative effort, is the first terrestrial based neutrino experiment that is sensitive to the favored Large Mixing Angle (LMA) solution in the two-active-neutrino oscillation parameter space. Allowed regions in the mixing parameter space set by this vacuum oscillation experiment must agree with the matter-enhanced oscillation scenario for the solar ν model or be explained by new physics.

2. The Experiment

KamLAND, the Kamioka Liquid-scintillator Anti-Neutrino Detector, is a long baseline neutrino oscillation experiment measuring the flux and energy spectrum of $\bar{\nu_e}$'s from nuclear power reactors. Located in the cavern first constructed for the Kamiokande experiment, KamLAND is situated near 20 Japanese and Korean nuclear power stations in which 85% of the neutrino flux source is between 140 and 210 km, giving an effective oscillation distance of 175 km.

A schematic of the KamLAND detector is presented in Figure 1. KamLAND was proposed in 1994. After 4 years of construction, and 1 year of filling the detector and integrating the components, data acquisition began on January 22, 2002.

The KamLAND detector is composed of 1 kton of liquid scintillator monitored with 32% coverage by 1325 17$''$ photomultiplier tubes (PMTs) for fast timing and 544 20$''$ PMTs. A 13 m diameter thin plastic balloon separates the inner scintillator region from a 2.5 m thick buffer oil region containing the detectors. A layer of 3 mm thick acrylic sheets shields the outer buffer region, reducing the migration of radon and other contaminates from the PMT glass and steel welds. The outer, veto detector region consists of 225 refurbished $20''$ PMTs in a cylindrical geometry, that serves as both a passive neutron shield and as a muon detector. Reflective Tyvek sheets cover the surfaces and are used to divide the outer detector into 4 regions for increased light collection efficiency and for increased tracking capability with regional information.

Reactor $\bar{\nu}$ experiments take advantage of a coincidence signature to identify events with an energy threshold of $E_{\bar{\nu_e}} = 1.8$ MeV. The prompt signal is the energy deposited from inverse beta decay of $\bar{\nu_e}$ on the proton given by $\bar{\nu_e} + p \rightarrow e^+ + n$ including the subsequent annihilation of the positron to two 511 keV γs. This signal is in coincidence with the delayed capture of the neutron, $n + p \rightarrow d + \gamma$ $(E_\gamma = 2.2\ MeV)$.

The well characterized $\bar{\nu_e}$ flux from the nuclear power reactors can be determined to $\sim 3\%$ from the power spectra and burn-up rates, thereby eliminating the need for a near detector. Comparing the measured and expected flux provides a direct determination of the flavor oscillation parameters. While the number of reactor cores involved prevents taking measurements with the source turned off, we expect to see seasonal fluctuations in $\bar{\nu}$ flux in accordance with power consumption. In addition, the shape of the detected prompt energy spectra (hence the $\bar{\nu}$ spectra) is sensitive to oscillations and provides a second means of determining the oscillation parameters.

Figure 2 shows the oscillation parameter space exclusion region if KamLAND sees no evidence of neutrino mixing in three years of acquiring data. Assuming a large mixing angle, $sin^2(2\theta) = 0.8$, KamLAND is predicted to be sensitive down to $\Delta m^2 \approx 7 \times 10^{-6}$. Assuming 80% reactor power over 5 years of data from a fiducial volume of 408 tons, and employing the rate and shape analysis, Figure 2 shows how KamLAND is maximally sensitive to (will verify or exclude) the LMA solution parameter space.

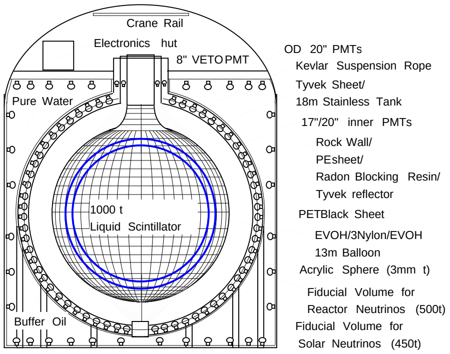

Figure 1. Schematic diagram of the KamLAND detector.

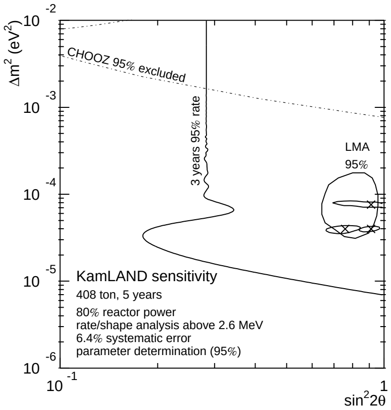

Figure 2. Sensitivity of KamLAND in the two neutrino oscillation parameter space.

3. Detector Calibration and Backgrounds

PMT waveforms are digitized in specially designed electronics based on a self-launching Analog Transient Waveform Digitizer circuit set for a threshold of 1/3 photoelectrons (pe). The PMT gains are set to a nominal value of 5×10^6 using filtered laser sources and blue LEDs. Using well characterized γ sources at known positions along the vertical axis, the waveform peaks are analyzed for charge and time to determine the energy calibration and vertex fitting respectively. Present analysis sets the photon yield at 260 pe/MeV. The position resolution is 60 cm at 1 MeV with a systematic error of 10 cm. The energy resolution is currently $7.5\%/\sqrt{E[\mathrm{MeV}]}$ with a systematic error of 2% in the overall energy scale. The position and energy resolutions are expected to improve as the analysis methods are refined.

The background radiation count-rate is concentrated primarily in the outer radial volume where the balloon and kevlar rope supports are located and is greatly reduced with appropriate fiducial volume cuts. The ^{40}K (primarily from the rope net), ^{238}U and ^{232}Th (primarily from the surrounding rock) levels are below 10^{-15} grams per gram of scintillator as determined by both the singles rate spectra and neutron activation analysis of scintillator samples. This level of contamination, producing less than an estimated limit of 6×10^{-4} accidental coincidences per day in a fiducial volume with radius of 5 m, is negligible for the reactor neutrino experiment.

The correlated background signal of concern is from muon induced spallation neutrons that scatter from a proton, depositing energy that imitates the prompt signal. The neutron can subsequently thermalize within the acceptable range and time, and capture on a proton producing the 2.2 MeV delayed γ signal. To suppress these events, the data is checked for correlated muon signals in either the inner or outer detector, and we are developing careful cuts in time and space surrounding muon events. Calculations and analysis of the muon data provide a good estimate of the background from neutron events and other spallation products (^{8}He and ^{9}Li).

4. Current Status

Data analysis for determining the measured $\bar{\nu}_e$ rate and energy spectrum is progressing rapidly. Continued monitoring of the detector parameters and refinement of the source calibration techniques, and continued improvement of the Monte Carlo and analysis routines will soon provide an early result with good systematics.

Plans are underway for a solar neutrino measurement concentrating on the low energy neutrinos from ^{7}Be. To achieve this goal, the background singles count-rate must be decreased. The U and Th levels are below the necessary limits ($< 10^{-16}$g/g), while the K, Pb, and Kr levels will need to be reduced. We are working on the purification system to reach these limits and believe the measurement of ^{7}Be neutrinos to be within reach at KamLAND.

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