An Update on Progress at KamLAND

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The first generation of solar neutrino experiments narrowed the allowed flavor mixing and mass parameter solutions (for $\nu_e \leftrightarrow \nu_x$) to a few isolated regions of $\sin^2 2\theta - \Delta M^2$ parameter space. Recently, the Small Mixing Angle (SMA) solution ($\sin^2 2\theta \sim 10^{-3} \rightarrow 10^{-2}$ and $\Delta M^2 \sim 10^{-5}$ eV$^2$), and the “just so” ($\Delta M^2 < 10^{-9}$ eV$^2$) solutions have been disfavored by results from Super-Kamiokande and SNO. The Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) recently became operational, and is particularly sensitive to the Large Mixing Angle (LMA) region ($\sin^2 2\theta \sim 1$ and $\Delta M^2 \sim 10^{-5} \rightarrow 10^{-3}$ eV$^2$). We believe the background impurity levels in the detector are low enough to conduct a successful experiment. The stability of the central balloon and PMTs has also been confirmed.

1 Introduction

The solar neutrino flux measurements of Homestake, GALLEX, SAGE, Kamiokande, Super-Kamiokande, and SNO were significantly lower than those predicted by Standard Solar Models (SSMs). This discrepancy was known as “the solar neutrino problem”, and can be explained as a natural consequence of neutrino flavor oscillations. Super-Kamiokande has observed a significantly lower ratio of $\nu_\mu$ to $\nu_e$ like events than expected from neutrinos produced by cosmic ray interactions in the upper atmosphere. This was also interpreted as evidence for neutrino flavor oscillations. In addition, LSND found evidence for $\nu_\mu \rightarrow \nu_e$ oscillations at the Los Alamos Meson Physics Facility.

Solar neutrino experiments are, by definition, long baseline experiments. They also tend to be low energy. Most laboratory experiments are short baseline. This has led to a lack of experimental coverage of the $\sin^2 2\theta - \Delta M^2$ plane near the LMA region.
2 The KamLAND Experiment

KamLAND is a medium energy, medium baseline reactor anti-neutrino experiment. It utilizes the large number of nuclear reactors that lie within a few hundred kilometers of the KamLAND site, which is situated inside the dome of the old Kamiokande experiment in Japan. Assuming no flavor oscillations, these reactors produce an average flux (at KamLAND) of $1 \times 10^6 \text{cm}^{-2} \text{s}^{-1}$ anti-neutrinos at an energy greater than 1.8 MeV\textsuperscript{9} (the neutrino capture threshold). In this scenario, KamLAND would detect $\sim 2$ per day.

A schematic of KamLAND is shown in Figure 1. The detector comes in three sections. The central balloon contains $\sim 1000$ tons of dodecane (80%), pseudocumene (20%) and diphenylazo (PPO) scintillator (1.5 g/L). A transparent nylon balloon contains this liquid scintillator and is stabilized by a mesh of Kevlar ropes suspended from the top (chimney) and bottom of the detector. Outside the balloon, and also acting as a support, is a mixture of paraffin oils. The paraffin oil is contained within an 18 meter diameter stainless steel spherical vessel and acts as a buffer region, shielding the balloon volume from gamma rays emitted by the Photo-Multiplier Tubes (PMTs) situated on the inner wall of the vessel. 1878 inward looking 20" and 17" PMTs are placed to detect scintillation light from neutrino interactions inside the balloon. The volume inside the stainless steel sphere is called the Inner Detector (ID). There are 1325 17" PMTs (which have the same shape as the 20" PMTs but better time resolution), and 553 20" PMTs evenly distributed around the ID. The ID sits in a cylindrical Outer Detector (OD), which is filled with water. The OD is used as a veto against muon events and radioactivity from the rock walls. On the inner wall of the OD are 240 20" PMTs.

KamLAND can be viewed as a two stage experiment. The first stage, and initially the most important, is the reactor experiment. In this phase, reactor neutrinos are detected via the inverse neutron beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). The $e^+$ is directly observable. The neutron is captured on a time scale of $\sim 200 \mu\text{s}$ by a nucleus in the liquid nearby according to the reaction $n + p \rightarrow d + \gamma(2.2 \text{ MeV})$. Therefore the neutrino signature is a double coincidence in time (delayed) and position. Additionally, the energy of the neutron capture must be consistent with a 2.2 MeV gamma. The statistical significance of any signal depends upon reducing the background as much as possible. To be successful, low levels of impurity are required in the Liquid Scintillator (LS). The requirements for important impurities such as U, Th and $^{40}\text{K}$ are...
Figure 2: A selection of modern neutrino experiments and the regions of $\Delta m^2$ vs $\sin^2 2\theta$ parameter space to which they are most sensitive. The figure shows that KamLAND is uniquely sensitive to the LMA region. Super-Kamiokande and SNO have recently published results that disfavor the SMA region. 

\[ \sim 10^{-14} \ \text{g/g or less, together with low levels of radon. Preliminary measurements of these backgrounds have been performed. The upper limits for U, Th and } ^{40}\text{K are } 6.4 \times 10^{-16} \ \text{g/g, } 1.8 \times 10^{-16} \ \text{g/g, and } 2.3 \times 10^{-16} \ \text{g/g respectively. Radon levels are much more variable, as they depend on the purification system (which is still being improved) and mine air. Radon contamination leads to the decay products } ^{208}\text{Tl, } ^{210}\text{Pb and } ^{210}\text{Bi, which tend to settle on the balloon surface and can be monitored by low energy event rate measurements. We can remove most of this effect by employing a fiducial volume cut in software on event vertices near the balloon.} \]

The second phase is the solar neutrino experiment. KamLAND has the capability to observe low energy neutrinos down to 0.6 MeV, enabling the detection of $^7\text{Be}$ solar neutrinos. This would require very low impurity levels ($\sim 2$ orders of magnitude lower than for the reactor phase, i.e. $\sim 10^{-16} \ \text{g/g or less of U/Th}^{40}\text{K}$). While more measurements need to be done, KamLAND may already be close to this goal. 

Other possible experiments include using KamLAND as a proton decay detector. The increased light output of scintillator over Cherenkov experiments make KamLAND a more efficient detector of the $K^+$ than water Cherenkov detectors. Simulations suggest that KamLAND may be almost as effective (for detecting the $K^+$ modes) as Super-Kamiokande, despite its smaller volume. Additionally, KamLAND has the capacity to study atmospheric neutrinos, as well as those produced by radioactive decay in the Earth’s crust and astrophysical sources.

Figure 2 shows the regions of $\Delta m^2$ vs $\sin^2 2\theta$ parameter space KamLAND will be most sensitive to in the reactor phase. It also shows where the SMA and LMA solutions are, relative to other experiments. This illustrates why KamLAND is such a unique project. As it is the only
medium baseline real-time reactor experiment, it will be most sensitive to the LMA solution around $\Delta M^2 \sim 10^{-4} \text{ eV}^2$ and $\sin^2 2\theta \sim 1$.

3 Results

Various forms of calibration are taking place. Energy calibrations will be performed by a number of radioactive sources. To date, a $^{65}$Zn source at 1.1 MeV energy and a $^{60}$Co source at 2.5 MeV have been used. Using only the 17” PMTs, early results give an average of 240 photo-electrons per MeV. This is a little higher than anticipated. During the reactor phase, only the fast timing 17” PMTs are required. The 553 20” PMTs have not yet been commissioned. To check the neutron detection efficiency, a number of Americium/Beryllium sources which emit a prompt gamma at 4.4 MeV and a fast neutron will be used. For PMT gain calibrations a number of blue LEDs have been placed around the periphery of the detector. A 337 nm nitrogen laser is also used. The light from the laser can be sent to the detector through a fiber. Once it reaches the LS, it scintillates, simulating a real event. For time calibrations, a nitrogen dye laser at 530 nm (which doesn’t scintillate) is used.

Official data taking began at KamLAND on January 22, 2002. The balloon and PMTs are physically stable and the balloon shows no signs of leaking. The event rate has averaged $\sim 25$ Hz at a threshold of $\sim 0.8$ MeV. The data rate has been $\sim 100$ G-Bytes per day, even at this low event rate. This is because flash ADC waveforms are recorded for every PMT triggered.

4 Summary

KamLAND has been operational since January 22 2002. The critical physical elements of the experiment, such as impurity levels, strength and integrity of the central balloon and PMTs have been confirmed. We expect that KamLAND will be able to successfully complete the reactor phase of the experiment, and make unique measurements of the LMA region of $\Delta M^2 - \sin^2 2\theta$ parameter space. We hope to be able to show results by late 2002 or early 2003.

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