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The KamLAND Experiment

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The motivation and design of the KamLAND neutrino experiment is described.

A significant discrepancy between the measured solar ν_e flux at the earth and the flux expected according to standard solar models is now well established. Based on the solar neutrino measurements to date, one of the strongest contenders to resolve this discrepancy is matter–enhanced neutrino oscillations. A fit of this hypothesis for two–flavor oscillations to the neutrino data gives a local minimum with acceptable χ^2 at $\sin^2 2\theta \sim 0.75$ and $\Delta m^2 \sim 2 \times 10^{-5}$ eV^2, which is commonly referred to as the large–angle MSW solution.

Given the large mixing angle of this solution, one can consider the possibility of testing it with a reactor neutrino experiment. Such an experiment would have the clear advantage of being entirely a terrestial experiment with the particularly attractive feature that the source is well understood. It would require a baseline on the level of 100 km (10^5 m) or more to have sufficient reach in Δm^2. To offset the strong reduction of L^{-2}, this experiment would require a high level of reactor power, a large target mass, and very good control of backgrounds.

The KamLAND experiment, being mounted by a collaboration of physicists from Japan and the United States, is such an experiment designed to provide a test of the large–angle MSW solution. It will be situated in the old Kamiokande cavern so that it is well–shielded (2700 mwe) from cosmic rays. The central detector will consist of 1000 tons of high–purity liquid scintillator. Within a 400 km radius there is a large number of Japanese power plants having a total thermal power of ~100 GW; the mean distance of the reactors from the experiment, weighted by their flux, is about 160 km.

Contigent upon very good control of backgrounds, KamLAND will also be able to attack the solar neutrino problem through direct observation of solar neutrinos. The experiment will be capable of making other measurements well–suited to a massive liquid scintillator detector operating with a low threshold, e.g. measurement of the anti–neutrino flux from terrestial radioactivity and detection of supernova neutrinos. Owing to limited space, these measurements are not further discussed in this paper.

The detector is shown schematically in Figure 1. The central detector consists of 1000 tons of liquid scintillator enclosed in a transparent balloon designed to have low permeability to radon. The central detector is viewed by ~1900 17–inch/20–

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inch PMT's mounted on a stainless steel sphere. The PMT's cover 30% of the total solid angle; for this coverage combined with the light yield and transparency of the scintillator and quantum efficiency of the PMT's, 190 photoelectrons/MeV are expected for energy deposits at the center of the detector. The faces of the PMT's are separated from the central detector by 2 m of isoparaffin, which provides shielding against natural radioactivity in the PMT's, stainless steel sphere, and rock as well as against fast neutrons produced by muon spallation in the rock. Not shown is an acrylic spherical shell just in front of the PMT faces to provide a diffusion barrier to radon emanating from the PMT faces. The stainless steel sphere is immersed in a tank of pure water viewed by PMT's; muons passing through the experiment are detected by the Cerenkov light they produce in this detector.

PMT signals will be processed by fast waveform digitizers to extract information on energy, timing, and particle ID. LED's, a UV laser system, and radioactive sources (γ, n, α, and β) will be deployed for detector calibration and monitoring.

$\bar{\nu}_e$'s will be detected via inverse beta decay. The experimental signature is a coincidence between a a prompt energy deposit–the positron kinetic energy and annihilation energy–and a 2.2 MeV energy deposit, delayed by an average of $\sim$200 μs, from capture of the neutron on a proton. The average event rate in the case of no oscillations is expected to be 2.2/day for a positron energy threshold of 1 MeV.

The main background sources are cosmic ray muons and natural radioactivity. Besides the production of fast neutrons in the earth surrounding the detector by muon spallation, one must also reckon with the backgrounds due to isotope activation by muons passing through the large detector (cosmogenesis). The backgrounds due to natural radioactivity arise mainly from (a) the decay chains of ^{238}U, ^{232}Th, and ^{40}K naturally present in the surrounding rock and detector materials and (b) decays of ^{60}Co added to stainless steel in manufacturing for quality control.

Some of the measures KamLAND will take to control backgrounds have already been mentioned (2700 mwe earth overburden, muon veto, isoparaffin buffer, radon barriers). We note other measures here. Radio–assay is being used to select detector materials which are low in radioactivity. The scintillator will be recirculated to remove radiocontaminants. Of course, event selection will also play an important role in suppressing backgrounds. Requiring the sequential prompt and delayed parts of the candidate event to be correlated to space as well as in time will reduce uncorrelated backgrounds and the experiment intends to use pulse shape discrimination (PSD) to distinguish events induced by fast neutrons. If necessary, the backgrounds can be further reduced by increasing the effective thickness of the buffer by restricting the fidcuial volume.

A detailed detector simulation has been carried out to estimate the background singles and delayed coincidence (500 μs window) rates after all control measures except PSD have been taken. The estimates incorporate actual measurements of the radiocontaminants in the detector materials and conservative treatment of the muon spallation background. The singles rate above 1 MeV is estimated to be $\sim$2 Hz. The delayed coincidence rate due to background is estimated to be 0.25

events/day. Thus the singles rate will be very manageable for the data acquisition system, and the S/B ratio for neutrino candidates is expected to be about 10:1

At the least, the correlated background–prompt and delayed subevents due to same process–can be measured with sufficient accuracy by correlation of the event rate with the thermal powers of the various reactors. The thermal power as a function of time varies by 30% annually, peaking as expected in the summer and winter seasons when energy demands are greatest. Additional constraints on the correlated background can be obtained from (a) the spatial distribution of events and (b) selecting neutron–induced events on the basis of PSD and studying their properties. The uncorrelated background rate can be estimated by looking at events with the wrong–sign time correlation or at right–sign events for delayed coincidence times long compared to the mean neutron capture time.

Figure 2 shows the expected sensitivity of the KamLAND experiment after three years of data taking for different assumptions on the background rate and the accuracy to which it is known. It can be seen that, even in the case where the background is determined only from the modulation of the reactor power, the region of sensitivity well encompasses the region comprising the large–angle MSW solution to the solar neutrino problem.

The KamLAND experiment is being funded by the Japanese Ministry of Education and the U.S. Department of Energy. Design and construction of the experiment is well underway. Data taking is scheduled to begin in 2001.

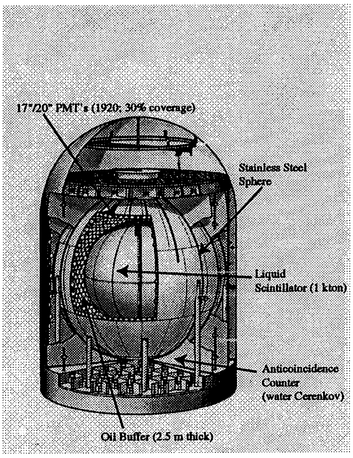

Fig. 1. Schematic view of the KamLAND detector.

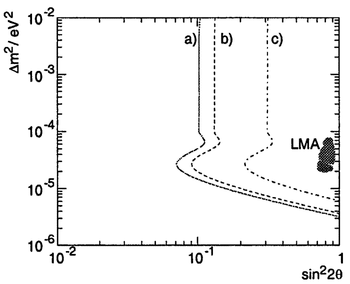

Fig. 2. Regions of parameter space that would be excluded by KamLAND at 90% C.L. if no evidence for oscillations were observed. (a) No background; (b) S/B=10:1 and background known to 25%; (c) S/B=10:1 and background determined from reactor power modulation alone.