

## 5 Neutrino Physics

### 5.1 KamLAND

On January 22, 2002, the Kamioka Liquid-scintillator Anti-Neutrino Detector, KamLAND, began taking data for the initial reactor phase of the experiment. In December 2002, the KamLAND collaboration announced the first results showing evidence for reactor anti-neutrino disappearance. Published in Physical Review Letters in January 2003, the abstract states: “In the context of two-flavor neutrino oscillations with CPT invariance, all solutions to the solar neutrino problem except for the “large mixing angle” region are excluded.” Specifically, the analysis of 162 ton-yr (145.1 days) of data shows the ratio of detected reactor anti-neutrinos to the number expected based on known reactor physics and neutrino propagation, assuming no oscillations, is  $0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$  for  $E_{\bar{\nu}} > 3.4$  MeV [Egu03].

KamLAND is the first terrestrial experiment to be sensitive to the neutrino oscillation parameters allowed by solar neutrino detector data. Numerous papers appearing in the months following the announcement refer to this result to update theoretical predictions and re-evaluate experimental limits. Global analysis combining solar neutrino data with the KamLAND results greatly restricts the allowed parameter region [Bal03].

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[Bal03] A. B. Balantekin and H. Yüксе, J. Phys. G, **29**, 665 (2003).

[Egu03] K. Eguchi *et al.*, Phys. Rev. Lett. **90**, 021802 (2003).

#### 5.1.1 Status of the KamLAND Neutrino Detector Project

*C.R. Gould, H.J. Karwowski, D.M. Markoff, J.A. Messimore, K. Nakamura, R.M. Rohm, W. Tornow, and A.R. Young*

The KamLAND Inner Detector (ID) neutrino target consists of 1 kt of ultra-pure liquid scintillator viewed by 1879 photomultiplier tubes (PMTs) optimized to detect low-energy anti-neutrinos in a coincidence measurement of inverse beta decay ( $\bar{\nu} + p \rightarrow n + e^+$ ) followed by neutron capture. An anti-neutrino candidate event is one with a prompt energy characteristic of the capture of a reactor  $\bar{\nu}$  of energy 1.8 to 8 MeV, followed by a correlated delayed neutron capture signal, the deposit of 1.8 to 2.6 MeV within specified ranges of time and position. Most background signals are suppressed by requiring the coincident event signature and by using strategic fiducial volume cuts that remove high contamination regions (namely the balloon that separates the liquid scintillator from the buffer oil and

PMT region). The most serious background comes from coincident events produced by muon-induced spallation neutrons that scatter off protons and subsequently are captured.

TUNL’s on-site responsibility is the maintenance of the Outer Detector (OD) region, a water Čerenkov detector designed to detect muons that pass near or through the central detector region. Muons are detected with a calculated 99% efficiency, providing a time-based veto in the offline analysis to eliminate background events from high-energy neutrons produced by muon spallation.

The OD consists of an array of 225 20-inch photomultiplier tubes located above, below and on the side in a cylindrical array surrounding the stainless steel sphere that houses the inner detector. To improve the OD sensitivity to muons passing through the detector, Tyvek, a reflective material produced by Dupont, was mounted on surfaces throughout the OD region to increase light detection from multiple directions.

At the time KamLAND began taking data in January 2002, 28 PMTs were identified as not responding properly caused by either a short in the high-voltage (HV) line or by a faulty signal generated when the tube held voltage. In the initial data-acquisition time, a number of tubes were identified as “failed” and deactivated. The rate of deactivation decreased to less than 2 per month in the second year of data taking. As of 1 July 2003, a total of 73 tubes have been turned off. The analysis of these tubes, their apparent failure modes, and the possibility of revival is discussed in Section 5.1.5.

TUNL’s computational efforts have concentrated on the efficiency of the OD considering the deactivation of PMTs and on the study of background neutrons that may enter the ID without a muon tag from the OD. In Section 5.1.2 is a discussion of the OD efficiency including predictions assuming continued deactivation of tubes. The neutron background analysis is presented in Section 5.1.3.

In addition, TUNL collaborators have contributed to the general running of the detector with experiment shifts. Each author contributed at least one required experiment shift. For the first year of running, TUNL researchers contributed 23 shifts, or 10% of the annual total required. In the second year of data acquisition, beginning January 2003, TUNL is scheduled for 18 shifts, a total of 9% of the annual collaboration total.

In July, 2003, TUNL graduate student Jason Messimore became the first US student to complete his PhD based on research done with the KamLAND detector [Mes03].

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[Mes03] J. A. Messimore, Ph.D. thesis, North Carolina State University, 2003.

### 5.1.2 Muon-Tagging Efficiency Simulations for the KamLAND Outer Detector

*C.R. Gould, H.J. Karwowski, D.M. Markoff, J.A. Messimore, K. Nakamura, R.M. Rohm, and W. Tornow*

The threshold settings of the KamLAND Outer Detector (OD) play an important role in determining the efficiency with which background muons are detected. In an effort to support the selected threshold values [Mes02] and model the muon-tagging efficiency in the OD, a series of simulations have been performed. The threshold value to be studied is the NSUM trigger, which is the number of PMTs that must fire for an event to be recorded. Implementation of the full tracking of Čerenkov light with a detailed model of the OD geometry was performed through the use of the FORTRAN based GEANT code, version 3.21 [App94].

Each simulation consisted of 5000 muon events. To determine the optimal NSUM threshold value for each of the four OD regions, all 225 PMTs were activated and several sets of thresholds were studied. Modeling of the muon-tagging efficiency was then performed using the optimal NSUM thresholds but with differing numbers of PMTs deactivated.

#### KamLAND Threshold Verification

Of the 5000 simulated muon events, there were 113 events that did not produce any photons, meaning that these events did not enter the Outer Detector and can be labeled as ‘rock’ events. There were 2 events which produced relatively few photons and were labeled ‘skimmer’ events because they had short track lengths and did not trigger any PMTs. Various cuts can be made on the same data set to analyze the different NSUM thresholds. Events that trigger at least one PMT in the OD but do not trigger more than the NSUM threshold in any region are declared ‘below threshold’ events. Although the number of below threshold events will vary with NSUM threshold, the number of rock and skimmer events will not be affected.

The sum of the rock, skimmer, and below threshold events comprise the total number of muons that are not detected by the OD. The overall Outer Detector efficiency for a set of NSUM thresholds is determined by the equation

$$\text{Efficiency} = \frac{\# \text{ simulated events} - \# \text{ total undetected}}{\# \text{ simulated events} - \# \text{ rock events}}. \quad (5.1)$$

Since the rock events never enter the Outer Detector, they can not be detected and are not used to determine the efficiency. The simulation results confirm that having NSUM thresholds as high as eight for each of the four regions enable the Outer Detector to meet the requirement of tagging  $> 99\%$  of the through-going cosmic-ray muons. Therefore,

KamLAND's current operating NSUM thresholds of 6-5-6-7 are determined online as a compromise of minimizing noise events and maximizing muon events. This assumes an operating efficiency greater than 99% with all PMTs activated.

### **Efficiencies for Various Outer Detector Scenarios**

During the startup period of KamLAND, several PMTs failed and several more have been deactivated over the course of the experiment [Mar02]. Therefore, it is necessary to repeat the above analysis and determine how the muon-tagging efficiency changes as PMTs are deactivated using the current operating NSUM thresholds.

Although some of the scenarios had PMTs removed in a symmetric sequence, this would be an unlikely occurrence in reality. A more random distribution of inactive PMTs may decrease the tagging efficiency due to localized areas of inactive PMT coverage. However, in the simulation cases, enough of the Čerenkov photons produced by the muons are detected by the remaining PMTs such that the efficiency does not decline very fast. These simulations indicate that the muon-tagging ability of the KamLAND Outer Detector does not decrease below  $95.1 \pm 0.4\%$  until more than half of the PMTs are deactivated.

For a comparison of the NSUM plots, the same 46 PMTs that were deactivated in KamLAND Run #677 were removed from the simulation. The NSUM plots show the same general features, although there are some differences. In the top region, Run #677 shows a large number of events at low NSUM values. It is believed that the Tyvek separating the upper and top regions has been compromised, allowing light to leak into the top region from below producing low NSUM events compared to the complete separation modeled in the simulation. In the upper region however, the KamLAND data lacks the low NSUM peak which in the simulation occurs because of light leakage between the upper and lower regions. This difference can be explained by the method in which the muon events were selected for this study [Nak02]. By choosing muon events that only pass through the Inner Detector, a bias towards muons that are not susceptible to shadowing is introduced and therefore, low NSUM events are largely eliminated. In general, the plots validate the ability of the simulations to reproduce KamLAND data.

Using similar proportions of inactive PMTs per region as the current (June 30, 2003) loss configuration of 78 PMTs, a simulation was performed with a distribution of 126 PMTs removed. Therefore, the top region has 15 inactive PMTs, the upper region has 26, the lower region has 35, and the bottom region has 50. These inactive PMTs are randomly distributed throughout each region. Because the bottom region only has five active PMTs, an NSUM threshold of seven effectively prevents this region from tagging any muons. Therefore, it becomes necessary to determine the effect of a change in the NSUM thresholds on the muon-tagging efficiency when the number of deactivated PMTs in a region approaches the threshold. Using NSUM thresholds of 5-5-5-5 yields a muon-tagging efficiency of  $95.0 \pm 0.4\%$  while thresholds of 3-3-3-3 produces an efficiency of  $97.8 \pm 0.3\%$ . The conclusion drawn is

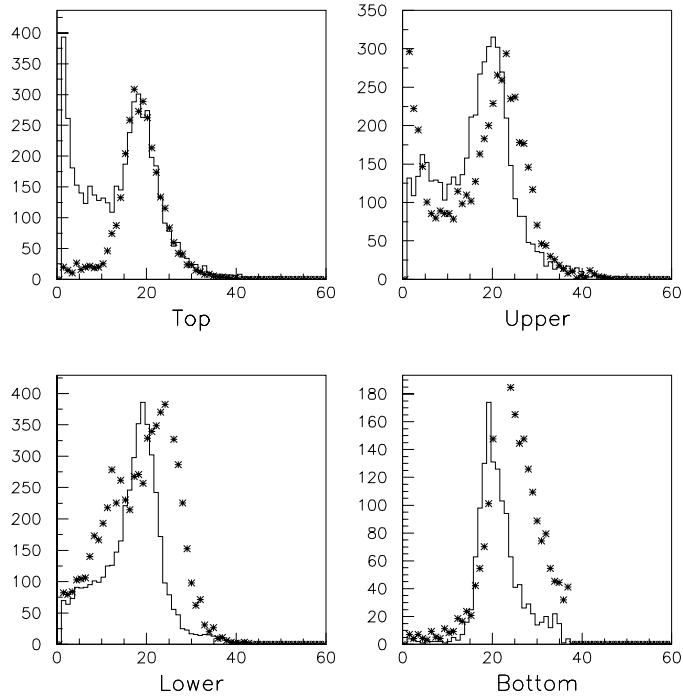


Figure 5.1–1: Comparison of normalized NSUM plots with deactivated PMTs for the four Outer Detector regions. The simulation NSUM plots for the four regions of the Outer Detector (denoted by \*) are overlaid with the actual NSUM plots for data run #677 (solid line). This simulation removed the same 46 PMTs that were deactivated in Run #677. See text for further discussion.

that when the number of deactivated PMTs becomes large, it is possible to raise the muon-tagging efficiency by lowering the NSUM threshold values.

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[App94] Application Software Group, *GEANT: Detector Description and Simulation Tool*, CERN, 1994.

[Mar02] D. Markoff *et al.*, TUNL Progress Report, **XLI**, 78 (2002).

[Mes02] J. A. Messimore *et al.*, TUNL Progress Report, **XLI**, 80 (2002).

[Nak02] K. Nakamura *et al.*, TUNL Progress Report, **XLI**, 82 (2002).

### 5.1.3 Neutron Background Simulations for the KamLAND Outer Detector

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Spallation induced neutrons are a major source of background for KamLAND because these neutrons can mimic the neutrino signal. The neutrino interacts in the Inner Detector (ID) via the inverse beta-decay reaction on a proton. The signature is a delayed coincidence of the positron, with neutron capture occurring approximately 200  $\mu\text{s}$  after the positron annihilation. A spallation neutron can scatter off of protons in the ID, with the recoils possibly mimicking the positron signal. If the neutron is then captured, a fake signal could be produced.

In an effort to determine this background, an in-depth simulation was performed using the FORTRAN based GEANT code [App94] with a neutron spectrum described by Wang *et al.* [Wan01]. Calculations were also performed to determine the muon-tagging efficiency for when the Outer Detector (OD) becomes ineffective due to the deactivation of PMTs.

The same spatial and energy cuts that are used in the KamLAND data analysis were used in the simulation to determine the number of neutrons that could cause a fake signal. From a total of 250,000 simulated neutrons, only seven produced a fake signal. To determine the number of neutron background events,  $N_n$ , that are produced by through-going muons, the following equation was used

$$N_n = R_\mu(1 - \Upsilon)R_{\mu \rightarrow n}\chi\xi\Lambda R_f, \quad (5.2)$$

where  $R_\mu$  is defined as the muon flux rate (in Hz) through the region of interest,  $\Upsilon$  is the tagging efficiency for the through-going muons,  $R_{\mu \rightarrow n}$  is the number of neutrons that are produced per muon per  $\text{gcm}^{-2}$ ,  $\chi$  is the effective thickness of the region in  $\text{gcm}^{-2}$ ,  $\xi$  is the fraction of neutrons that are directed in towards the detector volume,  $\Lambda$  is the survival factor due to attenuation, and  $R_f$  is the percentage of neutrons that cause a fake signal.

Because the muon-tagging efficiency in the ID is considered 100%, the neutron background stems from two situations: (1) that which is produced from muons that travel only through the rock annulus, denoted  $N_{nr}$ , and (2) that which comes from the untagged muons traversing through the OD, labeled  $N_{nOD}$ . The total background is the sum of these two cases.

$R_\mu$  and  $\chi$  were determined by simulation using a one meter rock annulus to surround the detector so that the muon flux through the different regions of the detector and the average path length through these regions could be calculated. The effective thickness,  $\chi$ , is obtained by multiplying the average path length by the density for each region. The neutron yield as a function of muon energy is calculated by using Wang *et al.* [Wan01] and a mean muon energy at KamLAND of  $\approx 216$  GeV.

Attenuation in the water is incorporated by the simulation. However, attenuation through the rock annulus is not. Assuming a uniform production in the rock, the survival factor,  $\Lambda_{rock}$ , was calculated by accounting for the variation in attenuation length with respect to neutron energy and population.

If it is assumed that roughly half of the neutrons travel in towards the detector, the number of fake events for the case of rock only muons is  $N_{nr} = (1.2 \pm 0.4) \times 10^{-7}$  Hz, while the number of fake events caused by untagged muons that enter the OD is  $N_{nOD} = (1.1 \pm 0.3) \times 10^{-8}$  Hz. Adding these numbers and converting the result to the total number of fake events over 145.1 days gives a background of  $1.3 \pm 0.4$  neutrons, comparable to the value of 0.5 neutrons cited in the first paper of the KamLAND experiment [Egu03]. The simulation confirms that for the current OD muon-tagging efficiency of 99.5%, the background due to spallation neutrons is indeed small and does not affect KamLAND's results.

The effectiveness of the OD becomes questionable when  $N_{nOD} \approx N_{nr}$  because the neutron background starts to become dominated by neutrons produced by untagged muons. Setting  $N_{nOD} = 1.2 \times 10^{-7}$  Hz and solving for the efficiency  $\Upsilon_{OD}$ , the minimum OD efficiency is determined to be  $94.8 \pm 0.1\%$ . Based on the results of the muon-tagging efficiency simulations with deactivated PMTs, the OD is still effective with as few as 15 PMTs in each of the four regions. In addition, changing the NSUM thresholds to lower values as the number of deactivated PMTs increases will allow the OD to maintain a muon-tagging efficiency greater than the minimum. Removing the Outer Detector from operation would have resulted in  $29 \pm 9$  neutron fake events over the 145.1 day period. Therefore, it is important to keep the Outer Detector in operation as long as it is able to actively veto through-going muons.

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[App94] Application Software Group, *GEANT: Detector Description and Simulation Tool*, CERN, 1994.

[Egu03] K. Eguchi *et al.*, Phys. Rev. Lett. **90**, 021802 (2003).

[Wan01] Y.-F. Wang *et al.*, Phys. Rev. D, **D64**, 013012 (2001).

#### 5.1.4 Detector Simulations with GEANT4

*R.M. Rohm and R.A. Wendell*

Muon-induced backgrounds in the detector are being studied using *klg4sim*, a Geant4-based simulation of the KamLAND detector response. Updated versions of *klg4sim* are running on local workstations as well as at the National Energy Research Scientific Computing Center, NERSC, cluster facility PDSF, the Parallel Distributed Systems Facility.

In addition to simulating backgrounds from muon-induced spallation in the rock, this will provide an independent comparison for the Geant3 outer-detector simulation discussed in Sect. 5.1.3. The current focus is on code modifications to decrease the simulation time per event and to optimize for different experimental observables.

### 5.1.5 Analysis of KamLAND Outer Detector High-Rate Photomultiplier Tubes

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From the fall of 2001, when the water filling of the Outer Detector (OD) was completed, until June of 2003, 73 photomultiplier tubes were removed from the data-acquisition system. During the integration phase before data taking began and in the period soon after, approximately 10% of the installed tubes failed to sustain high voltage. Others held the correct voltage, but failed to produce a reasonable signal. Following this initial period, several tubes were turned off after they failed to sustain the high-voltage set value, however, many more tubes were turned off after exhibiting high pulse rates. The deactivation rate of PMTs has decreased to an average of two per month during the second year of running that began in January 2003.

At times, the noisy tubes were identified as causing nearby tubes to behave with a high rate of pulses above discriminator threshold. As a result of several tubes firing at a high rate, the OD trigger rate exceeds the usual value of about 10 Hz, and interferes with the data-acquisition system. These tubes are called “flashers” since the mechanism of inducing pulses in neighboring tubes was explained by the tube producing flashes of light that are subsequently detected. The OD rate returns to the baseline value after the high voltage for the troubled tube or tubes is turned off.

An electronics based explanation for high-rate OD tubes interfering with the data-acquisition system arises from the ability for large signals (greater than 1 V) to affect the ground level in nearby channels. By altering the base voltage, the incoming PMT signals can trigger above the discriminator threshold that is referenced to ground. If enough tubes are affected, the rate of triggering above the PMT trigger threshold in that region will greatly increase. In February 2002, signals from tube S-1-63 were periodically greater than 6 V as seen on the oscilloscope, while nearby tubes recorded a high rate of normal pulse sizes (on the order of 20 mV).

We investigated the behavior of the high-rate OD tubes that were identified as “flashers.” We analyzed the data from Runs 1486, 2227, and 1611 in which PMTs S-6-9, S-6-99, and T-1-243, respectively, were identified as flashers and turned off. After the tubes were turned off, the data rates returned to normal. We saw no specific evidence including the number of noise pulses or good pulses, the shape, timing or characteristics of the pulses that was particular to the “flasher” tube. The cluster of high-rate PMTs all showed similar pulse

behavior, and in some instances a neighboring tube exhibited the more extreme behavior in one or more of the categories of pulse characteristics studied.

An external source causing multiple tubes to produce pulses at a high rate would show a large correlation ( $\sim 100\%$ ) between two affected tubes. In the high-rate tube cluster data runs mentioned above, the largest correlation between a high-rate tube and any other tube was less than 0.3. A study of the timing of the pulses showed that on average no one single tube recorded a pulse before any other tube; the average reference times for the pulses of several tubes were the same within statistical errors. In addition, the timing between the pulses of two tubes did not coincide with the difference in time for light to travel the separation distance in water between a source (flashing) PMT and these tubes. These data do not identify any one PMT or show evidence of an external source as the initiator of the time-correlated pulses. We conclude that the mechanism of a tube producing light, or flashing, cannot explain the data in these runs.

Our current understanding of the data supports the conclusion that a number of high-rate tubes that were turned off could be safely reactivated. The noise rate of a number of tubes would be reduced with a lower high-voltage setting and may require raising the electronics discriminator threshold.

Testing of OD PMTs will take place during the next detector downtime currently scheduled for the end of 2003.