R&D for possible future improvements of KamLAND

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Abstract. Research and development are being undertaken for possible future plans of KamLAND. Electronics, the liquid scintillator, and the photodetectors are targets of modifications and improvements, aiming at further low-background and high-sensitivity neutrino physics.

1. Introduction
KamLAND, a 1-kt liquid scintillator neutrino detector, succeeded in precisely measuring reactor neutrino oscillation and investigating “geoneutrinos” experimentally for the first time. Currently, the KamLAND scintillator is being re-purified for the detection of solar \(^{7}\)Be neutrinos. For possible plans after that, the detection of solar pep and CNO neutrinos, a search for neutrinoless double beta decay, and directional measurements of antineutrinos are being studied.

2. MoGURA, Dead-Time Free Electronics for KamLAND Solar Phase

2.1. \(^{11}\)C Tagging with KamLAND
One of the interesting KamLAND goals is detection of the CNO and pep neutrinos, which dominate the solar neutrino flux above the \(^{7}\)Be neutrinos’ energy region. A contradiction between the recent research results from Standard Solar Model (SSM) and Helioseismology could be investigated by observing these neutrinos. In KamLAND, these neutrinos are overwhelmed by cosmogenic \(^{11}\)C background, which is produced in cosmic muon-induced spallation. We aim to reject those \(^{11}\)C events by tagging almost all cosmogenic neutrons after each muon, since more than 95% of the \(^{11}\)C production modes accompany one or more neutrons. This technique is called “\(^{11}\)C Tagging” [1].

To detect all neutron capture signals (mostly 2.2-MeV \(\gamma\) for proton capture) with a multiplicity of up to \(~100\) within \(~210\ \mu\)s after each muon, a dead-time-free data acquisition (DAQ) is needed. Concerning the amplitude and width of the smallest PMT signals (2 mV and 20 ns), high resolutions of both the voltage and the time are required. On the other hand, the amplitude of huge signals (up to 10 V, corresponding to the showering muon signals) requires a wide dynamic range. This range (up to \(~10^5\)) requires baseline stabilization, since baseline distortion made by a huge muon signal easily overwhelms the smallest 1 photoelectron (1 p.e.) signals from the following neutron events.
For this purpose, our newly designed front-end electronics (MoGURA: Module for General-Use Rapid-Application) equips Flash ADC (FADC) and FPGA for high-resolution dead-time-free DAQ and a baseline restorer (BLR) for baseline stabilization.

2.2. Dead-Time Free Electronics
The FADC and FPGA used in line are key components for dead-time-free electronics. One 1-GS/s 8-bit FADC and three 200-MS/s 8-bit FADCs are utilized for one MoGURA input channel, each of which accepts waveforms from different gain amplifiers. This combination realizes high resolution (0.1 mV, 1 ns) and a wide dynamic range (0.1 mV~10 V) simultaneously, as well as a dead-time-free ability. We utilize FPGA in three ways: Front-End FPGA (FEF) and System FPGA and User FPGA. FEF works as a transient memory, and also performs Zero Suppress on demand. System FPGA provides versatile functions for in line signal processing: Single Hit Rate for salvaging events from noise, Auto Baseline Scanning for digital baseline determination and Digital Hit Detection, and Independent Hit Time Information Recording for accurate time determination. User FPGA also works as an on-board signal processor, which may perform TQ analysis and data compression.

2.3. Baseline Restorer
KamLAND PMTs have AC coupling on their output circuits. Due to this AC coupling, the overshoot of a huge signal overwhells the following small signals. This causes fluctuation in effective threshold, as well as the saturation of the highest-gain channel. The time constant of this overshoot (~500 μs) strongly requires BLR, since otherwise we may be blind in the meantime. We call our BLR as Asymmetric LPFed Active Baseline Subtraction BLR. In this BLR, the positive component of the baseline of the input waveform is extracted by ideal diodes then averaged and held by a capacitor, and then subtracted from the input waveform. In this manner, an overshoot, which originated positive bias compared to the original baseline, is restored, but negative pulses, which should be signals, are not distorted. With this circuit, any baseline distortion by overshoot is restored in 1 μs.

2.4. Conclusions
Detection of the CNO and pep neutrinos requires ¹¹C Tagging. This leads us to dead-time free electronics with high resolution and a wide dynamic range. We designed new front-end electronics, MoGURA, by utilizing FADC and in line FPGA. Baseline distortion due to AC coupling in the PMT is restored by 100-times faster with our BLR. MoGURA will be set in KamLAND in 2008.

3. Study of double beta decay in KamLAND
For a possible search for neutrinoless double-beta decay, using the large-volume and low-background KamLAND environment, numerical simulations have been performed for two isotopes, i.e., ¹³⁶Xe and ¹⁵⁰Nd. The data of KamLAND show that the low-energy region (E < 3 MeV) of the single spectrum is dominated by long-lived spallation products (¹⁰C and ¹¹C), while, the region E > 3 MeV is dominated by short-lived ones, which can be rejected in an off-line analysis. Then an isotope whose Q-value is more than 3 MeV should be worthy of study. We marked ¹⁵⁰Nd because of the advantages of a high Q-value (3.37 MeV) and a high natural abundance (5.6%). On the other hand, it is very attractive that Xe gas can be dissolved [2] in the current liquid scintillator (LS) up to 2 wt%, without further development; we thus also choose ¹³⁶Xe (Q-value is 2.48 MeV). Possible milestones are: (i) to verify or exclude the KKDC claim [3] on the effective neutrino mass, <m>, between 240 and 580 meV with the best-fit 440 meV, and (ii) to explore the case of the inverted mass hierarchy, i.e., <m> ~ 30meV.

The results of a simulation show that the expected sensitivity of ¹³⁶Xe is at the level of 440 meV under the following conditions: 80% enriched ¹³⁶Xe, 2 wt% of Xe dissolved in 544-ton LS, an energy resolution of 6.5% / √E(MeV), and a 3-year observation. There are much spallation ¹⁰C backgrounds around Q-value of ¹³⁶Xe, so we need to reduce them with dead time free electronics described above. The expectation of ¹⁵⁰Nd seems to be promising, reaching not only the KKDC level, but also the
inverted mass hierarchy (30 meV) with 5-sigma, assuming 60% enriched $^{150}$Nd, 1 wt % of Nd dissolved in 544-ton LS, an energy resolution of $6.5\% / \sqrt{E(\text{MeV})}$, and a 3-year observation. Furthermore, if we develop a liquid scintillator with a 50% higher light yield than the current KamLAND LS, the 5-sigma sensitivity will be 20 meV.

Of course, there are many things to do. The first thing that we have to do is to develop a new 1 wt % Nd-loaded liquid scintillator (good light emission, good transparency, and also achieve stability and safety etc.). We also have to investigate other possible backgrounds ($^{208}$Tl, gamma-ray, spallation products from target, another radioactive impurity etc), research ways of enrichment (time and cost) and purification, study the energy resolution, and calculate the sensitivity including all backgrounds and systematic uncertainties. Many of these studies will be carried out in the near future.

4. Directional measurement of electron anti neutrinos

The detection of electron antineutrinos ($\bar{\nu}_e$) with KamLAND is via the traditional inverse $\beta$–decay mode, $\bar{\nu}_e + p \rightarrow e^+ + n$, where the prompt signal from $e^+$ and the delayed 2.2-MeV $\gamma$ from neutron capture on a proton make a delayed coincidence. In addition to powerful background rejection, this coincidence can be used to measure the direction of $\bar{\nu}_e$ [4] by measuring the relative position of prompt and delayed vertexes, since, especially for low-energy $\bar{\nu}_e$'s, kinematics and differential cross sections allow only neutrons emitted in forward directions. In the current KamLAND, however, the position resolutions are not enough to detect the expected displacement between the prompt and delayed vertexes, because of the diffusion of thermal neutrons, a long interaction length of 2.2-MeV $\gamma$, and a limited time resolution of PMT’s. For future geoneutrino research [5], there are plans to improve those issues for directional measurements of $\bar{\nu}_e$'s, which would enable us to ‘map’ earthly powers of uranium and thorium with a geoneutrino probe. We also aim at it with the following techniques.

4.1. Lithium-loaded liquid scintillator

For effective neutron detection, one can employ liquid scintillator doped with $^6$Li, $^{10}$B, or Gd. For our purpose, $^6$Li is the best candidate, because, in addition to the large cross section for thermal-neutron capture 940 barns, the reaction $n + ^6$Li $\rightarrow \alpha + ^3$T yields $\alpha$ and triton ($^3$T), which are confined in a small volume. We estimate that 0.15 wt% of $^6$Li is required to be dissolved in the liquid scintillator, so that the diffusion of thermal neutrons is sufficiently small and the lifetime of neutrons is about 5 $\mu$s. We have already started developing Lithium-loaded scintillator with a high light yield, high transparency, a low quenching effect, long-term stability, and sufficiently low cost per unit volume. We are trying various kinds of solute (e.g., LiCl, Li-carbonate, Li-acetate, etc) and solvents (e.g. Ethylene glycol, Octanol, Toluene, etc).

4.2. Vertex detection by optical imaging

Recently, imaging cameras have become possible to be used for the detection of scintillation track [6]. We are trying to apply an imaging camera to detect prompt and delayed vertexes, although there are many challenging issues. Assuming KamLAND size, the depth of field is very large, e.g., between 2.5 and 15.5 m. Also, high light collection efficiency is required, because the photo-coverage cannot be smaller than the current PMT system (34%). A large target size and a small area of possible photodetectors (see the next subsection) require extremely small magnification ($\sim 10^{-3} \sim 10^{-5}$). At the same time, however, a small aberration is needed, because the necessary position resolution is on the order of the displacement between the prompt and delayed vertexes $\sim$10mm. The naïvely estimated focal length is about 10mm.

Considering this small focal-length compared with the large depth of field, one possible design is “pan-focus”, where the far boundary of the depth of field is infinity. In the pan-focus design, the number of free parameters is reduced by a strict relation in this framework. Based on such a simplified
model, we are performing simulations to find the best optics. Currently, the estimated number of optical modules is unrealistically large, but we expect that it can be reduced by setting less strict requirements for aberration, depth of field, and light collection efficiency etc.

4.3. Photodetector

Candidates for the photodetector systems are (i) an image intensifier (I.I.) and a CCD camera assembly, or (ii) a pixelated photon detector (PPD) with 4 readout channels, just like a position sensitive detector (PSD) assembly. In both cases, the minimal requirements are satisfied, i.e., sufficiently high gain for one photoelectron detection with sufficiently high quantum efficiency, and fast data acquisition that enables two successive events with an interval of 1 μs to be acquired with no data loss.

We started with a test of the I.I. and CCD assembly with cosmic-ray muon events (Fig. 1). Three plastic scintillators (“PS” in the figure) detect muons going through the liquid scintillator (LS). The three-fold coincidence of these PS signals issues a trigger to open the CCD’s gate. The I.I. amplifies scintillation track with a gain ~10^6 to display an afterglow at the fluorescence plane at the rear end, which is viewed by the CCD. Fig. 2 shows a resultant image of a cosmic-ray muon. We are now trying the next stage, i.e., detecting low-energy events from a ^{137}Cs source.

![Fig. 1. Schematic view of the test of I.I. and CCD assembly to detect cosmic-ray muons.](image1)

![Fig. 2. An acquired image of a cosmic-ray muon.](image2)

References

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