Research and development toward KamLAND2-Zen

R. Nakamura, H. Sambonsugi, K. Shiraishi and Y. Wada
Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
E-mail: rikuo@awa.tohoku.ac.jp

Abstract. The KamLAND2-Zen experiment is a future plan of KamLAND-Zen, which searches for neutrino-less double-beta decay \(0\nu\beta\beta\) of \(^{136}\text{Xe}\), with low background measurements. The goal of this experiment is to reach a sensitivity of \(\langle m_{\beta\beta} \rangle < 20\) meV which covers the inverted hierarchy region. It can be achieved by increasing the light yield with light collecting mirrors, new brighter liquid scintillator and higher quantum efficiency photomultiplier tubes (PMTs) and scintillation vessel. In this paper, we describe the R&Ds for KamLAND2-Zen experiment.

1. Introduction
The KamLAND-Zen\(^{[1]}\) is an experiment to search for \(0\nu\beta\beta\) of \(^{136}\text{Xe}\) with the KamLAND detector which has a 1 kt of liquid scintillator (LS). KamLAND2-Zen is planning stage to further improve the sensitivity over KamLAND-Zen. A scintillation balloon, liquid scintillator, light collecting mirror and associated high QE PMT are under development toward this plan.

2. Scintillation balloon
In KamLAND-Zen 800\(^{[2]}\), Xe-loaded LS is contained in a 1.92 m-radius nylon made inner balloon (IB). The IB was made as low radioactive as possible, however the contamination level of \(^{238}\text{U}\) is \(3 \times 10^{-12}\) g/g and it’s daughter nuclei \(^{214}\text{Bi}\) will be the largest background events. Therefore we are planning to use the polyethylene naphthalate (PEN) film for scintillation IB in KamLAND2-Zen\(^{[3]}\). It enables us to tag \(^{214}\text{Bi}\) by delayed coincidence counting with \(^{214}\text{Po}\). However, because of short life-time (430nsec) and visible energy shift, \(^{212}\text{Bi}\)-\(^{212}\text{Po}\) pile-up events would become new background for \(0\nu\beta\beta\). This background would be rejected by pulse shape discrimination (PSD) if the waveform of LS and PEN are significantly different. Fig. 1 shows the template waveforms obtained using alpha-rays emitted by \(^{214}\text{Po}\) in a vial and 2inch PMT. Using them, tests were performed to check if PSD between LS and PEN is possible in a vial. We used PC-LS (PC:20% Decane:80%, PPO:2 g/L, bis-MSB:0.16 g/L), LAB-LS (LAB:100%, PPO:2 g/L, bis-MSB:0.16 g/L), and PEN. Signals of LS and PEN were fitted by each template waveforms. Fig. 2 and Fig. 3 show the difference of the \(\chi^2\) distributions. Red line, blue line and black line shows the difference of the \(\chi^2\) distributions of PC-LS, LAB-LS and PEN. According to this result, PSD with LS and PEN is possible with high efficiency.

3. New liquid scintillator
As we mentioned above, we are planning to use a IB made of PEN in KamLAND2-Zen. However, the PEN film has absorption at wavelength of LS light emission. A wavelength shifter is required.
A candidate for a wavelength shifter is bis-MSB. We measured a light yield using the back scattering electron (477 keV) of $^{137}$Cs $\gamma$ ray. The measured light yields are summarized in Table 1, each LS with bis-MSB have higher light yield. We have measured the transparency of the LS with bis-MSB. As seen in Fig. 4, it was confirmed that the wavelength is shifted due to addition of bis-MSB. Solid line and dots line show the transparency and light emission of LS.

This shows that the problem of the transparency of PEN is solved and that the light yield is increased by using LS with bis-MSB.

| Sample LS           | Composition                        | Ratio  | ADC-ch   |
|---------------------|------------------------------------|--------|----------|
| Kam-LS              | PC:19.8%, Dodecane:80.2% + PPO 1.36g/L | 1.000  | 142.3±2.3|
| LAB-LS              | LAB:100% + PPO 2.00g/L             | 1.002  | 142.6±2.3|
| Kam-LS+bis-MSB      | Kam-LS + bis-MSB 15mg/L            | 1.124  | 159.9±2.6|
| LAB-LS+bis-MSB      | LAB-LS + bis-MSB 15mg/L            | 1.126  | 160.2±2.6|

4. Light collecting mirrors
KamLAND has 1,879 PMTs. However, there is dead spaces between the PMTs. By mounting light collecting mirrors on the PMTs would reduce dead space and increase the light yield. Light collecting mirror is one of the key improvements in KamLAND2-Zen.

There are two candidates for the mirror shapes. One is circular mirrors and the other is polygonal mirrors. Fig. 5 shows the light yield alteration by mounting circular mirrors on PMTs in setup of KamLAND size for measurement of angle dependency. According to this measurement, the light yield for the PMT with the mirror increased by a factor of 1.8 compared with the PMT without a mirror.

We expect that the polygonal mirrors can reduce further the dead space compared with circular mirror. Fig. 6 shows the performance of the mirrors in a simulation of prototype detector for KamLAND2-Zen. The light yield for PMT with mounted the polygonal mirrors increased by a factor of 2.4 compared with the PMT without the mirror in the prototype detector.

5. Low impedance PMTs
Currently, the number of the low-gain PMTs is increasing gradually. When we measured impedance of low-gain PMTs, we found abnormal low impedance. This is an important problem to be solved toward KamLAND2-Zen. We suspect that the cause of the low impedance PMTs is due to the shorted capacitor in the breeder circuit. We studied the behavior of PMT with
replacement of one capacitor with 0 Ω resistance. As a result of this experiment, the gain and the transit time change a little and these changes are not sufficient to explain the low gain PMTs at KamLAND. We also performed an endurance test by repeating to charge and dis-charge the capacitor by turning HV on and off. Fig. 7 shows the circuit diagram, we measured the sum of capacitance of 4 capacitors before and after the test. The number of switching is equivalent to charge/discharge by muon event for 9.53 hours at KamLAND running in expected. As a result of this test, only a 5% decrease of the capacitance of the 4 capacitors for 6.5 years equivalent of KamLAND running is expected. Even if this test was continued until 15 years equivalent to KamLAND running, dielectric breakdown does not happen.

6. Summary
KamLAND2-Zen experiment is under research and development. By using a scintillation balloon and new liquid scintillator, there is possibility of rejecting $^{212}$Bi-$^{212}$Po pile-up background. By mounting light collecting mirror, the light yield for PMT increases. The research is on going to solve problem of the low impedance PMTs.

References
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