First results of KamLAND-Zen 800

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Abstract. KamLAND-Zen is a neutrinoless double beta decay ($0\nu\beta\beta$) search experiment using xenon 136 and ultra-low background environment of KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector). KamLAND-Zen collaboration has prepared the KamLAND-Zen 800 project with almost 750 kg of xenon and cleaner container for xenon loaded liquid scintillator. The container production was started in May 2017 and KamLAND-Zen 800 data acquisition was started in January 2019. In this paper, we will describe the KamLAND-Zen 800 project and report on the detector condition, data quality, the first analysis results, and the prospects.

1. Introduction

Neutrinoless double beta ($0\nu\beta\beta$) decay is a key for physics beyond the Standard Model of elementary particles. If we observe this decay, then the neutrino behaves as a Majorana particle[1] and the decay process violates lepton number conservation. If the neutrino is Majorana type, extremely light neutrino mass is explained via the seesaw mechanism[2, 3] and may also explain the baryon asymmetry via leptogenesis[4]. The decay rate of $0\nu\beta\beta$ is proportional to the square of the effective neutrino mass, thus the event rate determines the mass scale of light neutrino mass. In order to conduct high sensitivity search for the $0\nu\beta\beta$ signal we need many double beta decaying nuclei, a long live time, and a background-free environment or powerful background rejection methods to eliminate noise events.

2. KamLAND-Zen

KamLAND-Zen is a $0\nu\beta\beta$ decay experiment using ^{136}Xe loaded liquid scintillator in the KamLAND detector [5]. KamLAND is located at 1,000 m depth (2,700 m.w.e.) where the cosmogenic muon rate is $\sim$0.3 Hz in whole the detector. In order to restrict the muon spallation products and solar ^{8}B neutrinos backgrounds which are proportional to the volume, xenon loaded liquid scintillator (Xe-LS) is located in a nylon made inner balloon (IB) surrounded by 1,000 tons of LS contained in a 13 m diameter outer balloon (Figure 1). Xe-LS can contain xenon at almost 3% by weight and isotopic abundance of ^{136}Xe is enriched to $\sim$91%. Xenon can be extracted from Xe-LS by vacuum and nitrogen bubbling, and be purified by distillation and filtration. It can also realize the ^{136}Xe blank measurements if we find the indication of $0\nu\beta\beta$ signal. KamLAND has achieved a 5×10^{-18} g/g and 1.3×10^{-17} g/g contamination level for ^{238}U and ^{232}Th respectively in liquid scintillator[6], thus it's very clean container allows a high sensitivity search for $0\nu\beta\beta$ decay. The IB for Xe-LS is made of 25 μm thickness nylon film (Figure 1) and is suspended at the center of KamLAND detector. KamLAND-Zen includes a series of projects: past KamLAND-Zen 400, current KamLAND-Zen 800, and future KamLAND2-Zen. KamLAND-Zen 400 terminated in October 2015, and released a lower limit for the half life of

$0\nu\beta\beta$ decay of $T_{1/2} > 1.07 \times 10^{26}$ years at 90% C.L corresponding to $\langle m_{\beta\beta} \rangle < 61-165$ meV [7]. KamLAND2-Zen will use 1 ton of xenon and is scheduled to start in 2027, and R&Ds are ongoing. The current project KamLAND-Zen 800 was started in 2015 and data acquisition was started in January 2019.

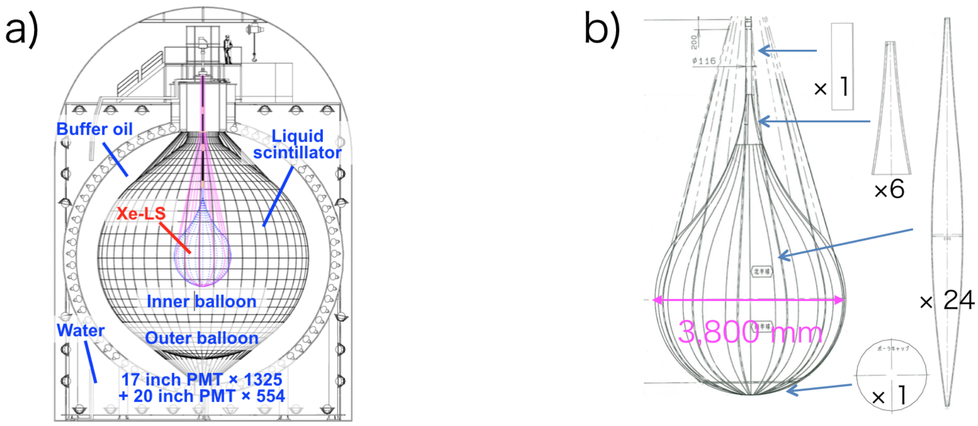

Figure 1. a) Schematic view of KamLAND-Zen. b) Nylon film parts used in the inner balloon.

3. Preparations for KamLAND-Zen 800
The main preparation of KamLAND-Zen 800 was fabrication of radioactively clean IB by nylon films. The nylon film for the IB has 99% transparency and a contamination level of $\sim 2\times10^{-12}$ g/g level for ^{238}U. All IB production was performed in class-1 super clean room, and all tools were used after the cleaning by ethanol, isopropyl alcohol, detergent, and ultra sonic cleaning with ultra pure water. The procedures of IB fabrication were as follows: film washing by ultra pure water with ultra sonic cleaning, film cutting for each part, heat welding to connect the films, leak check by helium and helium detector, and repairing by patching with a piece of nylon and glue.

Due to the spherical shape of the detector and access point to inside the KamLAND detector being only 50 cm in diameter, we folded the IB keeping its shape using perforated teflon sheet and teflon tubes. We installed the IB with heavier LS (+0.4%) compared to the KamLAND LS density. After sinking of IB in KamLAND LS, teflon sheets and cover nylon films were removed and pulled up. After the installation, we filled slightly heavier LS (+0.015%) without xenon, and the IB was expanded.

We purified non-xenon-loaded LS in the IB by distillation after the filling because ^{232}Th level was slightly high O(10^{-15}) g/g. Pile-up event by daughter nuclei ^{212}Bi - ^{212}Po makes the signal in the region of interest (ROI) of $0\nu\beta\beta$. After the purification, the ^{232}Th level was restricted to the same level as the un-removable solar ^{8}B neutrino backgrounds.

Xenon dissolving into LS was performed from December 2018 to January 2019. We drained the pure LS from upper area of IB and filled the slightly heavier Xe-LS to the bottom area thus making LS layer due to temperature and weight differences. We introduced xenon in LS with 2.6 wt% at the 1st circulation and 3.0 wt% after the 2nd circulation, loading totally 745 kg of xenon in the detector.

4. $0\nu\beta\beta$ search analysis
After waiting for the decaying of the ^{222}Rn coming from the emanation of piping line ($T_{1/2}$= 3.8 days), we started the data acquisition for $0\nu\beta\beta$ analysis on January 22, 2019. In this section, we

describe the detector condition, analysis methods and $0\nu\beta\beta$ search results for the initial 132.7 live-days of data.

Figure 2 shows the two dimensional vertex distribution at KamLAND-Zen 400 and KamLAND-Zen 800. Because of the contamination caused by pump failure at the KamLAND-Zen 400, bottom part of IB had a lot of background events. This IB also had ^{137}Cs coming from Fukushima reactor accident and ^{238}U and ^{40}K which were contaminated at the production. On the other hand, $2\nu\beta\beta$ dominates in all volume at the KamLAND-Zen 800 with exception of small area of bottom part. The ^{238}U contamination on/in the IB can be estimated by the vertex distribution of ^{214}Bi in the energy range of 2.35 – 2.70 MeV. From the analysis, the ^{238}U level is $\sim 3 \times 10^{-12}$ g/g and similar to the initial value of the nylon film. The ^{238}U contamination in the previous project was 4.6×10^{-11} g/g, thus the ^{238}U background level is improved by factor of ∼10.

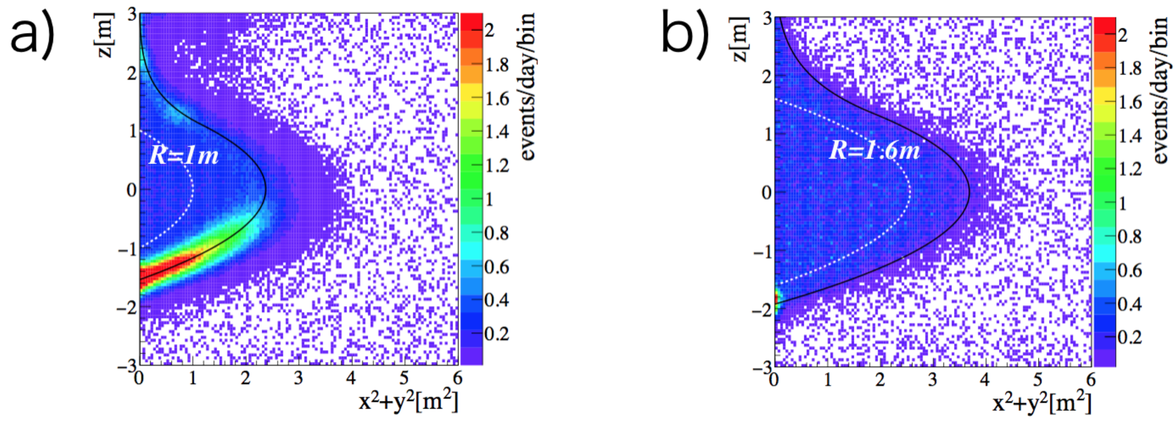

Figure 2. The vertex distribution in the energy range $1.0 < E < 2.3$ MeV in the KamLAND-Zen 400 phase II (a) and the KamLAND-Zen 800 (b).

In order to estimate the background effects, we defined 40 equal volume segments in the region of 250 cm radius as shown in Figure 3 a. The outer area is sensitive to the backgrounds from IB, and the inner area is used in the $0\nu\beta\beta$ search. We applied simultaneous fitting for 40 energy spectra to estimate the $0\nu\beta\beta$ and background events. The energy spectrum with inner 10 bins which are sensitive area for $0\nu\beta\beta$ search are shown in Figure 3 b. Some events remain in the region of interest (2.35 – 2.70 MeV), however, these are consistent with background estimations. The very preliminary 90% confidence level upper limit of $0\nu\beta\beta$ events from the simultaneous fitting are 6.0 events/day/kton-Xe-LS. It corresponding to the lower limit of $0\nu\beta\beta$ half-life of 4 $\times 10^{25}$ years.

The 90% confidence level upper limit sensitivity from the present analysis was estimated by the no $0\nu\beta\beta$ signal with best-fit background rate. The 50% sensitivity from toy MC model was 8×10^{25} years, and the probability of our very preliminary result is 92%.

Currently we are working on the analysis tuning and improvements. The possible backgrounds in ROI are the energy tail of $2\nu\beta\beta$, γ-ray from ^{214}Bi in IB, pile-up event from ^{212}Bi - ^{212}Po in LS, and cosmo-genic muon spallation products (^{10}C, ^{137}Xe etc.). In order to eliminate these possible backgrounds, the improved analysis methods are in progress as shown in Table 1.

5. Summary

$0\nu\beta\beta$ search experiment KamLAND-Zen 800 started at Jan. 22, 2019. The backgrounds from the xenon loaded liquid scintillator vessel was reduced by a factor of 10. The very preliminary

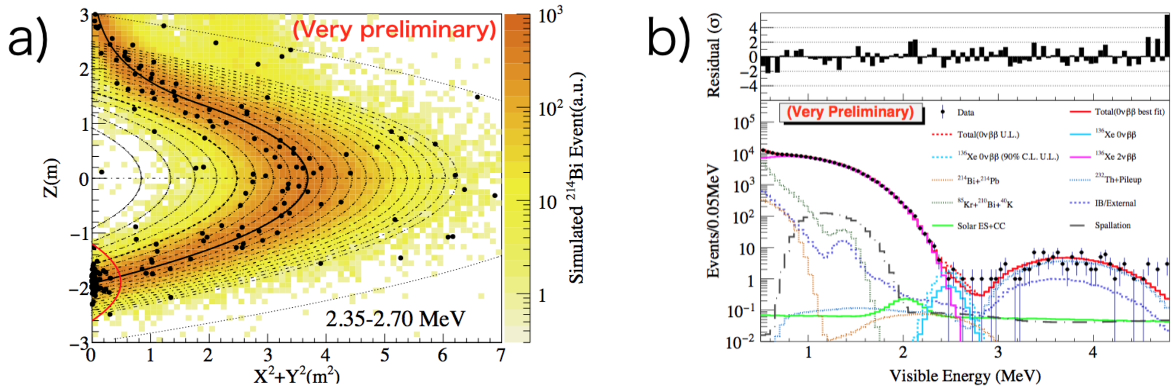

Figure 3. a) The areas of 40 bins used for simultaneous spectrum fitting. The inner area of redline has contamination and is not used in the spectrum fitting. b) The energy spectrum and fitting curve for the inner 10 bins.

Table 1. Lists of analysis tuning and improvements

Backgrounds 1	Rejection criteria	Reduction estimate
$2\nu\beta\beta$	Re-use of low gain PMTs	$\sim 2/3$
Film B.G.	PID (neural network tool)	$< 1/2$
Pile-up ^{212}Bi	Double pulse shape fit	
	neural network	$< 1/2$
^{10}C	Neural network tool	
	μ, n tagging improvement	
	electronics upgrade	$< 1/2$
Spallation (short-lived)	Muon correlation analysis tuning	$\sim$ neglisible level
Spallation (^{137}Xe)	Electronics upgrade	
	(neutron capture tagging improvement)	$< 1/4$

analysis of 132.7 days data gives lower limit for the $0\nu\beta\beta$ of 4 $\times$ 10^{25} years (90% confidence level), and the sensitivity is 8 $\times$ 10^{25} years. We are working on the further analysis tuning and improvements to the experiment.

References

[1] J. Schechter and J. W. F. Valle, *Phys. Rev. D*, **25**, 774 (1982).
[2] T.Yanagida, in *Proceedings of the workshop on Unified Theory and Baryon Number of the Uninverse,* eds. O.Sawada and A.Sugamoto (KEK) p.95.
[3] M.Gell-Mann, P.Ramond and R.Slansky, in *Supergravity,* eds. P.van Nieuwenhuizen and D.Freedman (North-Holland, Amsterdam) (1979).
[4] M. Fukugita, T. Yanagida, *Phys. Lett.* B**174** (1986) 45−47.
[5] K. Eguchi *et al.* (KamLAND Collaboration), *Phys. Rev. Lett.* **90** 021802 (2003)
[6] A.Gando *et al.* (KamLAND Collaboration) *Phys. Rev.* C **92**, 055808 (2015).
[7] A.Gando *et al.* (KamLAND-Zen Collaboration), *Phys. Rev. Lett.* **117** 082503 (2016).