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Latest results from KamLAND-Zen second phase

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Abstract

We report on preliminary results from the second phase of KamLAND-Zen double beta decay search experiment based on 114.8 days with 383 kg of ^{136}Xe. Second phase of KamLAND-Zen was started after the purification to reduce the dominant ^{110m}Ag background identified by first phase data. The background was reduced by more than a factor of 10 by purification for liquid scintillator and xenon gas. By combining the first and second phase data and applying the improved event selection, we obtained a preliminary lower limit for the neutrinoless double-beta decay half-life, $T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr at 90% C.L. We also present the prospects about current phase of KamLAND-Zen and next phases with upgrades.

1. Introduction

Majorana neutrino is one of the most interenting properties for particle physics and cosmology. If neutrino is Majorana particle, considering the see-saw model, unnatural light neutrino mass may be explained by introducing the heavy right handed neutrino. At the cosmology, Majorana property can be cause for matter dominant universe by leptgenesis theory. However the only realizable experimental search of this property is neutrino-less double beta decay. This process also requires neutrino mass to exchange the helicity, and half-life of decay is connedted with scale of neutrino mass. The experimental target parameter region was clarified by neutrino oscillation experiments, therefore many experiments with each double beta decay nuclei and each technique are working and proposed in the world.

KamLAND-Zen is a neutrinoless double beta decay search experiment with ^{136}Xe. Figure 1 shows schematic diagram of the KamLAND-Zen detector. The 90.6% enriched xenon gas dissolved in the liquid scintillator (Xe-LS) is contained in transparent nylon balloon (inner-balloon). The scintillation lights from double beta decay, neutrino reaction and radioactivity are detected by 1879 photo multiplier tubes (PMTs) on the inner surface of stainless tank. The vertex and energy of event are reconstructed by the light detected timing and number of photo-electrons, and the resolutions are 14.1 cm and 6.8 MeV / $\sqrt{E(MeV)}$, respectively. KamLAND-Zen first phase with 320 kg xenon was started in 2011 and ended in 2012. The exposure of first phase was 89.5 kg yr of ^{136}Xe with 213.4 live-days and we released some results about double beta decay search [1][2][3]. At the first phase of KamLAND-Zen, we set the lower limit on the $0\nu\beta\beta$ decay half-life of $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% C.L.

We found the problematic background in the region of interest (2.2MeV - 2.8MeV) at the first phase. The main background was identified as ^{110m}Ag by the energy spectrum and lifetime measurement (Lifetime = 250 days). We had two possibility about contamination by ^{110m}Ag. One is cosmogenic spallation products of xenon gas. The enriched xenon gas was transported by air, then flux of cosmic ray was almost 100 times higher than ground. M.C. simulation results based on the production cross section of ^{110m}Ag form ^{136}Xe with proton [4] indicated this possibility, but we couldn't find how ^{110m}Ag comes from gas cylinder to liquid scintillator piping line. Another is fallout from Fukushima reac-

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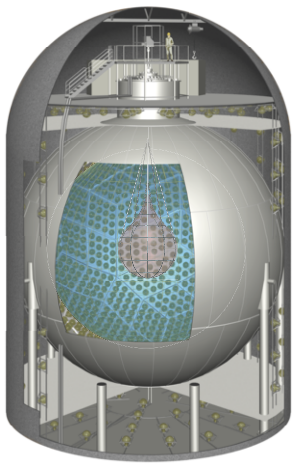

Figure 1: Schematic diagram of KamLAND-Zen detector. 3.08m, 13m, 18m diameter inner-balloon, outer-balloon, stainless tank contains xenon loaded scintillator, liquid scintillator and mineral oil, respectively. Outside of stainless tank is used as anti-counter based on the PMTs and pure water to remove cosmic ray muon.

tor accident after the terrible erathquake in Japan. Observation of ^{134}Cs and ^{137}Cs on the inner balloon, and the ratio of Cs are also indicated the contamination by fallout. Origin of ^{110m}Ag was not clear, but we tried to remove the backgrounds by purification for high sensitivity $0\nu\beta\beta$ decay search after the first phase.

2. Purification

Before the purification, we removed xenon gas from Xe-LS and operated the data collection to check where is the ^{110m}Ag. The ^{110m}Ag was remained in liquid scintillator (LS), therefore contaminated LS was drained from inner balloon and new LS was filled at the same time. After the data collection with new LS, we found the ^{110m}Ag was reduced to 1/3 to 1/4 level. The reason could be explained that some amount of contaminated LS was mixed to new LS and surface contamination of inner balloon film was moved to LS. In any case, it was obvious that we need more purification and LS exchange in inner balloon. The purification was done by distillation for each component of liquid scintillator. The purified and slightly weighter LS was feed to bottom of inner balloon and contaminated LS was drained from upper part. Total purified LS was corresponds to 3 times circulation to inner balloon volume. The purified LS was drained again and new LS was feed. Finally,

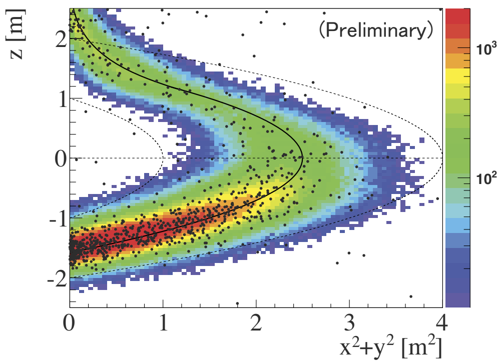

Figure 2: Vertex distribution of candidate events (black points) and expected ^{214}Bi background events estimated by M.C. simulation (color histgram) for 2.3 MeV to 2.8 MeV energy region. The solid line indicates the position of inner balloon and doted line is radious is 2.0 m.

xenon gas which was purified by distillation and filter was dissolved to LS. The new Xe-LS for second phase contains 383 kg xenon gas.

3. Data analysis

We report on data collected between December 11, 2013 and May 1, 2013. For the second phase, we improved some analysis methods.

Cosmic ray muons and ^{12}C make two neutrons and ^{10}C (β^+, τ=27.8 s, Q=3.65 MeV). Because neutron tagging efficiency was improved by dead time free electronics, triple coincidence by muon, 2.2 MeV gamma rays from neutron capture by proton and ^{10}C could be used for the rejection of backgrounds. The ^{10}C rejection efficiency and livetime rejection were 72 ± 5 % and 7 %, respectively. The number of identified and rejected backgrounds was 6.

At the LS circulation for the first stage of purification, pump trouble was happened and ^{214}Bi backgroud events were increased especially for bottom region as shown in Figure 2. In order to tune the upper and lower asymmetric background on the surfece of inner balloon, multi-volume selection was used for radious. 20 bins based on the radial-equal-volume within radious is less than 2.0m for upper and lower hemisphere were set and signal to background were optimized for each bin. Due to the larger ^{214}Bi background on the inner balloon especially for the bottom, inner and upper region are expected to have a higher sensitivity.

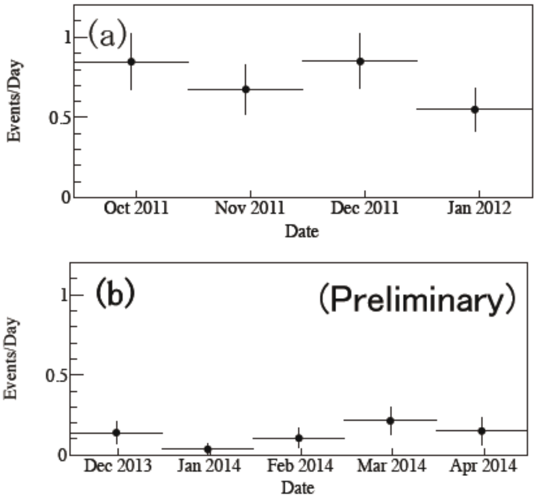

Figure 3: Event rate in 2.2 MeV < E < 3.0 MeV and Radious is less than 1.0m. (a) First phase 112.3 days data. (b) Second phase 114.8 days data.

Figure 3 shows event rate after the event selections at the enegy region is from 2.2 MeV to 3.0 MeV and radious is less than 1.0 m, for the first days of first phase and second phase. The backgrond was reduced by more than a factor of 10 by purification for xenon gas and liquid scintillator.

4. Preliminary results

4.1. Preliminary 2νββ decay results

In order to avoid a large ^{134}Cs, ^{137}Cs background at the surface of inner balloon, fiducial radious for $2\nu\beta\beta$ decay analysis was limited to within 1.0 m. Figure 4 shows the energy spectrum of $\beta\beta$ decay candidate with a spectral fit for $2\nu\beta\beta$ decay and backgrounds. The measured $2\nu\beta\beta$ decay half-life of ^{136}Xe is $T^{2\nu}_{1/2}$=2.32±0.05(stat.)±0.08(syst.)× 10^{21} yr [5]. This result is consist with the first phase of KamLAND-Zen data, $T^{2\nu}_{1/2}$=2.30±0.02(stat.)±0.12 (syst.)× 10^{21} yr [2], and with the result by EXO-200, $T^{2\nu}_{1/2}$=2.165±0.016 (stat.)±0.059(syst.)× 10^{21} yr [6].

4.2. Preliminary 0νββ decay results

The $0\nu\beta\beta$ decay analysis is done by the fit to 2 dimensional spectra in energy-volume in the 2.0 m radious. Firugre 5 shows the energy spectra for the internal volume (R < 1.0 m) with the best fit background composition to display simplified. Each potential background contribution in $0\nu\beta\beta$ signal region discussed in Ref. [1]

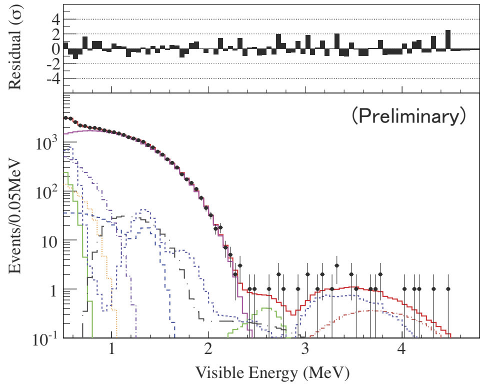

Figure 4: Preliminary energy spectrum of selected $\beta\beta$ candidate within 1.0 m fidcial radious. Each color shows best-fit backgrounds with the $2\nu\beta\beta$ decay fit. The residuals from the best-fit are shown in the upper panel.

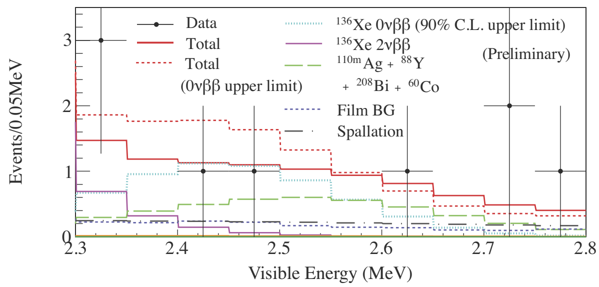

Figure 5: Preliminary energy spectrum of selected $\beta\beta$ candidates within the radius cut $R < 1.0$ m. Each colored lines show the best-fit backgrounds and the 90% C.L. upper limit for $0\nu\beta\beta$ decays.

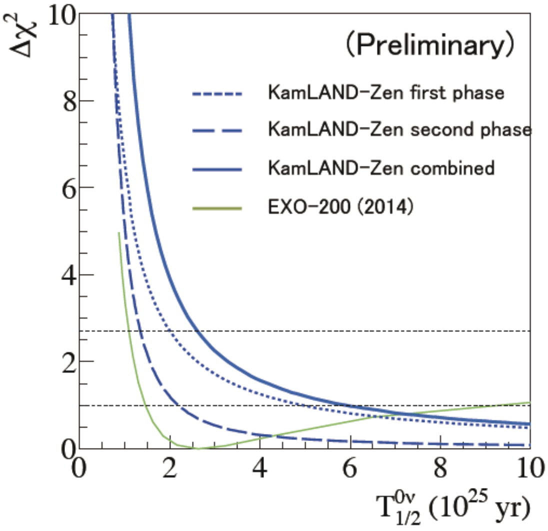

Figure 6: $\Delta\chi^2$-profile from the fit to the half-life of ^{136}Xe $0\nu\beta\beta$ decay of KamLAND-Zen second phase, first phase and combined KamLAND-Zen. The result from EXO-200 [6] is also shown for comparison.

(^{110m}Ag, ^{88}Y, ^{208}Bi, and ^{60}Co) are allowed to vary in the fit. We observed no significant excess over the background expectation. The 90 % C.L. upper limit on the ^{136}Xe $0\nu\beta\beta$ decay rate is < 17.0 /kton-LS/day. Considering the Xe concentration in Xe-LS, we obtained a limit on the ^{136}Xe $0\nu\beta\beta$ decay half-life of $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr at 90% C.L. The combined KamLAND-Zen result from first phase and second phase data gives a lower limit of $T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr at 90% C.L. (Firugre 6). The effective neutrino mass based on various (R)QRPA models [7] and combined KamLAND-Zen half-life limit is calculated as $\langle m_{\beta\beta}\rangle$ < (140 - 280) meV

5. Future prospects

The sensitivity of second phase assuming the best-fit background for current data is shown in Firugre 7. We expect that second phase sensitivity of $T^{0\nu}_{1/2}$ reaches 3 $\times$ 10^{25} yr at 90% C.L. within 2 years. We plan to replace the inner balloon to new and larger one for the next phase. The sensitivity of next phase with 600kg xenon is shown in Figure 7, but we think that we could use 700 - 800 kg xenon to search in inverted hierarchy. We also have future project called as KamLAND2-Zen to rearch a sensitivity of $\langle m_{\beta\beta}\rangle \sim 20$ meV which covers the inverted neutrino mass hierarchy region. After the rejection of ^{110m}Ag and inner balloon contamination, main background component for $0\nu\beta\beta$ decay search is

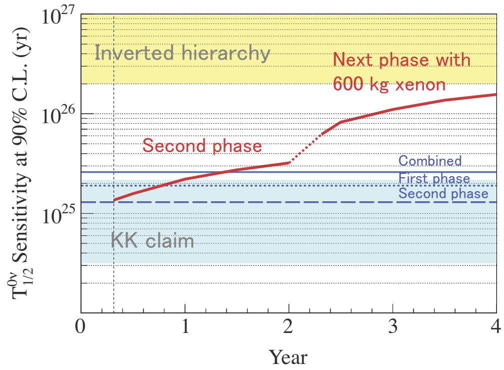

Figure 7: Expected $T^{0\nu}_{1/2}$ sensitivity at 90% C.L. in the neat fure for KamLAND-Zen. Red line less than 2 years is current second phase and the next period indicate next phase with 600 kg xenon. The three blue lines are lower limit by first phase, 114.8 days of second phase and combined results.

$2\nu\beta\beta$ decay events. We don't have methods to eliminate $2\nu\beta\beta$ decay events in $0\nu\beta\beta$ decay singnal energy region. Therefore we plan to improve the energy resolution from 4.0% to less than 2.0% at the Q-value of ^{136}Xe $\beta\beta$ decay by introducing high quantum efficiency PMTs, light collective mirrors surrounding PMTs, and brighter LS.

6. Summay

Second phase of KamLAND-Zen neutrino-less double beta decay search experiment was started after the effective background rejection by purification using distillation methods. The ^{110m}Ag background was reduced by more than a factor of 10. Preliminary new results from 114.8 days of second phase were reported. In the near future, we will replace the inner balloon to raise the sensitivity. We also planned to improve the detector for high sensitivity search, and R&D are on going.

Acknowledgments

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