Results and future plans for the KamLAND-Zen experiment

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Abstract. KamLAND-Zen is an experiment searching for the neutrinoless double beta decay (0νββ) of 136Xe nuclei with (320~380) kg-enriched Xe using the facility of the 1,000 ton liquid scintillator (LS) detector, KamLAND. In this brief report the latest analysis results including the full data set corresponding to an exposure of 504 kg yr of 136Xe taken after the purification of the Xe and LS is presented. Also reported are the ongoing detector upgrade for the new phase with ~ 750 kg of enriched Xe and the future prospect.

1. Introduction

Discovery of the neutrino mass has opened a fundamental problem whether neutrinos are Majorana particles or not. If Majorana, it would open a very high-energy scale physics which may clarify the problem of the matter dominance of the Universe. Neutrinoless double beta decay (0νββ) of a nucleus is a key process to test the Majorana nature of neutrinos. Furthermore, by assuming the light Majorana-neutrino exchange to be the dominant process, the half-life $T^{0\nu}_{1/2}$ is connected to the effective Majorana neutrino mass, $\langle m_{\beta\beta} \rangle$, which contains all of the essential information of neutrinos. To date, there is no clear evidence of $0\nu\beta\beta$ and $T^{0\nu}_{1/2}$ is considered to be much longer than $10^{26}$ yr, making the $0\nu\beta\beta$ search very challenging.

Among the many double-beta decay nuclei, $^{136}$Xe ($Q_{\beta\beta}$=2.458 MeV, natural abundance=8.9%, the half life of 2νββ decay ($T^{2\nu}_{1/2}$ $\sim$ 2 $\times$ 10$^{21}$ yr) is an excellent choice because Xe is a noble gas and satisfies various key requirements: isotopic enrichment and purification techniques, high chemical stability for safety and easy handling, and repeated purification to realize excellent scalability. Furthermore, it has the high solubility to LS with $\sim$ 3.5 wt%, and combination of Xe with LS makes unique strategy for the search.

2. KamLAND-Zen experiment

2.1. The Detector

KamLAND-Zen (Zero neutrino double-beta decay experiment) is a high sensitivity experiment searching for 0νββ of $^{136}$Xe using the facility of KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector), which is the world’s largest LS neutrino detector providing a large-volume ultra-clean environment essential for the 0νββ search. Figure 1 shows the detector.

The detector location is 1,000 m underground in the Kamioka mine in Gifu prefecture in Japan, where cosmic ray muon flux is $10^5$ times less than that of the ground level. The central
part of the KamLAND detector is a 18m-diameter stainless steel spherical tank which contains 1,000 ton of ultra-pure LS in a balloon of 13 m in diameter and viewed through transparent buffer oil of 1.8 m thickness by 1,879 17-inch and 20-inch PMTs covering 34% of 4π. Outside the tank, there is a 3,200 ton water Cherenkov detector for muon identification which serves as a radiation shield from the surrounding rock.

As shown in Figure 1, KamLAND-Zen is a minor modification of KamLAND, accomplished just by putting a small balloon (the inner balloon, IB) in the center of the detector. The IB is made of transparent clean nylon film of 25 μm thick and 3.08 m in diameter filled with enriched Xe (with 91% 136Xe) dissolved in decane-based LS (Xe-LS) provided by a newly constructed Xe system and existing LS purification system. By using the KamLAND facility, KamLAND-Zen benefits from a quick start with relatively low cost, flexible operation for carrying out blank runs and repeated purification, easy scaling up, and capability of doing other physics (geo- and astrophysical ν’s) in parallel. Furthermore, response of the detector has been well understood since the start of KamLAND in 2002 through many studies on reactor ν_e oscillation and the measurement of geoneutrinos [1].

**Figure 1.** KamLAND-Zen detector. In the center of the detector there is the inner balloon (IB) filled with enriched 136Xe-loaded LS.

**Figure 2.** Vertex distribution of the selected events (black points) in the 0νββ region (2.3 < E < 2.7 MeV) and the MC simulated 214Bi backgrounds (color). The black and dotted lines show the shape of the IB and R<1m region. Thin dashed lines show the 40 equal-volume spherical half-shell regions in upper and lower hemispheres in the fiducial volume of 2 m in radius.

2.2. Phase-I of KamLAND-Zen

KamLAND-Zen started data taking in October 2011 with 320 kg enriched Xe until June 2012, which we call phase-I. From the corresponding exposure of 89.5 kg yr of 136Xe a 90% C.L. limit on $T_{1/2}^{0\nu}$ is obtained as $>1.9 \times 10^{25}$ yr [3] and a combined limit with EXO-200 [4] refuted the KK claim in 76Ge [5] for various nuclear matrix elements (NME).

In the observed energy spectrum in phase-I there was a peak around the signal region which was dominated by 110mAg β− decay contamination ($t=360$ days, $Q=3.01$ MeV) identified by the spectral shape and the time variation of the rate consistent with 110mAg decay. The 110mAg is considered to be the fallout from the Fukushima reactor accident in 2011, when the IB was constructed in a super-clean room facility in Tohoku University in Sendai. This finding is supported by the ratio of the observed 134Cs and 137Cs backgrounds.
The sensitivity is limited by $^{110m}$Ag, and other backgrounds were identified as $^{214}$Bi decay ($\beta + \gamma$, $\tau = 28.7$ min, $Q = 3.27$ MeV) around the IB, $^{10}$C ($\beta^+$, $\tau = 27.8$ s, $Q = 3.65$ MeV) in the Xe-LS produced by muons and the high-energy tail of the $2\nu\beta\beta$ decay. After the phase-I data taking a Xe-LS purification campaign was carried out until October 2013 by vacuum distillation of LS in three IB volume cycles and Xe purification by distillation, filtration and getter.

2.3. Phase-II of KamLAND-Zen

The new run (phase-II) was started in November 2013 by increasing the amount of the enriched Xe to 380 kg. It was found that the $^{110m}$Ag was successfully removed by a factor $\sim 10^6$ from the data of the first 115 days. Phase-II continued until October 2015 when the detector calibration run was made by using gamma ray sources along the central vertical axis ($z$) of the IB. The observed energy resolution is $\sigma/E = 7.3\%/\sqrt{E$(\text{MeV})}$, and the position dependent energy and vertex biases are found as less than 1% and 1 cm, respectively, within $|z| < 1.0$ m of the IB. The total live time of phase-II is 534.5 days after the muon spallation cuts, and the amount of the phase-II data set corresponds to an exposure of 504 kg yr of $^{136}$Xe. Detailed description of the analyses is presented in Ref. [2].

Event selection is made by applying the following conditions: selection of vertex within the distance from the detector center ($R$) < 2 m, rejection of muons and events within 2 ms after muon, $^{214}$Bi-$^{214}$Po ($\tau = 237\mu$s) and $^{212}$Bi-$^{212}$Po ($\tau = 0.43\mu$s) rejection by the delayed coincidence and the double-pulse identification analysis method, and the cuts for reactor $\tau_r$ and poorly reconstructed events. Figure 2 shows the vertex distribution of the selected events (black points) in the $0\nu\beta\beta$ window ($2.3 < E < 2.7$ MeV) of the whole phase-II data set. In the figure color shows predicted background of $^{214}$Bi evaluated from the MC simulation which is made by Geant4 detector simulation where the decay vertex is tuned to reproduce the observed vertex distance of the $^{214}$Bi-$^{214}$Po sequential decays from the initial $^{222}$Rn-rich period in the Xe-LS.

Figure 3 (a) shows radial distribution of the candidate events as a function of $R^2$ to eliminate the $R^2$ weight factor. $^{214}$Bi background is dominant around the IB film which is shown by the curve IB, but it decreases significantly in the $R < 1$ m region where $^{110m}$Ag still remained. Assuming secular equilibrium, $^{238}$U concentration is 80 times larger than the ICP-MS analysis of the film. The strong position dependence of the $^{214}$Bi shows that the dust on the film makes the dominant contribution for the $^{214}$Bi, which is supported by a fact that the high $^{214}$Bi region near the IB film is also contaminated by $^{134}$Cs in the energy region of $2\nu\beta\beta$ decay. The analysis is made to utilize whole $^{136}$Xe by taking $R < 2$ m as a fiducial volume, and the spectra in the 20 equal-volume spherical half-shell regions in each of the upper and lower hemispheres are analyzed by simultaneous fit. Figure 3 (b) shows an example of the spectra of a high $^{214}$Bi region in a lower hemisphere and close to the IB film in $1.47 < R < 1.53$ m in a shaded region in Figure 2.

**Figure 3.** (a) $R^2$ distribution of candidate events in the $0\nu\beta\beta$ window of $2.3 < E < 2.7$ MeV. (b) Energy spectra of the one of the 40 equal-volume spherical half-shell regions which is close to the bottom of the IB film. The curves show the best-fit background model components.

$^{10}$C background by muon spallation is rejected by triple coincidence of muon-neutron-$^{10}$C by applying spherical cuts (<1.6 m) around the neutron vertices within 180 s after the muon. The
cut conditions are set by the studies including the outer LS region (R<3.5 m). The neutrons are detected by the new electronics system (MoGURA) with efficiency of 64±4%. Other muon-spallation background, $^{137}$Xe ($\beta^-$, $\tau = 5.5$ min, $Q = 4.17$ MeV) is produced dominantly by neutron capture by $^{136}$Xe which is estimated by the spallation neutron rate and the capture cross section.

Figure 4. (a) Energy spectrum of selected $\beta\beta$ candidates within 1 m radius spherical region in period-2 with best-fit backgrounds, $2\nu\beta\beta$ spectrum, and the 90% C.L. upper limit of $0\nu\beta\beta$ decay. (b), (c) Close-up of the spectra in (a) for $\beta\beta$ candidates and the best-fit backgrounds in period-1 and period-2, respectively.

Figure 4 shows the energy spectra for the central spherical region and the best fit background composition. Considering the time dependence of $^{110m}$Ag rate, data is divided into two almost equal periods and fits are made independently. Figure 4(b) and (c) show the zoomed up spectra for period-1 and period-2, respectively. Significant decrease of $^{110m}$Ag background in period-2 is found. A possible explanation is the dust containing $^{110m}$Ag fell to the bottom region of the IB and not reconstructed. It can be seen that there is no excess over the backgrounds.

Table 1 summarizes the background in the $0\nu\beta\beta$ window in the R<1 m for period-1 and period-2. In the Xe-LS $^{110m}$Ag background disappeared in period-2. $^{10}$C background remains but can be further removed by improving the neutron detection. $^{136}$Xe $2\nu\beta\beta$ background would be removed by improving the energy resolution in future. The external $^{214}$Bi background is removed by replacing the IB by a cleaner one in the next phase. Spallation background of $^{137}$Xe is slightly changed by correction and shown in Table 1.

From $\Delta\chi^2$ analysis a 90% C.L. limit is obtained on $T^{0\nu}_{1/2}$ from phase-II as $9.2 \times 10^{25}$ yr, which is combined with the one in phase-I [3] to obtain the limit as $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr at 90% C.L. Figure 5 shows the corresponding upper limit on $\langle m_{\beta\beta} \rangle$ as $< (61-165)$ meV by using an improved phase space factor and commonly used NME calculations, and assuming the axial coupling constant $g_A \simeq 1.27$. The result is a big improvement over the previous limits and extends the $\langle m_{\beta\beta} \rangle$ limit below 100 meV getting close to the IH region. Also the limit on the lightest neutrino mass $m_{\text{lightest}}$ is obtained as (180-480) meV at 90% C.L.

The $2\nu\beta\beta$ half-life is obtained by using the events in the R<1 m region as $T^{2\nu}_{1/2} = 2.21 \pm 0.02$ (stat.) $\pm 0.07$ (sys.) $\times 10^{21}$ yr. The systematic error (3.1%) is dominated by the uncertainty of the fiducial volume (3.0%) which is consistent with the radial vertex bias of 1 cm from the source calibration run. The value is consistent with the previous results from the phase-I data [7] and the results by EXO-200 [8].
Table 1. Summary of the numbers of the observed events, and those of the estimated and best-fit backgrounds in the $0\nu\beta\beta$ window ($2.3 < E < 2.7$ MeV) in $R < 1$ m for period-1 and period-2.

|                | Period-1 (270.7 days) | Period-2 (263.8 days) |
|----------------|------------------------|------------------------|
| Observed events| 22                     | 11                     |
| Background     |                        |                        |
| $^{136}$Xe $2\nu\beta\beta$ | -                      | 5.48                   | -                      | 5.29                   |
| Residual (Xe-LS) |                        |                        |
| $^{214}$Bi ($^{238}$U series) | 0.23±0.04              | 0.25                   | 0.028±0.005            | 0.03                   |
| $^{208}$Tl ($^{232}$Th series) | -                      | 0.001                  | -                      | 0.001                  |
| $^{110m}$Ag    | -                      | 8.5                    | -                      | 0.0                    |
| External (IB)  |                        |                        |
| $^{214}$Bi ($^{238}$U series) | -                      | 2.56                   | -                      | 2.45                   |
| $^{208}$Tl ($^{232}$Th series) | -                      | 0.02                   | -                      | 0.03                   |
| $^{110m}$Ag    | -                      | 0.003                  | -                      | 0.002                  |
| Spallation products |                  |                        |
| $^{10}$C      | 2.7±0.7                | 3.3                    | 2.6±0.7                | 2.8                    |
| $^{6}$He      | 0.07±0.18              | 0.08                   | 0.07±0.18              | 0.08                   |
| $^{12}$B      | 0.15±0.04              | 0.16                   | 0.14±0.04              | 0.15                   |
| $^{137}$Xe    | 0.5±0.2                | 0.5                    | 0.5±0.2                | 0.4                    |

Figure 5. Effective Majorana neutrino mass ($m_{\beta\beta}$) as a function of the lightest neutrino mass, $m_{\text{lightest}}$. The dark shaded regions are from the best-fit neutrino oscillation parameters for the NH and IH mass hierarchies. Light shaded regions are the 3$\sigma$ ranges of the oscillation parameter uncertainties. Horizontal bands indicate 90% C.L. upper limits on the $\langle m_{\beta\beta} \rangle$ from KamLAND-Zen and other experiments.

3. Schedule and outlook
Phase-II was terminated in the last October, and the IB was extracted from the detector. A new double-sized IB for $\sim$ 750 kg is under construction in a super-clean room facility in Tohoku University under much improved cleanliness control. The construction work will be finished soon, and the IB will be installed in the next month. In addition, the outer water Cherenkov detector was refurbished by replacing the PMTs with new 20-inch ones in the early spring for
better detection efficiency. The new phase will be started in the autumn of 2016 which we call KamLAND-Zen 800 as opposed to the phase-I and phase-II periods which we call KamLAND-Zen 400. Expected sensitivity in the new phase for $\langle m_{\beta\beta} \rangle$ would reach to $\sim 40$ meV.

In the future it is planned to reduce $2\nu\beta\beta$ background by improving the energy resolution by a factor of 2 to get $\sigma_E/E \sim 2\%$ at the Q-value. Various R&D works are underway for better $\Delta E$: LAB-based LS with higher light yield, high quantum-efficiency PMTs with light collectors, background rejection by new LS purification method, an imaging sensor system for $\beta$-$\gamma$ discrimination and a scintillating balloon for removal of $^{214}$Bi background. A pressurized Xe-LS environment for increased amount of Xe is also considered. The plan called KamLAND2-Zen aims to make the $\langle m_{\beta\beta} \rangle$ sensitivity to reach $\sim 20$ meV which would fully cover the region of IH, and reach the branch point of IH and NH mass hierarchy. The results would make a great impact on the field of cosmology and astrophysics as well as the intensive experimental and theoretical studies on neutrinos.

4. Summary
- KamLAND-Zen phase-II (post purification phase) data showed successful reduction of $^{110m}$Ag, and corresponding $^{136}$Xe exposure of 504 kg yr improved the $0\nu\beta\beta$ sensitivity.
- Combined limits on $0\nu\beta\beta$ from phase-I plus phase-II (KamLAND-Zen 400) are $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr (90% C.L.) which is 6-fold improvement over phase-I, and $\langle m_{\beta\beta} \rangle < (61-165)$ meV (90% C.L.) which is approaching the IH region.
- Preparation is ongoing for the next phase of KamLAND-Zen 800: a new IB for enriched Xe of $\sim 750$ kg will be installed next month and data taking will be started in the autumn aiming for the sensitivity for $\langle m_{\beta\beta} \rangle \sim 20$ meV entering the IH region.
- Various R&Ds are ongoing for the future KamLAND2-Zen for better energy resolution aiming to reach $\langle m_{\beta\beta} \rangle < 20$ meV fully covering the IH region.

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