Results from KamLAND-Zen neutrino-less double beta decay experiment with 136Xe

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KamLAND-Zen is an experiment for neutrino-less double-beta decay search with ^{136}Xe. A newly constructed balloon was installed inside the current 13 m-diameter KamLAND balloon and filled with Xe-loaded liquid scintillator in 2011. The data taking was started in September 2011 and the physics results were obtained with an exposure of 112.3 days with 125 kg of ^{136}Xe. We measured the two-neutrino double-beta decay half-life of ^{136}Xe, $T_{1/2}(2\nu) = 2.30 \pm 0.02(stat) \pm 0.12(syst) \times 10^{21}$ yr and obtained an improved lower limit for the neutrino-less double-beta decay half-life, $T_{1/2}(0\nu) > 6.2 \times 10^{24}$ yr at 90% C. L.

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1. Introduction

Double-beta decay is a rare radioactive decay process in which a nucleus with atomic number Z decays into a nucleus with atomic number Z+2 at the same time. The process occurs when the single-beta decay is energetically forbidden or suppressed due to a large change of spin. In the decay process, the nucleus emits two electrons and anti-neutrinos.

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e \qquad (1)$$

This, two-neutrino double-beta (2νββ) decay, can be understood within the Standard Model and has been observed for several nuclides. On the other hand, the hypothetical neutrino-less double –beta (0νββ) decay occurs only if the neutrino is a Majorana particle and has finite mass.

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} \qquad (2)$$

The 0νββ decay mode would be a promising probe for physics beyond the Standard Model and provide information of the Majorana nature of the neutrino, the neutrino mass hierarchy, lepton number violation and leptogenesis. So far, the 0νββ decay has not been observed except for the one claim in the Heiderberg-Moscow experiment[1].

KamLAND-Zen is an experiment to search for the 0νββ decay of ^{136}Xe. The setup is placed inside the KamLAND detector, which has been running since 2002 for the reactor neutrino experiment [2]. Thanks to utilizing the already available equipment, the 0νββ decay experiment was quickly started after 2 years for the preparation. In this paper, the result of the KamLAND-Zen experiment with data collected since October 2011 will be reported.

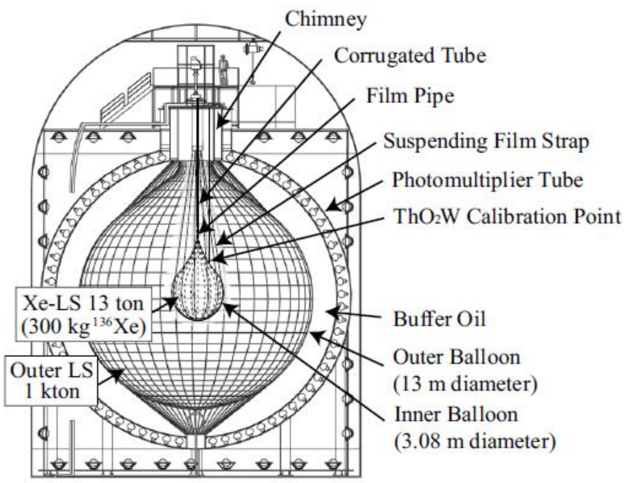

Fig.1 Schematic view of the KamLAND detector and the inner balloon containing the Xe-LS.

2. Experimental setup

The overall setup is shown in Fig. 1 [3]. The detector is located 1000 meter underground in the Mozumi Mine in the Kamioka area. A 3.08-m-diameter inner balloon (IB) containing 13 tons of Xe-loaded liquid scintillator (Xe-LS) is located at the center of the KamLAND detector. The Xe-LS consists of 82% decane and 18% pseudocumene (1,2,4-trimethylbenzene) by volume, 2.7 g/liter of PPO (2,5-diphenyloxazole). It contains (2.44 ± 0.01)% by weight of enriched xenon gas, obtained by gas chromatography. The concentration of ^{136}Xe in the enriched gas was measured to be (90.93 ± 0.05)% by residual gas analyzer. The IB is suspended in 1-kiloton LS contained in a 13-m-diameter nylon-based balloon. This outer balloon is in a 18-m-diameter spherical stainless-steel containment vessel filled with nonscintillating oil. On the inner surface of the vessel, 1325 17-inch photomultiplier tubes (PMTs) and 554 20-inch PMTs are equipped. The ingredients of the 1-kiloton LS are decane (80%), pseudocumene (20%) and 1.52 g/litter of PPO. The outer LS has been developed to be ultra-pure with little radioactive isotopes for detecting reactor, solar and geo-neutrinos and becomes a good shield against external radiation for the KamLAND-Zen experiment.

The IB was made of 24 parts of 25-μm-thick nylon film. After the film was ultorasonic cleaned, it was cut and glued by thermal welding in a class-1 clean room to form a spherical shape. After the IB construction, it was transported to the Mozumi-Mine. The IB was first bundled up and installed in the KamLAND detector from the top flange of the vessel. It was then inflated by filling LS inside. The density of the Xe-LS in the IB is 0.1% larger than the outer LS so that the IB should not be floated up.

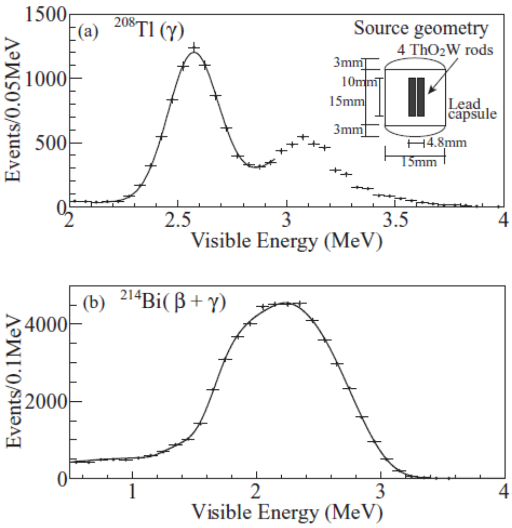

Fig. 2 Energy spectra of decays of ^{208}Tl (a) and ^{214}Bi in the Xe-LS.

3. Calibration and systematic uncertainties

To estimate the energy scale of events in the Xe-LS, we used two calibration sources. One is a ThO_2W rod, in which ^{208}Tl decays and emits 2.614 MeV gamma-ray. The ThO_2W rods are covered with a Pb shield so that most of the emitted electrons stop in the shield. We put down the source through the outer-LS from the top flange of the detector and located it near the IB surface. The measured energy spectrum is shown in Fig. 2(a). The lower peak in the figure corresponds to 2.614 MeV gamma ray. The energy resolution was measured to be (6.6 ± 0.3)% at 2.6 MeV. The other source used for the energy calibration is ^{214}Bi decay in the Xe-LS, which follows ^{222}Rn decay in the ^{238}U-chain. Since the Xe-LS had been stored in a stainless steel tank outside of the KamLAND detector before the installation, it contained a large amount of ^{222}Rn due to the emanation from the inner surface of the tank when installed into the IB. The Rn-rich period at the beginning of the KamLAND-Zen experiment was good for the ^{214}Bi energy calibration. The ^{214}Bi decay event can be tagged by detecting an alpha particle from the following ^{214}Po decay. The measured energy spectrum of the ^{214}Bi decay is shown in Fig. 2(b). Using 2.2 MeV neutron-captured gamma produced after muon-induced spallation, we estimate that the stability of the energy scale over the measurement period is less than 1% and the variation of the energy scale over the fiducial volume is also less than 1%.

The radial distribution of events in the IB is shown in Fig. 3 for each energy region. Due to the radioactivity in the balloon film, there is a peak around R = 1.54 m. Because some alpha particles from ^{214}Po decay stopped inside the film, a certain amount of ^{214}Bi events cannot be tagged by the ^{214}Bi-^{214}Po delayed coincidence and remains as a background. The fiducial volume was determined considering the effect of ^{214}Bi decay in the IB film and we set R < 1.35 m as a fiducial volume.

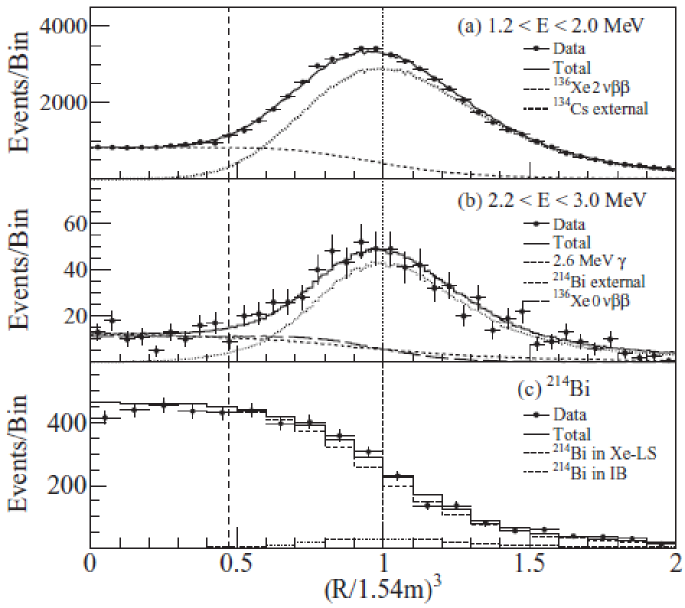

Fig.3 Radial distribution of events in (a) the 2νββ decay energy region and (b) the 0νββ decay energy region and (c) of ^{214}Bi decay after selected by the ^{214}Bi-^{214}Po delayed coincidence.

We estimate the systematic uncertainty used for the 2νββ halflife measurement which includes uncertainties of the fiducial volume, the enrichment factor or ^{136}Xe, the xenon concentration, the detector energy scale, the Xe-LS edge effect and the detection efficiency. Among them, the main contribution comes from the uncertainty of the fiducial volume. The fiducial volume was checked using the ratio of ^{214}Bi-^{214}Po events between in the fiducial volume and the total IB volume. The resultant systematic uncertainty of the fiducial volume is 5.2%. The overall systematic uncertainty is also 5.2%.

4. Results and discussion

To reduce background events, we applied the following event selections. a) fiducial volume cut, b) 2 ms veto after cosmic muon events, c) removing consecutive events within 3 ms for the Bi-Po rejection, d) reactor anti-nu CC reaction cut, e) vertex-time-charge test to cut noise events. The visible energy spectrum after the event selection is shown in Fig. 4. Possible background spectra are included to be fitted to the data. Using the dataset between October 12 2011 and February 9 2012, we obtained the 2νββ lifetime of $2.30\pm0.2(\text{stat})\pm0.12(\text{sys})\times10^{21}$ yr [4], which is consistent with the previously reported EXO-200 result [5].

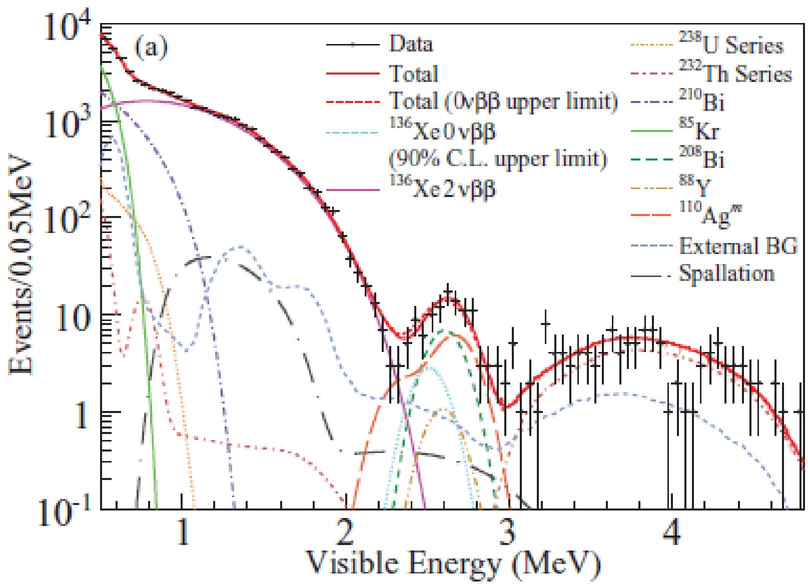

Fig. 4: Visible energy spectrum after the event selection. Lines are expected spectra of each signal or background source fitted to the data.

A peak around 2.6MeV is observed in the energy spectrum, which is near the energy region of the 0νββ decay signals. One possibility is that the peak is due to the spallation product, which can be constantly produced during the measurement period. Firstly, we checked events after muons up to 100 seconds but found no decay curve other than known spallation products from the LS components [6] which cannot explain the peak around 2.6 MeV. Secondly, for the spallation products from Xe with lifetime between 100 seconds and 30days, we surveyed the ENSDF nuclear database [7] to check whether their energy spectra can reproduce the observed one but found no candidates for the 2.6 MeV peak. The other possibility is that the radioactive impurity came from outside during the installation. In this case, the background rate should decrease with the lifetime of the nuclides. Because the data shows no significant decrease during 112 days, we searched unstable radio-isotopes with lifetime longer than 30 days in the ENSDF database. Four candidates were found by this search; ^{110m}Ag, ^{88}Y, ^{208}Bi and ^{60}Co. The spectra of those nuclides and 0νββ decay were used for the fitting to the measured energy spectrum at the same time. With the same dataset of the 2νββ decay analysis, we obtained the upper limit of the 0νββ decay halflife of $T_{1/2} > 6.2\times10^{24}$ yr [8].

5.Summary

KamLAND-Zen started data-taking in Sepetember, 2011 and provided the ^{136}Xe halflife of 2νββ decay and the lower limit of the ^{136}Xe 0νββ decay halflife with an exposure of 112.3 days with 125 kg of ^{136}Xe. The peak around 2.6 MeV in the visible energy spectrum affects the sensitivity of the 0νββ decay search. In future, it is necessary to remove the background by the purification of the Xe-LS.

References

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