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KamLAND-Zen 800

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KamLAND-Zen searches for neutrinoless double beta decay with ^{136}Xe loaded liquid scintillator. After the successful completion of KamLAND-Zen 400, KamLAND-Zen 800 started data taking in 2019 with almost double the amount of xenon and a low radioactive LS container. With an exposure of 970 kg-yr of ^{136}Xe and various improvements for the analysis method, we set a lower limit for ^{136}Xe $0\nu\beta\beta$ half-life on $T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr at 90% C.L. KamLAND-Zen 400 data set is also reanalyzed with a new analysis scheme, and we obtain a combined limit for half-life on $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr at 90% C.L. Corresponding upper limits on the effective Majorana neutrino mass is 36 – 156 meV.

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1. Introduction

Neutrinoless double-beta ($0\nu\beta\beta$) decay is a lepton-number-violating nuclear transition and it requires two characteristic neutrino properties: the neutrinos have mass and are a Majorana type lepton [1]. Observation of the decay leads to the conclusion that the neutrino is a Majorana particle. Furthermore, if $0\nu\beta\beta$ transition is mediated by a light Majorana neutrino (the minimal mechanism of the decay), the $0\nu\beta\beta$ decay rate is proportional to the square of effective Majorana neutrino mass, $\langle m_{\beta\beta}\rangle \equiv \left|\Sigma_i U_{ei}^2 m_{\nu_i}\right|$. It provides information on the neutrino mass ordering and the absolute neutrino mass scale. Due to the importance of the $0\nu\beta\beta$ decay search, various experiments with diverse isotopes and techniques are actively promoted in the world.

2. KamLAND-Zen

KamLAND-Zen searches for $0\nu\beta\beta$ decay with xenon loaded liquid scintillator. Xenon is dissolved into liquid scintillator with approximately 3% by weight. The target isotope is 90-91% enriched ^{136}Xe and its Q-value is 2.458 MeV. KamLAND-Zen started in 2011 as KamLAND-Zen 400. From $\sim$ a half year and 2 years of data taking for Phase I and II, it set a lower limit on ^{136}Xe $0\nu\beta\beta$ decay half-life at $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ years at 90% C.L., corresponding to effective Majorana neutrino mass $< 61 - 165$ meV[2]. KamLAND-Zen 800 is now running and a future experiment KamLAND2-Zen is planned with $\sim$1 ton of isotope (Fig. 1).

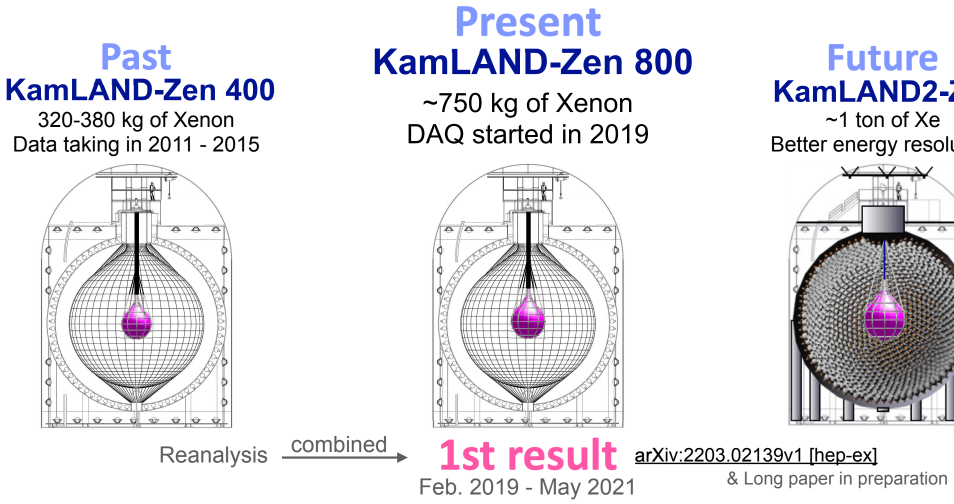

Figure 1: Schematic diagram of past, present, and future KamLAND-Zen detector.

The detector, KamLAND is a neutrino detector with 1000 tons of liquid scintillator and was primarily designed to observe a few to tens MeV neutrinos. It has a large and clean environment: the concentration of ^{238}U and ^{232}Th in the liquid scintillator is 5.0×10^{-18} g/g and 1.3×10^{-17} g/g, respectively [3]. This liquid scintillator acts as an active shield for double-beta decay search. Liquid scintillator is contained in a 6.5-m-radius 135-μm-thick balloon made of ethylene-vinylalcohol copolymer and nylon. Scintillation light produced by signal/background is detected by 1,325 17-inch and 554 20-inch photo-multiplier tubes (PMTs) mounted on the inner surface of the 9-m-radius stainless steel tank. The outer detector (19-m-diameter and 20-m-height cylindrical rock cavity) is filled with 3,000 tons of pure water and surrounds the inner detector. It vetoes/shields muons, muon-induced fast neutrons, and external gamma rays from surrounding rock using 225 PMTs of 20-inch diameters.

KamLAND-Zen 800 started science data-taking in January 2019. Two major hardware improvements have been made. One is the amount of xenon. It uses (745± 3)kg of 91% enriched xenon, almost twice the target isotope mass of the previous experiment. Another improvement is a bigger and cleaner container of xenon loaded liquid scintillator, a 1.90-m-radius 25-μm-thick nylon inner balloon. One of the main backgrounds in KamLAND-Zen 400 was ^{214}Bi originated from ^{238}U contamination in/on the inner balloon. It came from dust brought in by the working people during fabrication and installation procedures. Therefore, we thoroughly revised the work process and environment such as clean wear control, static-electricity control, particle flow check, film cover setting, semi-automatic welding machine, etc, and successfully produced a cleaner inner balloon. According to inductively coupled plasma mass spectrometer measurements, the amount of ^{238}U in the film after washing by supersonic cleaning with ultra pure water was 2×10^{-12} g/g. After installation of the inner balloon into the detector, we measured the amount of ^{238}U by KamLAND data and it was $(3 \pm 1) \times 10^{-12}$ g/g, almost the same as washed film. Compared to KamLAND-Zen 400 2nd phase, it is reduced by a factor of 10. Detailed production procedure and background analysis are summarized in Ref. [4].

3. Backgrounds

The main background of KamLAND-Zen 400 was muon-induced carbon spallation products (especially for ^{10}C), ^{214}Bi from the inner balloon, ^{137}Xe from neutron captures on ^{136}Xe, ^{110m}Ag contained in the inner balloon and xenon loaded liquid scintillator, and inevitable ^{136}Xe $2\nu\beta\beta$ decay. As already mentioned in the previous section, we successfully reduced ^{238}U (parent of ^{214}Bi) in the inner balloon to almost the same level as washed films. ^{110m}Ag(τ = 360 day, Q = 3.01 MeV) has a 2.6 MeV peak and it was probably due to the contamination from the Fukushima-I fallout. We did not find this peak in this analysis. Short-lived carbon spallation events are rejected with 150 ms cut after muons. This cut removes 99.4% of ^{12}B (τ = 29.1ms, Q = 13.4 MeV). We also improved other carbon spallation and ^{137}Xe rejection method by a combination of ordinary used triple coincidence with muon-neutron-spallation products and a newly developed likelihood method based on muon energy deposition (muon shower tagging). This new rejection scheme can remove spallation events even if we miss a neutron. Likelihood profiles of muon shower tagging are constructed with the probability density functions for energy deposition along with the muon track, the distance between the track and the spallation candidates, and the time difference between the muon and the spallation candidates. Rejection efficiencies of ^{10}C (τ = 27.8s, Q = 3.65 MeV), ^{6}He (τ = 1.16s, Q = 3.51 MeV), and ^{137}Xe (τ = 5.5min, Q = 4.17 MeV) are >99.3%, (97.6 ± 1.7)% and (74 ± 7)%, respectively.

Thanks to the background rejection, a new background, xenon spallation products appeared. ^{136}Xe (91%) and ^{134}Xe (9%) contained in the inner balloon are spallated with muon and various radioactive isotopes with high mass numbers are produced (Fig. 2, left). To assess their total yield, we performed a simulation with FLUKA and GEANT4. As shown in Fig. 2 (right), their

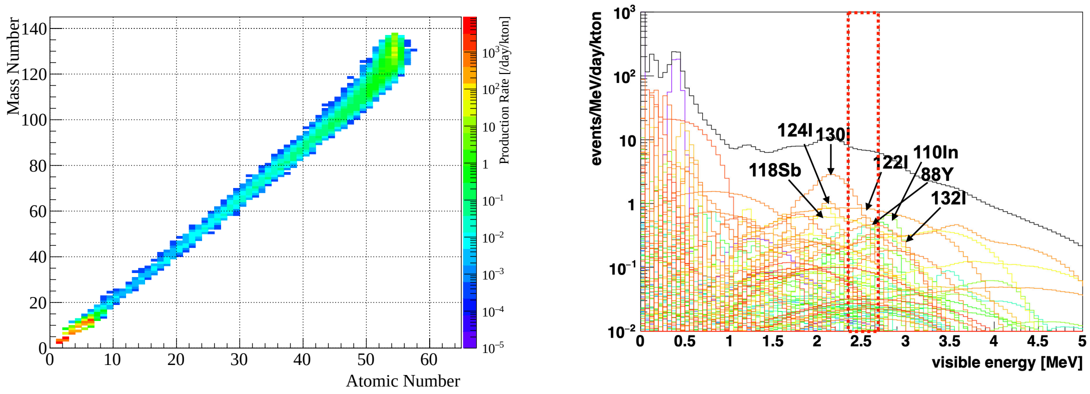

Figure 2: (Left) Production rate of spallation event simulated with FLUKA. Muons are injected into xenon loaded liquid scintillator. (Right) Expected energy spectra of spallation products in KamLAND-Zen. Red dotted region indicates our region of interest and black line shows the total yield.

individual yields are small but many candidates are produced. Major 32 nuclei contribute 90% yield in ROI (e.g. ^{132}I, ^{130}I, ^{124}I, ^{122}I, ^{118}Sb, ^{110}In, and ^{88}Y). Unfortunately, they have hours to days of half-lives and remain after triple coincidence and muon shower tagging veto. Another characteristic issue of the products is higher neutron multiplicities compared to carbons. Therefore, we developed a likelihood method with the time difference from a muon, the distance between xenon-spallation and neutron capture gamma, and an effective number of neutrons, a kind of neutron multiplicity. Effective number of neutrons is calculated from the probability density function of the distance to neutrons for each spallation product and accidental event. Rejection efficiency becomes (42.0±8.8)%. We also use this rejected long-lived data set for a simultaneous fitting to estimate $0\nu\beta\beta$ rate.

4. Analysis and result

The data used in this analysis is collected between February 2019 and May 2021. Basic event selection is as follows: we collect events in $R < 2.5$m except for 0.7m away from the bottom to avoid dust contamination. Events $>$ 2 ms after muons are rejected. Sequential radioactive decays (^{214}Bi-^{214}Po and ^{212}Bi - ^{212}Po) and $\overline{\nu}_e$ candidates are vetoed and identified by delayed coincidence cut. Poorly reconstructed events are also rejected by a time-charge-vertex discriminator.

The $0\nu\beta\beta$ decay rate is estimated from simultaneous fitting with 86 energy bins (0.5-4.8 MeV, 0.05 MeV/bin), 20 equal-volume bins each in the upper and lower hemispheres in $R < 2.5$m, and 3 time bins for each single and long-lived data. Backgrounds from ^{238}U decay chains of ^{222}Rn-^{210}Pb and carbon spallation products in the Xe-LS are allowed to vary in the fit but constrained by each estimated rate. Uncertainties of 3 energy scale parameters of the detector energy response model are constrained from the ^{222}Rn-induced ^{214}Bi data. Other events, such as $2\nu\beta\beta$ signals, contribution from the Xe-LS such as ^{210}Bi ^{85}Kr, the ^{228}Th-^{208}Pb sub-chain of the ^{232}Th series, and long-lived spallation products, are unconstrained in the fit. The parameter of energy spectral distortion for the long-lived spallation background is also allowed to float freely. Obtained energy spectra for single and long-lived data are shown in Fig. 3. To visualize the fit result, internal 10 volume bins

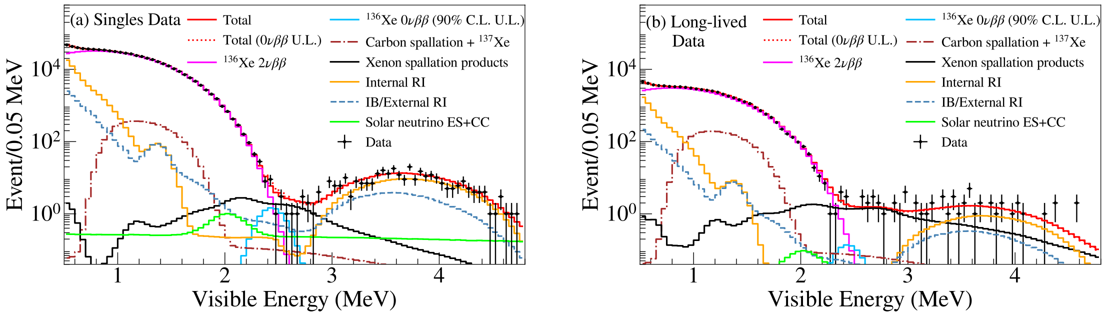

Figure 3: Energy spectra for (a) singles data and (b) long-lived data within a 1.57-m-radius spherical volume [5]. Cyan spectrum is upper limit of ^{136}Xe $0\nu\beta\beta$ at 90% C.L.

(1.57-m-radius spherical volume) × 3 time bins are shown here. Singles data is sensitive to $0\nu\beta\beta$ rate and long-lived product data is used to constrain the long-lived product rate. Livetime for singles and long-lived data are 523.4 days and 49.3 days, respectively. No excess was found and we set an upper limit on ^{136}Xe decays of < 7.9 events which correspond to $T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr at 90% C.L. KamLAND-Zen 400 data is reanalyzed with updated background rejection techniques and long-lived spallation consideration. Combined limit on ^{136}Xe $0\nu\beta\beta$ half-life is $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr at 90% C.L., corresponding to upper limits on the effective Majorana neutrino mass of 36 – 156 meV with various nuclear matrix elements calculations assuming the axial coupling constant $g_A \sim 1.27$ [5]. Figure 4 shows the allowed region of the effective Majorana neutrino mass as a function of the lightest neutrino mass. It is the first test for the inverted mass ordering.

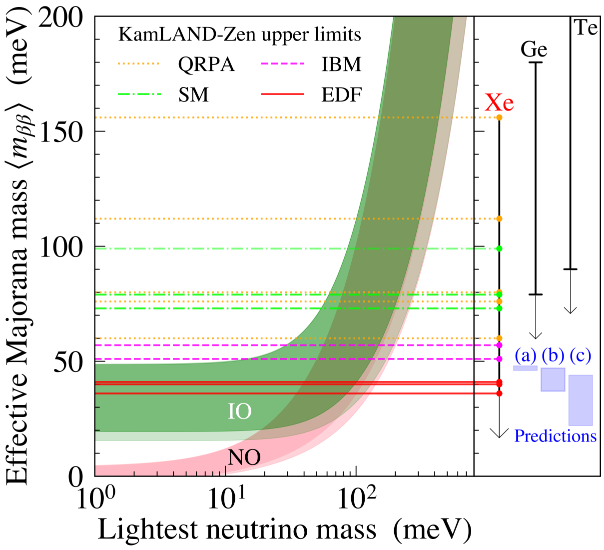

Figure 4: Effective Majorana neutrino mass as a function of the lightest neutrino mass [5]. The shaded regions are predictions based on best-fit values of neutrino oscillation parameters for the normal ordering (NO) and the inverted ordering (IO). The side panel shows the corresponding limits for each nucleus and theoretical predictions.

5. Future prospects

KamLAND-Zen 800 has an improvement plan for near future analysis. The current major background is long-lived products from xenon spallation so beta/gamma discrimination is important. Particle identification with neural networks is developed [6] and will be implemented. Analysis will be also improved with an updated waveform analysis tool and newly developed machine learning based vertex and energy reconstruction.

To search for the inverted hierarchy, we need better energy resolution. Therefore, we plan to modify KamLAND to KamLAND2. KamLAND2 will use high QE PMTs with Winston cone to improve light collection efficiency and photo coverage. Liquid scintillator is also replaced with a linear alkylbenzene based 1.5 times brighter one. KamLAND2-Zen will use 1 ton of xenon. Xe-LS container should be cleaner compared to the current one, however, no further improvement can be expected for the production since the ^{238}U level is almost the same as washed film. Therefore a scintillating balloon is considered. If the inner balloon itself scintillates with α-particles from ^{214}Po, the tagging efficiency of ^{214}Bi in the inner balloon will be increased. Current removal efficiency is about 50% and it will be improved to 99.7% [7]. New electronics is also developed to improve background suppression, especially for long-lived products. Target effective Majorana neutrino mass for KamLAND2-Zen is 20 meV in 5 years.

References

[1] J. Schechter and J. W. F. Valle, *Neutrinoless double-β decay in SU(2)×U(1) theories*, *Phys. Rev. D* **25** (1982) 2951.

[2] A. Gando *et al.* (KamLAND-Zen Collaboration), *Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen*, *Phys. Rev. Lett.* **117** (2016) 082503 [`hep-ex/1605.02889`].

[3] A. Gando *et al.* (KamLAND Collaboration), *^{7}Be Solar Neutrino Measurement with KamLAND*, *Phys. Rev. C* **92** (2015) 055808 [`hep-ex/1405.6190`].

[4] Y. Gando *et al.* (KamLAND-Zen Collaboration), *The nylon balloon for xenon loaded liquid scintillator in KamLAND-Zen 800 neutrinoless double-beta decay search experiment*, *JINST* **16** (2021) P08023 [`physics.ins-det/2104.10452`].

[5] S. Abe *et al.* (KamLAND-Zen Collaboration), *First Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen*, [`hep-ex/2203.02139`].

[6] A. Li *et al.*, *KamNet: An Integrated Spatiotemporal Deep Neural Network for Rare Event Search in KamLAND-Zen*, [`physics.ins-det/2203.01870`].

[7] S. Obara, Y. Gando, and K. Ishidoshiro, *Scintillation Balloon for Neutrinoless Double-Beta Decay Search with Liquid Scintillator Detectors*, *PTEP* **2019** (2019) 073H01 [`physics.ins-det/1903.10736`].