PROCEEDINGS OF SCIENCE

KamLAND-Zen

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KamLAND-Zen is a high sensitivity experiment searching for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe nucleus by using a large volume ultralow-radioactivity environment of KamLAND detector. In this talk results of the KamLAND-Zen experiment using up to 380 kg of enriched xenon (KamLAND-Zen 400) is presented together with the current status of the new phase, KamLAND-Zen 800, with 750 kg enriched Xe aiming at a search in the inverted mass hierarchy (IH) region, and the planned experiment of KamLAND2-Zen.

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1. Introduction

Observation of the neutrino oscillation has established the finite masses of neutrinos. Currently many studies are being made for precise determination of the oscillation parameters including the neutrino mass hierarchy and the CP violation phase. On the other hand, another fundamental problem whether neutrinos are Majorana or Dirac particles is still unsolved. If neutrinos are Majorana particles, then the extremely small masses of existing neutrinos is naturally explained by super-heavy neutrinos through the see-saw mechanism. In other words, the super-heavy neutrinos would open a window to extremely high energy physics. It also might explain the evolution of the early stage of the Universe to make the today's matter dominance world. Therefore, study of the Majorana nature of neutrinos is quite important and attractive to be settled experimentally.

Neutrinoless double beta decays ($0\nu\beta\beta$), $(A,Z) \rightarrow (A,Z+2) + 2e^-$, unobserved to date is the only feasible way to check the Majorana nature of the neutrinos. The process violates the total lepton number conservation and beyond the standard model. Measured value or the limit of the half-life ($T^{0\nu}_{1/2}$) is connected to the effective Majorana neutrino mass, $\langle m_{\beta\beta} \rangle \equiv \left| \sum_i U^2_{ei} m_{\nu i} \right|$, containing the absolute masses of the neutrinos.

The key of the experiment is to prepare as much as possible the nucleus which undergo double beta decays with high Q values. The nucleus is preferable if provided with a high natural abundance or can be isotopically enriched. Also, it is very important to prepare very low radioactivity environment and various techniques for background rejection. Furthermore, the experiment should have excellent scalability.

^{136}Xe nucleus (Q=2.458 MeV, natural abundance = 8.9% and $T^{2\nu}_{1/2} = 2.2 \times 10^{21}$yr) is excellent for the $0\nu\beta\beta$ search. Because of rare gas, the enrichment and purification techniques are well established, and the high chemical stability makes it easy for handling and the scaling up the experiment.

Moreover, xenon has high solubility to organic liquids like liquid scintillator (LS), and it does not affect the characteristics of the LS. It is also easily collected from LS for re-purification and reusing. These characteristics makes the combination of Xe with LS an excellent strategy. A large volume of LS detector like KamLAND can therfore provide a unique method for $0\nu\beta\beta$ search.

2. KamLAND-Zen detector

Figure 1 shows the experimental apparatus of the KamLAND-Zen. It is a small-scale modification of KamLAND by putting a balloon (3.1m in diameter) called mini-balloon (MIB) at the center of the main balloon (13 m in diameter) filled with 1000 ton ultrapure LS. The experimental cite is located in 1000 m (2700 m.w.e.) underground in Kamioka mine in Japan. The MIB is filled with enriched Xe (91% ^{136}Xe)-dissolved LS (Xe-LS) made of decane, PC, and PPO. The Xe amount is 320 kg in the 1st phase (phase I) and 380 kg in the 2nd phase (phase II). Scintillation photons from the LS are detected through the buffer oil by PMTs (1325 17-inch and 554 20-inch) bolted on the inner surface of a stainless steel spherical tank of 18 m in diameter. The outside of the tank is the 3200 ton water Cherenkov detector equipped with 225 20-inch PMTs to identify cosmic-ray muons and to serve as the radiation shield against the radioactivity of the surrounding rock.

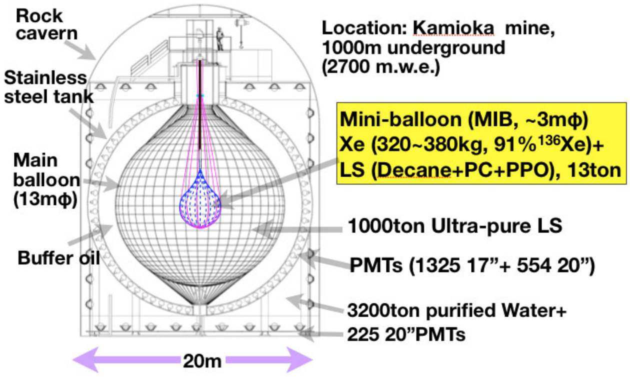

Figure 1: Detector apparatus of KamLAND-Zen.

The small modification of the existing detector facility made possible the quick start of the experiment with relatively low cost. And the detector response has been well understood. The simple system makes it easy for the operation such as collecting and purifying Xe, and doing a blank run without Xe. Due to the large LS volume of the main balloon, the system has excellent scalability. In addition, other physics program such as measurement of geoneutrinos and supernovae neutrinos etc. can be made in parallel.

KamLAND-Zen started physics run in October 2011 and continued until June 2012 (phase I). Then, Xe was collected to conduct purification of Xe and LS separately. A new run started in December 2013 and continued until October 2015 (phase II) with an increased amount of enriched Xe of 380 kg. The collected data corresponds to the ^{136}Xe exposure of 89.5 kg yr (phase I) and 504 kg yr (phase II). We call the phase I and phase II KamLAND-Zen 400 together.

The MIB is made of thin transparent nylon film (25μm thick) of reduced concentration of K, U and Th. The film sealing was made by the impulse welding method. After several tests with trial balloons, construction of the real balloon was made in a super-clean room in Tohoku University. The MIB was installed in the detector in August 2011, and the phase-I data taking was started.

After the phase II the MIB was extracted, and the outer detector was reconstructed between January and March in 2016 by replacing the all PMTs with new 140 20-inch PMTs. During the period from 2015 to 2016 we constructed a new clean MIB with twice the volume to start preparation for a new phase using 750 kg enriched Xe which we call KamLAND-Zen 800.

3. Results of phase I

Figure 2 shows the observed energy spectrum of the selected events collected in phase I together with fitted backgrounds [1]. A peak is found in the energy region of 2.2-3.0 MeV around the Q value, however the position and the shape are slightly different from the $0\nu\beta\beta$ signal. It was identified as the β^- decay of $^{110\mathrm{m}}$Ag (τ =360 days, Q=3.01 MeV), because it reproduces well the observed spectral shape, and the observed event rate variation is consistent with the half-life of the $^{110\mathrm{m}}$Ag. The origin of the $^{110\mathrm{m}}$Ag is speculated as the fallout from the Fukushima reactor accident in March 2011 which took place just before the start of the MIB construction in Tohoku University located at $\sim$100km away from the reactor station. The speculation is supported by the structure in the 1-2 MeV region which can be identified as the $\beta+\gamma$ decays of ^{134}Cs at the MIB surface. ^{134}Cs and ^{137}Cs are the dominant activities in the fallout, and the observed rate of ^{134}Cs to ^{137}Cs (0.662 MeV γ) is consistent with the contamination by fallout.

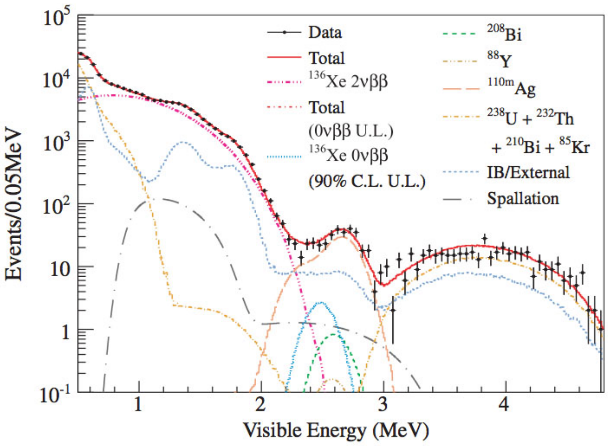

Figure 2: Visible energy spectrum of the selected candidates (dots with error bars) in phase I and the fitted backgrounds (colored lines) [1]. Selection is made within a fiducial volume of nominally 1.35-m-radius spherical region from the center and by applying cuts against cosmic-ray μons (<2ms), delayed coincidence events of ^{214}Bi-^{214}Po, and reactor neutrinos.

Other backgrounds are identified as $\beta+\gamma$-ray emissions of ^{214}Bi from the MIB as the sub-dominant one and ^{10}C decay (β^+, Q=3.65 MeV, τ=27.8 s) produced by the muon spallation of ^{12}C nuclei, and the high-energy tail of the $2\nu\beta\beta$ decays of ^{136}Xe. The obtained half-life limit (90% C.L.) of $0\nu\beta\beta$ is $T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr. When it is combined with the EXO-200 results [2], the limit is obtained as $T^{0\nu}_{1/2}$>3.4×10^{25} yr (90%C.L.) which corresponds to the limit of the limit of the effective Majorana neutrino mass as $\langle m_{\beta\beta}\rangle$ <(120-250)meV (90%C.L.). The limit disfavors the long standing positive claim of ^{76}Ge [3] at 97.5% C.L.

After the phase I a purification campaign was conducted to remove ^{110m}Ag background for Xe and LS separately. Xe was purified by filtration, distillation and refining with a zirconium getter. The LS was purified by water extraction and three times distillation for full MIB volumes. As a result ^{110m}Ag was found significantly reduced by a factor ∼10. We confirmed that the purification method is quite effective.

4. Results of phase II

The analysis results of the phase-II data is shown in Figure 3, where the vertex distribution of the selected candidates in 2.3-2.7 MeV region ($0\nu\beta\beta$ window) and the $(R/1.54\text{m})^3$ vertex distribution in the $0\nu\beta\beta$ window are presented [4]. The vertex distribution and the spectral analysis show that the backgrounds are dominated by the ^{214}Bi decays at the MIB. The ^{214}Bi backgrounds extends to the inner region, but sharply decreasing when going inwards from the MIB. It also shows strong z-dependence being larger in lower hemisphere. The colored histogram shows MC simulation of the ^{214}Bi events which are precisely tuned by the Geant4 simulation for the observed ^{214}Bi→^{214}Po decay vertex distance of the ^{222}Rn-rich data in the initial stage of the data taking. As for the ^{10}C background they are rejected by triple coincidence of the muon-neutron-^{10}C detection. Detection of neutrons just after the muons are made by the newly introduced dead-time free electronics (MoGURA). Events are rejected if they are within the spherical region of 1.6 m around the neutron and within 180 s from the muons.

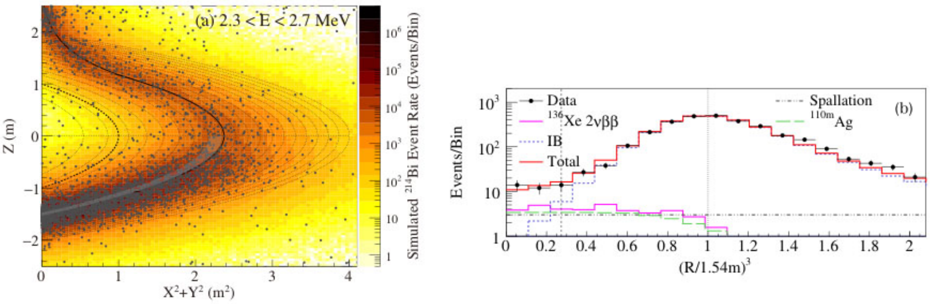

Figure 3: a) Vertex distribution of the candidate events in the energy region of $2.3 < E < 2.7$ MeV. b) Radial distribution of the candidates as a function of the cubic of the normalized radial distance by the MIB-radius [4].

We divided the phase-II data into period 1 (270.7 days) and period 2 (263.8 days) with roughly the same as the life-time of $^{110\text{m}}$Ag to examine the effect of the remaining $^{110\text{m}}$Ag background. Since the dominant ^{214}Bi background has a strong radial attenuation and z-position dependence, the fiducial volume (FV) is taken as the 2-m spherical volume around the detector center to make full use of the Xe and to examine the behavior of the background in the outer region of MIB. The FV is divided into 20 equal-volume spherical shells and further divided to upper and lower parts. Simultaneous fit is made to the energy spectra for all the bins in the energy region of $0.8 < E < 4.8$ MeV and independently for period 1 and period 2.

Figure 4 shows the energy spectrum of the selected $\beta\beta$ candidates within 1-m radius sphere from the center in period 2. The best-fit backgrounds and the upper limit for the $0\nu\beta\beta$ decays are also shown. The right panel shows the enlarged spectra in the $0\nu\beta\beta$ window (2.3-2.7 MeV) for period 1 (top) and period 2 (bottom). Significant reduction of $^{110\text{m}}$Ag background in period 2 is speculated that the dusts containing $^{110\text{m}}$Ag sank to the MIB bottom and not reconstructed in the inner Xe-LS region.

No excess of events in the $0\nu\beta\beta$ window over the backgrounds is found. Combining the results of the period 1 and period 2, upper limit on the $0\nu\beta\beta$ half life from phase II is obtained as $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr (90%C.L.). A MC study assuming the best-fit backgrounds without $0\nu\beta\beta$ shows the sensitivity of 5.6×10^{25} yr.

The limit obtained by combining the phase I and phase II gives $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr (90%C.L.). Corresponding limit on the $\langle m_{\beta\beta} \rangle$ is given as (61-165) meV at a 90% C.L. by using commonly used NME calculations assuming the axial coupling constant $g_A \simeq 1.27$. The results are shown in Figure 5 together with the previous $0\nu\beta\beta$ searches for other nuclei, and the allowed regions of the inverted (IH) and normal (NH) mass hierarchy by neutrino oscillation experiments as a function of the lightest neutrino mass.

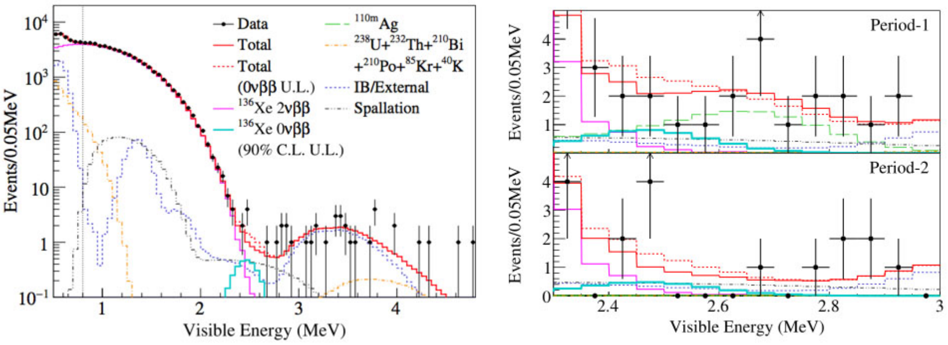

Figure 4: Left: Observed energy spectrum of $\beta\beta$ candidates within 1-m-radius spherical volume in period 2 together with the best-fit backgrounds and the upper limit for $0\nu\beta\beta$ decays. Right: Enlarged spectra for 2.3-3.0 MeV region including the $0\nu\beta\beta$ window (2.3-2.7 MeV) for period 1 (top) and period 2 (bottom) [4].

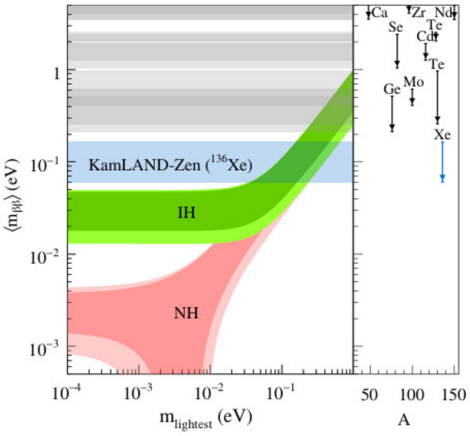

Figure 5: Allowed regions of $\langle m_{\beta\beta}\rangle$ for IH and NH regions from neutrino oscillation experiments and the limits from KamLAND-Zen 400 and previous searches as a function of the lightest neutrino mass, m_{lightest} [4].

5. Current efforts and prospects

The $^{110\text{m}}$Ag background has gone, and the remaining backgrounds are identified as ^{214}Bi, ^{10}C and the high-energy tail of $2\nu\beta\beta$. ^{10}C can be removed by further improving the analysis. $2\nu\beta\beta$ can be reduced by improving the energy resolution, which will be made in future. ^{214}Bi can be removed by replacing with a cleaner MIB.

As already described, we constructed a new MIB with twice the volume for 750 kg enriched Xe in a much improved cleanliness control in 2015 to 2016. It was deployed into the KamLAND detector last summer. The data collected using a dummy LS (without Xe) in the MIB showed that the new MIB was much cleaner than the previous one. In fact, the backgrounds originated from the ^{238}U and ^{232}Th series from MIB decreased by factors of 2∼3 compared to the previous MIB. Unfortunately, a leak from the MIB was found and it was taken out. Careful inspection of the MIB and the various studies on the welding method have been made for a new MIB construction which is now underway. It will be deployed this autumn aiming to the $\langle m_{\beta\beta}\rangle$ sensitivity to ∼40 meV entering the IH region.

We are planning a next project of KamLAND2-Zen with $>$1ton of enriched Xe. In KamLAND2-Zen we aim to much improve the $0\nu\beta\beta$ sensitivity to explore the full coverage of the IH region. It is essential to reduce the $2\nu\beta\beta$ background. This can be done with much better energy resolution by increasing the number of detected photons. We aim at σ_E/E $\sim$2% at the Q value. R&Ds are ongoing for the new LAB-based LS with high light yield, new PMTs with high quantum efficiency and the light collection cones. In addition, other R&Ds are ongoing for new LS purification by introducing metal scavengers to remove ^{210}Pb, β/γ discrimination by imaging cameras, detection of ^{214}Bi decays at the balloon film by introducing a scintillating balloon, and ^{10}C rejection by electronics improvements. The high sensitivity search would make a great impact not only on the accelerator and reactor $\overline{\nu}_e$ experiments, but on the studies of astrophysics and cosmophysics.

6. Summary

- KamLAND-Zen is an unique experiment searching for $0\nu\beta\beta$ decay of ^{136}Xe using the MIB with Xe-LS in the ultra-low background facility of KamLAND.

- The phase I (320 kg Xe) and phase II (380 kg Xe) after the Xe-LS purification campaign of the first stage (KamLAND-Zen 400) accumulated data corresponding to ^{136}Xe exposure of 593.5 kg yr.

- The analysis has provided the limit on the $0\nu\beta\beta$ half-life as $T^{0\nu}_{1/2}$ >1.07×10^{26}yr (90%C.L.), and constrains $\langle m_{\beta\beta}\rangle$ < (61-165) meV (90%C.L.), which is the most stringent limit and approaching the IH region.

- A new phase of KamLAND-Zen 800 with 750 kg of enriched Xe is under preparation for making a much cleaner MIB. After a trial in the last summer, the new phase will start this autumn to explore the IH region.

- Our future plan is the KamLAND2-Zen using >1ton enriched Xe. Many R&Ds are ongoing to make the full-coverage of the IH region.

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