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KamLAND-Zen Experiment

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Study of Majorana nature of neutrinos is very important in fundamental physics, because it would clarify the extremely smallness of the neutrino mass and open the physics of very high-energy scale which might provide a key to solve the matter dominance of the current Universe. Neutrinoless double beta decay ($0\nu\beta\beta$) of nucleus is a unique process to test the Majorana nature of neutrinos. KamLAND-Zen (KamLAND Zero-Neutrino Double-Beta Decay) is an experiment searching for $0\nu\beta\beta$ of ^{136}Xe nucleus using KamLAND detector in Kamioka mine in Japan. The experiment has provided the most stringent limit on the ^{136}Xe $0\nu\beta\beta$ lifetime of 1.07×10^{26} yr (90% C.L.) corresponding to the upper limit (90% C.L.) of the effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle < (61-165)$meV. In this talk current status and future plan of the KamLAND-Zen experiment are reported.

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1. Introduction

Although neutrinos have finite masses, their extremely smallness comparing to other charged leptons and quarks is not understood. This might suggest physics mechanism of very high energy scale. The problem might be explained by Majorana nature of neutrinos, that is neutrinos are equivalent to their antiparticles. Since neutrinos have no electric charge, the mass terms of the Lagrangian density have additional terms like $\overline{\psi^c}_R \psi_L$ and $\overline{\psi^c}_L \psi_R$ called Majorana mass terms which connect a particle and its antiparticle. Then, the mass eigenvalues of the mass matrix can be lead to a relation, $M_\nu = M_{q,l^\pm}/M_N$ through the widely known "Sea-saw mechanism", providing explanation of the smallness of the neutrino masses and suggesting the existence of super heavy neutrinos. The heavy neutrinos would play a crucial role in the "Leptogenesis" in the very beginning stage of the Universe and lead to the current matter-dominance of the Universe. Therefore, the problem of whether neutrinos are Majorana particles or not is a very fundamental problem in the particle physics and astrophysics which must be solved.

Neutrinoless double beta decay ($0\nu\beta\beta$) is a crucial process to make clear the Majorana nature of neutrinos. There are two kinds of nuclear double beta decays; one is the 2nd order weak process of the SM, $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$, which is indicated as $2\nu\beta\beta$ and has been observed directly in 10 nuclear isotopes with very long halflives of 10^{19}-10^{21} yr.

If neutrinos are Majorana particles, then the other process without neutrino emission, $(A,Z) \rightarrow (A,Z+2) + 2e^-$ would occur. It is the lepton number violation process ($\Delta L = 2$) beyond the SM, and has not been observed to date. The $0\nu\beta\beta$ is considered predominantly through the exchange of light Majorana neutrinos. However, it should be noted that any process of $0\nu\beta\beta$ means the transition of neutrinos to anti-neutrinos, that is, observation of $0\nu\beta\beta$ means that neutrinos are Majorana particles.

If $0\nu\beta\beta$ occurs through the light Majorana neutrino exchange, the halflife ($T^{0\nu}_{1/2}$) is expressed as $1/T^{0\nu}_{1/2} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$, where $G^{0\nu}$ is the phase space factor, $M^{0\nu}$ is the nuclear matrix element (NME) and $\langle m_{\beta\beta}\rangle$ is the effective Majorana neutrino mass. Although $G^{0\nu}$ is reliably calculated, $M^{0\nu}$ has some theoretical uncertainties. $\langle m_{\beta\beta}\rangle$ contains every particle physics information of neutrinos; oscillation parameters including unknown Dirac and Majorana CP-phases and the neutrino masses. Figure 1 shows $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass, $m_{lightest}$. In the figure allowed regions by the oscillation experiments are shown for mass structures of the normal (NH) and inverted hierarchy (IH) which merges into the quasi-degenerate region (QD). The most stringent limit on $\langle m_{\beta\beta}\rangle$ has been provided by KamLAND-Zen [1] which is (61-165) meV (90% C.L.) by the halflife limit of 1.07×10^{26} y (90%C.L.) for ^{136}Xe nucleus. From the results the QD region ($m_1 \approx m_2 \approx m_3 \gtrapprox$ 100meV) is almost excluded and the next step is to explore the IH region of $\langle m_{\beta\beta}\rangle = 20 \sim 50$ meV.

2. Experimental challenge

Signature of $0\nu\beta\beta$ decay would appear as a monochromatic peak at the Q-value ($Q_{\beta\beta}$) in the spectrum of summed electron energies of $2\nu\beta\beta$ decays. The sensitivity for the $T^{0\nu}_{1/2}$ is provided by an equation,

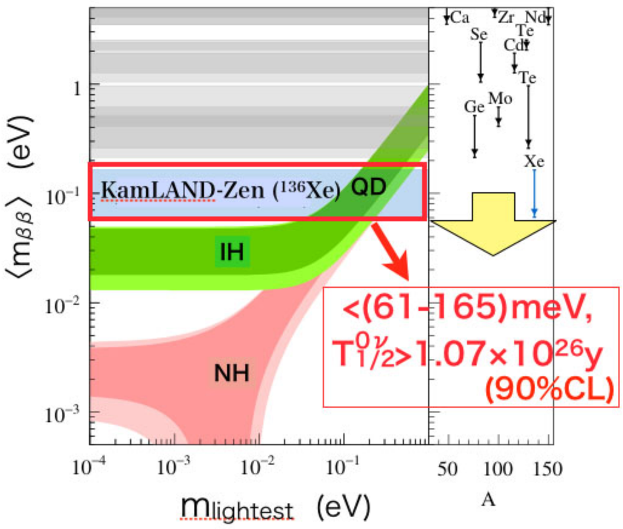

Figure 1: Allowed region of $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass, $m_{lightest}$ from neutrino oscillation parameters for different mass hierarchies indicated by NH, IH and QD. The most stringent limit (90%C.L.) given by KamLAND-Zen [1] is shown with previous limits using other nuclei.

$$T_{1/2}^{0\nu} = \ln 2 \times \eta \varepsilon \frac{N_A}{A} \sqrt{\frac{Mt}{b\Delta E}} \propto 1/\langle m_{\beta\beta} \rangle^2, \tag{2.1}$$

where η is the mass fraction of the isotope, ε is the detection efficiency, N_A is the Avogadro number, A is the atomic weight, M is the detector mass, t is the experimental period, b is the background index given by the unit of (kg^{-1}keV^{-1}yr^{-1}), and ΔE is the energy window.

From the view point of the discovery potential, the large target isotope mass of O(100) kg $\sim$ O(1) ton and the extremely low background condition are crucially required. Therefore, scalability of the experiment which enables the step-by-step increase of the target nuclear mass is important. In addition not only thick shields and high radio-purity of the detector material, but also various techniques to extract information for background discrimination together with excellent energy resolution are required. As for the selection of the nuclear isotopes, higher $Q_{\beta\beta}$ and natural isotopic abundance, and a long halflife of $2\nu\beta\beta$ are also taken into account. Therefore, the selection of nuclei and the strategy of $0\nu\beta\beta$ search are not trivial. Various searches using different isotopes and techniques are now carried out or planned worldwide. All of them are aiming at increasing the sensitivity for $T_{1/2}^{0\nu}$ from the current $10^{25} - 10^{26}$ yr to much longer than 10^{27} yr.

^{136}Xe is one of the excellent isotopes for the $0\nu\beta\beta$ searches. It has good properties of relatively high $Q_{\beta\beta}$ (2.458 MeV), high natural isotopic abundance (8.9%), and the longest $2\nu\beta\beta$ decay halflife ($T_{1/2}^{2\nu}$) of 2.2×10^{21} yr [1][3]. More importantly, Xe is the noble gas and provides excellent properties for $0\nu\beta\beta$ search; (i) long-time chemical stability which makes Xe nontoxic and easy-handling element, (ii) existence of well-established techniques of isotopic enrichment and purification. These properties make it possible to get large amount of the isotope with high radio-purity and with excellent scalability. In addition, Xe has a high solubility to organic liquids like liquid scintillator (LS) ($\sim$3 wt%) which makes the combination of Xe and LS a unique strategy as taken in KamLAND-Zen experiment. From the above properties ^{136}Xe is used in several $0\nu\beta\beta$ experiments with variety of strategies.

3. KamLAND-Zen experiment

The cite of KamLAND-Zen is located 1,000 m underground ($\sim$2,700 m.w.e) in Kamioka mine in Japan. As shown in Figure 2, the experimental apparatus is a minor modification of the KamLAND detector which is the world's largest 1,000 ton LS detector by deploying a small balloon at the center filled with LS of $\sim$15 m^3 dissolved with enriched-Xe gas (91% of ^{136}Xe). KamLAND detector has been successfully operated since 2002. It has made great contributions to the neutrino physics by the first observation [4] and precise measurement of the reactor anti-neutrino oscillation [5]. It also made the first challenge of the geoneutrino detection in 2005 [7] and has continued the flux measurement of the geoneutrinos [6].

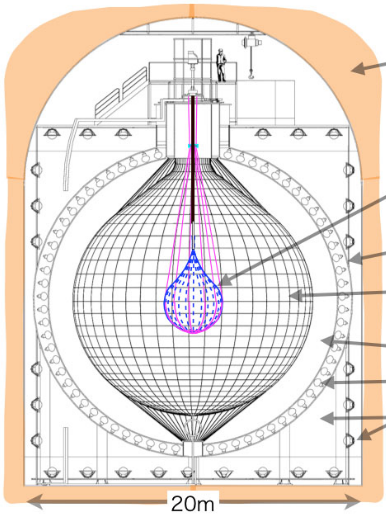

Figure 2: KamLAND-Zen detector.

The KamLAND-Zen central balloon is 3.1 m in diameter made of a thin transparent nylon film of 25 μm thick. The Xe amount was initially 320 kg and then increased to 380 kg. The balloon is surrounded by the 1,000 ton ultrapure LS contained in the outer balloon of 13 m in diameter and viewed through the paraffin oil by 1,879 PMTs (1,325 17-inch and 554 20-inch PMTs) mounted on the inner wall of the spherical stainless tank of 18 m in diameter. The outside region of the spherical tank is a 3,200 ton water Cherenkov detector equipped with 225 20-inch PMTs. It identifies cosmic ray muons and serves as the radiation shield against the surrounding rock. The ultra-low radioactivity environment given by the large-volume active shield of 1,000 ton LS makes KamLAND-Zen a unique and high sensitivity $0\nu\beta\beta$ experiment with excellent scalability of Xe. It also enables in situ background studies without Xe and provides other physics capabilities of the geoneutrino measurement and the Supernova neutrino detection.

KamLAND-Zen started data taking from October 2011 to June 2012 (phase-1) and November 2013 to December 2015 (phase-2), corresponding to the ^{136}Xe exposure of 89.5 kg yr and 504 kg yr, respectively, by using 320 kg (phase-1) and 380 kg (phase-2) of enriched Xe. We call these phases as KamLAND-Zen 400. Figure 3 shows the measured energy spectrum of the candidate events and the background components. Details of the analyses are described elsewhere [1] [2].

As shown in Figure 3(a) the observed spectrum in phase-1 is dominated by a peak at around $Q_{\beta\beta}$ which is identified as ^{110m}Ag decay (β^-, $\tau = 360$ d, $Q = 3.0$ MeV) by the spectral shape and the time variance [2]. The background is considered to be caused by the contamination of the fallout from the Fukushima reactor accident in 2011 when the balloon fabrication was going on in a clean room in Sendai locating at $\sim$100 km away from the Fukushima power station. After purification by filtration of the Xe-LS by circulation, we stopped the phase-1 and made a long-period purification campaign; distillation and refinement of Xe followed by replacement of LS with new and distilled LS.

We started data taking of phase-2 and found significant decrease of ^{110m}Ag by a factor $\sim$10. The energy spectrum in the phase-2 is shown in Figure 3(b) for the central region (R<1m) which makes the largest contribution to the sensitivity [1]. Remaining backgrounds are ^{10}C ($\beta^+, \tau = 28s, Q = 3.65$ MeV, produced by muon spallation), the high-energy tail of $2\nu\beta\beta$ decays and ^{214}Bi decays (^{238}U series, $\beta^-, Q = 3.27$ MeV). Among them ^{10}C decays are rejected by triple coincidence (muon-neutron-^{10}C) of the spallation events, and further rejection by an improvement of the neutron detection efficiency which is now underway. Reduction of the $2\nu\beta\beta$ will be made in a future plan by improving the energy resolution. ^{214}Bi decays in the Xe-LS are rejected to a negligibly small level by using the delayed coincidence of the ^{214}Bi($\beta+\gamma$)-^{214}Po(α, $\tau = 237\mu$s) decays.

We found no excess over the expected background. Combining the results of the two phases we obtain the limit of $T^{0\nu}_{1/2}$ and the corresponding limit of $\langle m_{\beta\beta}\rangle$ by commonly used calculations of NME as shown in Figure 1. However, the sensitivity is limited by ^{214}Bi decays which dominate around the balloon and sneak into the central region due to the limited detection efficiency of the α particle from ^{214}Po decay on the balloon. They belong to the ^{238}U decay chain and dominantly come from the contamination of the balloon by dusts during the balloon construction. To remove them we decided to replace the balloon with a new clean one. The phase-2 was stopped in October 2015.

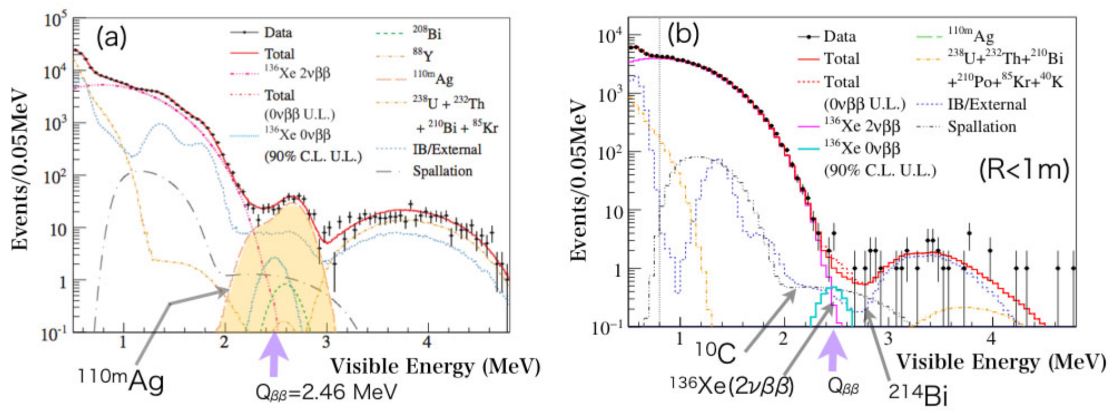

Figure 3: (a) Energy spectra of the candidate events and the background components for the data taken in phase-1 [2]. (b) The same spectra for the central region ($R < 1$ m) in phase-2 [1] after a long-time purification campaign of the Xe and LS.

4. New challenge of KamLAND-Zen 800

Construction of the new balloon started in early 2017 in the super-clean room of Tohoku University and finished last month (April 2018). We aim to get the target sensitivity for $\langle m_{\beta\beta} \rangle$ $\sim$ 40 meV to enter the IH region. The balloon has an enlarged capacity of 750 kg enriched Xe. We call the new phase KamLAND-Zen 800. Actually, we completed the balloon construction in a work from 2015 to 2016 and deployed it in the detector in summer of 2016. Unfortunately, leakage happened on the balloon after the inflation of the balloon with dummy LS (without Xe). The cause of the trouble was fixed by carefully checking the collected balloon and taking measure in the construction process.

In the new challenge every efforts are made to keep the balloon as clean as possible throughout the process together with improved welding methods. New welding machines were introduced after careful studies to improve the strength of the welded films. Also, more strict leak hunting of the balloon than previous work as well as improved repair methods are adopted. Figure 4(a) shows the construction work in the clean room.

The new balloon was sent to Kamioka and successfully deployed into the detector on May 10th. Figure 4(b) shows the deployment work done above the KamLAND detector and the balloon inflated by the dummy LS. The balloon is now carefully watched by cameras, and backgrounds are examined with the collected data. If everything goes well, the dummy LS is replaced with the Xe-LS and the new phase will be started in a few months.

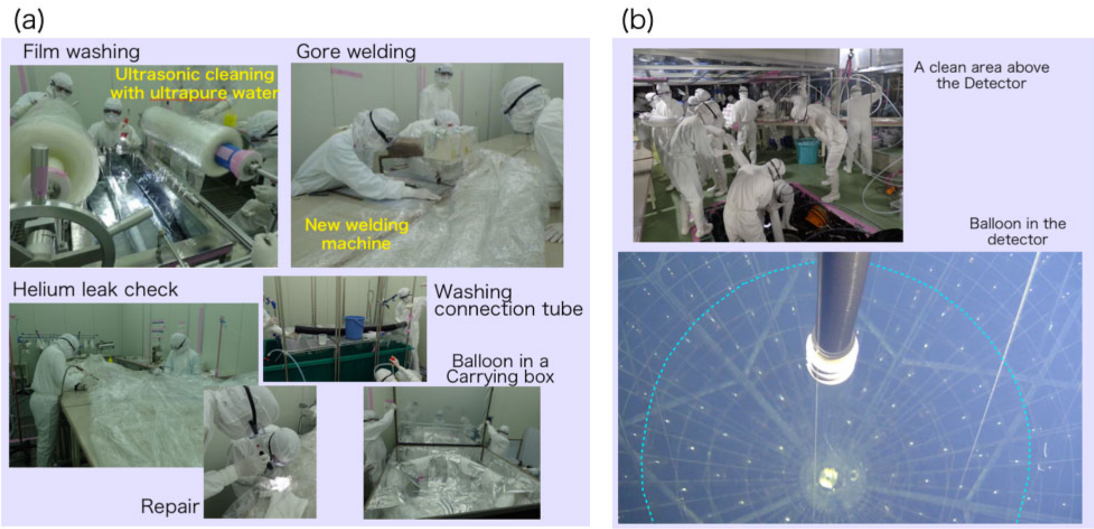

Figure 4: (a) Construction wok for the new KamLAND-Zen800 balloon in the super clean room of Tohoku University. (b) Deployment of the balloon into the detector (top) and the balloon in the detector (bottom). A broken line shows the balloon edge.

5. Future plan and prospects

We have a future plan of $0\nu\beta\beta$ search called KamLAND2-Zen by increasing the Xe amount to more than 1 ton and improving the energy resolution (σ_E/E) by a factor of >2, from 4.3% to

1.8% at $Q_{\beta\beta}$ to reduce the $2\nu\beta\beta$ background. The target sensitivity for $\langle m_{\beta\beta}\rangle$ is 20meV which fully covers the IH region.

In KamLAND-Zen collaboration, many R&Ds are actively ongoing to increase the light signals by adopting brighter LS based on linear alkylbenzene (LAB) and light collectors on the new high-quantum efficiency (HQE) PMTs with Box&Line focus type dinodes. Furthermore, studies on new purification methods for the LS using activated carbon to improve the light transmission and studies of metal scavenger to remove organic lead in the LS to reject ^{214}Bi backgrounds together with improving electronics and new trigger methods are underway. Also, studies of imaging detector system and a scintillating balloon for further increasing background rejection capabilities are going on.

Exploring the IH region is very important because not only it makes a simple extension of the search region but it also has a close relation of the obtained results to many important studies on neutrino masses; accelerator and reactor based oscillation experiments, direct neutrino mass measurement by precise beta-ray measurement, CMB observation and theoretical studies. All of the studies are the challenge to the neutrino mass problem. Moreover, improved theoretical calculations of NME and further constraints on the lightest neutrino mass push forward the studies. Some of the theoretical models make predictions on $\langle m_{\beta\beta}\rangle$ around 40 meV. If we are very lucky, big surprise may come out in the near future !

6. Summary

- Majorana nature of neutrinos would make a great impact on the fundamental research fields of particle physics, astrophysics, and cosmology.

- $0\nu\beta\beta$ is a key process to check the Majorana nature of neutrinos, and high sensitivity searches are going on and planned worldwide.

- KamLAND-Zen is a unique and high sensitivity $0\nu\beta\beta$ experiment using Xe-LS in the ultra-low radioactivity environment of KamLAND facility, and "KamLAND-Zen 400" using ~400 kg enriched Xe nuclei dissolved in the LS has provided the most stringent limit of $\langle m_{\beta\beta}\rangle <$ (61-165) meV at 90% C.L.

- With a new cleaner and double-sized Xe-LS balloon just deployed in this month, a new phase "KamLAND-Zen800" is going to start aiming to the sensitivity of $\langle m_{\beta\beta}\rangle \sim$ 40 meV to enter the IH region.

- Many R&Ds are ongoing for the future plan of "KamLAND2-Zen" to further improve the sensitivity to fully cover the IH region of $\langle m_{\beta\beta}\rangle \sim$ 20 meV.

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