PROCEEDINGS OF SCIENCE

Recent results from KamLAND-Zen

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A search for the neutrinoless double beta decay of ^{136}Xe was conducted with the xenon-loaded liquid scintillator detector KamLAND-Zen 800 using 970 kg·year of ^{136}Xe exposure. No significant signal excess from the expected background was observed from the energy spectrum fitting, and we set a lower limit on the half-life of 2.0×10^{26} years at a 90% confidence level. A combined fit of the KamLAND-Zen 400 and 800 data sets gives a lower limit of the half-life of 2.3×10^{26} years at a 90% confidence level. It corresponds to the upper limits on the effective Majorana neutrino mass of 36 – 156 meV with various nuclear matrix element calculations. It is the first test for inverted mass ordering.

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1. Introduction

The question of whether the neutrino is a Dirac particle or a Majorana particle is a longstanding issue in the particle physics field. If the neutrino is a Majorana particle, processes that violate the lepton number by two can take place. The observation of neutrinoless double beta decay ($0\nu\beta\beta$) would tell us the Majorana nature of the neutrino, the effective Majorana mass $\langle m_{\beta\beta}\rangle$ and the neutrino mass ordering from the decay rate of $0\nu\beta\beta$. Although a number of $0\nu\beta\beta$ experiments using various candidate nuclei and detection techniques have been performed, no signal of $0\nu\beta\beta$ has been observed so far [1–4]. The observation of $0\nu\beta\beta$ requires a massive amount of target nuclei and ultra-low background (BG) environment.

2. KamLAND-Zen experiment

KamLAND-Zen is a $0\nu\beta\beta$ decay search experiment with ^{136}Xe utilizing the KamLAND ultra-low BG detector. About 90% ^{136}Xe enriched xenon gas was dissolved into the liquid scintillator with 3 wt% (Xe-LS) and stored in nylon made inner balloon (IB). The IB is surrounded by 1 kton of the liquid scintillator (Outer-LS) contained by the outer balloon with a radius of 13 m. Outer-LS works as an active shield for $0\nu\beta\beta$ search. Scintillation lights from Xe-LS and Outer-LS are detected by 1325 17-inch photomultiplier tubes (PMTs) and 554 20-inch PMTs. KamLAND-Zen 400 experiment used 320 – 380 kg of enriched xenon gas. It started data acquisition in October 2011 and terminated in October 2015, including a purification period from June 2012 to December 2013. No significant excess over the expected BG was found and a 90% confidence level (C.L.) lower limit of the half-life for the $0\nu\beta\beta$ of ^{136}Xe, $T_{1/2}^{0\nu\beta\beta}$ of 1.07×10^{26} years, corresponding to $\langle m_{\beta\beta}\rangle < 61 – 165$ meV [5].

The dominant BGs in the KamLAND-Zen 400 experiment are $2\nu\beta\beta$, ^{214}Bi in the IB, and the cosmogenic spallation product such as ^{10}C. To improve the sensitivity, KamLAND-Zen 800 increased the target xenon mass to 745 kg and improved the cleanness of the IB to reduce ^{214}Bi BG, and the software to reduce cosmogenic spallation BG. To develop ultra-clean IB film, careful production work mentioned in Ref. [6, 7] was done in a class 1 level clean room. After the installation of the IB inside the KamLAND detector, we measured the contamination levels in the IB by KamLAND-Zen 800 data. the amount of ^{238}U and ^{232}Th are $(3\pm1) \times 10^{-12}$ g/g and $(3.8\pm0.2) \times 10^{-11}$ g/g, respectively. A factor of 10 reductions from the KamLAND-Zen 400 IB is achieved.

To improve the reduction performance of cosmogenic spallation BG such as ^{10}C, we newly developed the muon shower reconstruction tool to calculate light intensity profiles along the muon track. We performed the cut with a new likelihood discriminator based on the light profile, time from muon (ΔT), and the longitudinal distance from the muon track. By including this newly developed likelihood discriminator in addition to the conventional spallation BG cut, we achieved the rejection efficiency of >99.3%, (97.6±1.7%), and (74±7%) for ^{10}C, ^{6}He, and ^{137}Xe, respectively. After the effective reduction of the BG mentioned above, we found that the long-lived isotopes of xenon spallation products contribute to the BG for analysis. To tag the xenon spallation BG we developed another likelihood discriminator based on the neutron multiplicity, distance from neutron vertices, and ΔT.

3. Event selection and results

A search for the $0\nu\beta\beta$ was carried out with the KamLAND-Zen800 data accumulated from February 2019 to May 2021. The data went through several event selections: (i)The events whose vertices were reconstructed within 2.5 m from the detector center and 0.7 m away from the bottom. (ii)Muon events and events with a time difference from the muon event shorter than 2 ms are rejected. (iii)Sequential radioactive decays of ^{214}Bi-^{214}Po and ^{212}Bi-^{212}Po were identified and rejected by the delayed coincidence tag and identification of double pulses in a single event time window. (iv)Inverse β decay events induced by $\bar{\nu}_e$ were identified by the delayed coincidence tag and rejected. (v)Events such as electronic noise and accidental pile-up are identified by a vertex-time-charge discriminator and removed. (vi)Spallation event selection by ΔT, space correlation between neutron capture γ and spallation product, and the likelihood discriminator mentioned in section 2 is applied. Events both identified as long-lived isotopes (long-lived data, LD) and not identified (signal data, SD) are used for the energy spectrum fitting described below. The $0\nu\beta\beta$ signal rate is estimated by the simultaneous fitting with 86 energy bins from 0.5 MeV to 4.8 MeV, 20 equal-volume bins each in upper and lower hemispheres within the radius of 2.5 m from the detector center, and 3 time bins for SD and LD. No signal excess from the expected BG was observed and we set $T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{26}$ years at 90% C.L.. Figure 1 shows the combined energy spectrum.

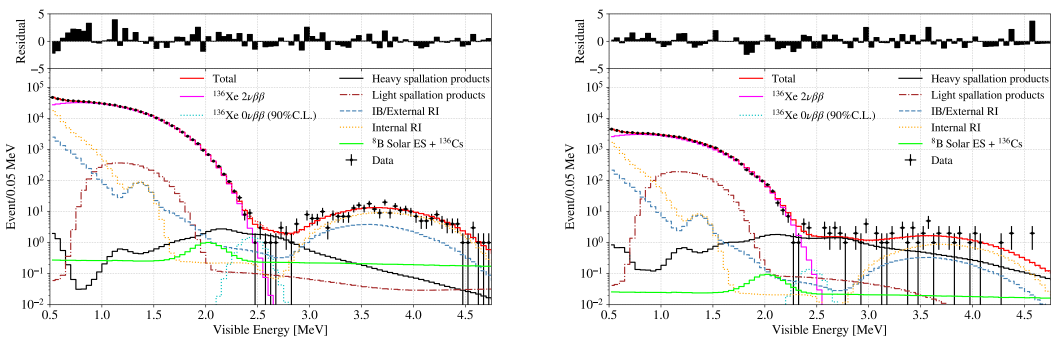

Figure 1: The energy spectrum combined internal 10 volume bins (both 5 bins for the upper and lower hemispheres), corresponding to a 1.57 m radius spherical volume, and 3 time bins for SD data set (left) and LD data set(right) [1].

A combined fit of the KamLAND-Zen 400 and 800 data sets gives $T^{0\nu\beta\beta}_{1/2} > 2.3 \times 10^{26}$ years. It corresponds to $\langle m_{\beta\beta} \rangle < 36 - 156$ meV with various nuclear matrix element calculations assuming the axial coupling constant $g_A \simeq 1.27$. It is the first test for inverted mass ordering. More details can be found in Ref [1].

4. Future prospects

The KamLAND-Zen experiment has a plan to improve to search for much lighter neutrino mass regions. The upgraded experiment KamLAND2-Zen plans to reduce the BG of xenon spallation products, $2\nu\beta\beta$, and ^{214}Bi in the IB. For the xenon spallation product, the primary process which contributes to BG is $\beta^{\pm} + \gamma$ emitter, which is different from the point-like $0\nu\beta\beta$

signal. Particle identification with neural network is developed and demonstrated the ability to increase the sensitivity [8]. We are also developing vertex and energy reconstruction tools using neural networks. State-of-the-art electronics can detect multiple neutrons induced by muons more effectively without dead time. It helps in the identification of xenon spallation products. The reduction of $2\nu\beta\beta$ BG requires improved energy resolution. KamLAND2-Zen plans to use a much brighter liquid scintillator based on linear-alkyl-benzene, high quantum efficiency PMT with a light collector. These improvements will improve energy resolution by a factor of 2. The performance check of the PMT and electronics using the prototype detector is ongoing. To eliminate ^{214}Bi BG, it is necessary to detect the energy deposition of the ^{214}Po α decay in the IB film. KamLAND2-Zen plans to use scintillation film to detect such energy deposition in the balloon film [9]. The optical characteristic check and material screening with a high-purity germanium detector and inductively coupled plasma mass spectrometer are ongoing. After these improvements, KamLAND2-Zen can explore the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$ down to 20 meV, which covers the whole inverted mass hierarchy region, with 5 years of data taking.

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