Hunting Massive Majoron Emission in Neutrinoless Double-Beta Decay of 136Xe with KamLAND-Zen

著者	Kamei Yuto
学位授与機関	Tohoku University
学位授与番号	11301甲第20180号
URL	http://hdl.handle.net/10097/00135380

博士論文

Hunting Massive Majoron Emission in Neutrinoless Double-Beta Decay of ^{136}Xe with KamLAND-Zen

(KamLAND-Zen による ^{136}Xe のニュートリノを伴わない
二重ベータ崩壊における有質量マヨロン放出過程の探索)

亀井　雄斗

令和３年

Hunting Massive Majoron Emission in Neutrinoless Double-Beta Decay of ^{136}Xe with KamLAND-Zen

(KamLAND-Zen による ^{136}Xe のニュートリノを伴わない二重ベータ崩壊における有質量マヨロン放出過程の探索)

Tohoku University B9SD2011 KAMEI Yuto

1 Introduction

Majorana nature of neutrinos is required that some theories such as the seesaw mechanism, which naturally explains the lightness of neutrino masses, and the leptogenesis, which postulates that the non-conservation of lepton number due to the decay of heavier neutrinos created a matter-dominant universe. The only pratical way to test for the Majorana nature of neutrinos is the searching for neutrinoless double-beta decay ($0\nu\beta\beta$). Various experiments are being performed around the world to observe the undiscovered $0\nu\beta\beta$. $0\nu\beta\beta$ is only allowed when the neutrino is a Majorana particle, and emits only two electrons as its atomic number increases by two. This decay can be observed only when normal beta decay is prohibited or strongly suprressed by the energy level or conservation of angular momentum. In addition, $0\nu\beta\beta$ violates the lepton number conservation by two units. If this is due to spontaneous violation of the global lepton number symmetory $U(1)_L$, a new Nambu-Goldstone particle can be created. This new particle is called majoron J, and $0\nu\beta\beta$ search experiments also attempt to observed majoron emission in $0\nu\beta\beta$ ($0\nu\beta\beta J$). The energy spectrum of $0\nu\beta\beta J$ is characterized by the spectral index n appearing in the phase space factor. When $n = 1$, majoron is called "ordinaly majoron".

In recent years, the lack of discovery of dark matter has led to interest in massive majoron. Dark matter is unknown matter in the universe that cannot be observed optically, and its existence has been pointed out by observing the rotational velocity of galaxies and gravitational lensing. Satellite experiments have shown that it accounts for about 30% of the energy in the universe today, but its true nature is still unknown. Normally, majorons are massless, but they can have mass as pseudo-Nambu-Goldstone particles, and if their mass is less than 2.8 MeV, they can become dark matter by a dark matter production mechanism called the freeze-in mechanism. Since $0\nu\beta\beta J$ is said to occur even in the case of massive matter, it can be explored in the $0\nu\beta\beta$ search experiment.

2 KamLAND-Zen experiment

The KamLAND detector is a large liquid scintillator (LS) detector with one-kton ultra-pure 1,2,3-trimethylbenezene-based LS. It is located approximately 1000 m under the peak of Mount Ikenoyama, Japan. We installed an LS container, so-called Inner Balloon (IB), loaded with xenon gas 91% enriched in ^{136}Xe into KamLAND to perform the KamLAND-Zen experiment (See Fig. 1.). KamLAND-Zen is one of the experiments to search neutrinoless double beta decay ($0\nu\beta\beta$) in the world.

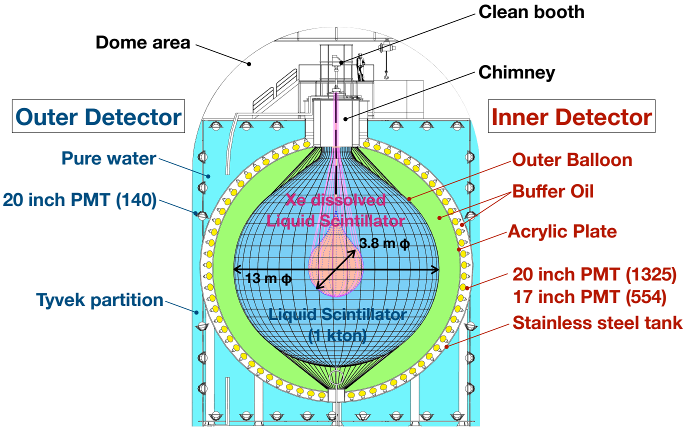

Fig. 1: KamLAND-Zen detector

KamLAND-Zen data-set is divided into several phases. The first phase, KamLAND-Zen 400, ran between 2011 and 2015. The KamLAND-Zen 400 data-set is further divided into two smaller phases, Phase-I and Phase-II. KamLAND-Zen 800 is the second phase that has been observing 745 kg of xenon since 2019.

Currently, KamLAND-Zen 400 Phase-I, which was using ~380 kg xenon (^{136}Xe 91% enrichment), set the limit on $0\nu\beta\beta J$ half-life of $T^{0\nu J}_{1/2} > 2.6 \times 10^{24}$ yr (90% C.L.) corresponding to $\langle g_{ee} \rangle < (0.8 - 1.6) \times 10^{-5}$ for massless majoron[2]. However, there were an unexpected background, ^{110m}Ag (Q-value 3.01 MeV, half-life 350 day), and radiactivities contamination on IB in KamLAND-Zen 400 Phase-I. It left a great deal of room for improvement. Therefore we doubled the amount of ^{136}Xe and reducing the background events originating from IB in KamLAND-Zen 800. The preparation of the new IB with doubled volume was started in the spring of 2017 in a superclean room with class 1 or lower, and was introduced to the KamLAND detector in May 2018. After the LS purification and xenon disolving, KamLAND-Zen 800 started the $0\nu\beta\beta$ search on January 2019. As a result of the observation, almost no external contamination were found to adhere to the IB, and the ^{238}U contained in the IB was reduced to $\sim$1/10 compared to the KamLAND-Zen 400[3]. Additionally, the amount of ^{232}Th in the xenon-containing LS was reduced to less than solar neutrino events by LS purification by distillation, which successfully expanded the low background event region and increased the effective volume by about three times.

KamLAND is experiencing an increasing number of PMT failures due to its operation for about 20 years, well beyond its useful life. Measures have been taken from both hardware and software perspectives, such as lowering the applied voltage, installing electrical circuits with signal multipliers, and introducing an energy reconstruction method that utilizes data from PMTs that are treated as bad PMTs because of their poor data quality.

With this effort, KamLAND-Zen 800 continued stable data aquisition, and the observation period of 523.4 days became available for analysis.

3 Background

(i) **$2\nu\beta\beta$ event**

The energy spectrum of emitted two-electrons from $0\nu\beta\beta J$ is overlapped on $2\nu\beta\beta$ spectrum. It is necessary to understand shape of energy spectrum exactly.

(ii) **Natural Radioisotopes**

The background level of ^{232}U, ^{238}Th is less than solar neutrino events. The ^{238}U contained in the IB was reduced to $\sim$1/10 compared to the KamLAND-Zen 400. There were other backgrounds, such as ^{40}K、 ^{85}Kr and ^{210}Bi.

(iii) **Unstable isotopes from spallation event**

Cosmic-ray muons come into KamLAND by about 3 Hz and create unstable isotopes by breaking XeLS consituent atoms (^{12}C, ^{136}Xe). Spallation events have several characteristics such as the emission of neutrons. Using these characteristics, triple-coincidence method (muon, neutron capture and unstable isotope decay) and likelihood method are useful to reject spallation events.

(iv) **Others**

There are solar neutrino events and external γ-ray from PMT or structure around detector.

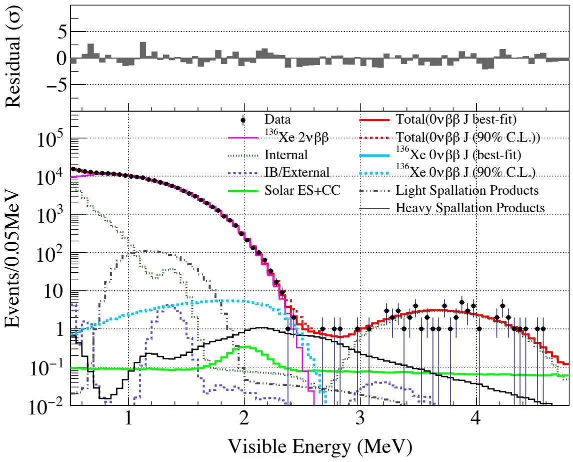

Fig. 2: Result of energy spectrum fitting for massless majoron emittion in $0\nu\beta\beta$

4 Conclusion

This dissertation reports first result of $0\nu\beta\beta J$ from KamLAND-Zen 800. We obtained the combined result with KamLAND-Zen 400 for $0\nu\beta\beta J$ half-life of $T^{0\nu J}_{1/2} > 5.6 \times 10^{24}$ yr (90%C.L.) corresponding to $\langle g_{ee} \rangle < (3.9 - 8.0) \times 10^{-6}$ for massless ordinaly majoron. In the case of massive majoron emission, the constraints are shown in Fig. 3 and this is the world best constrain.

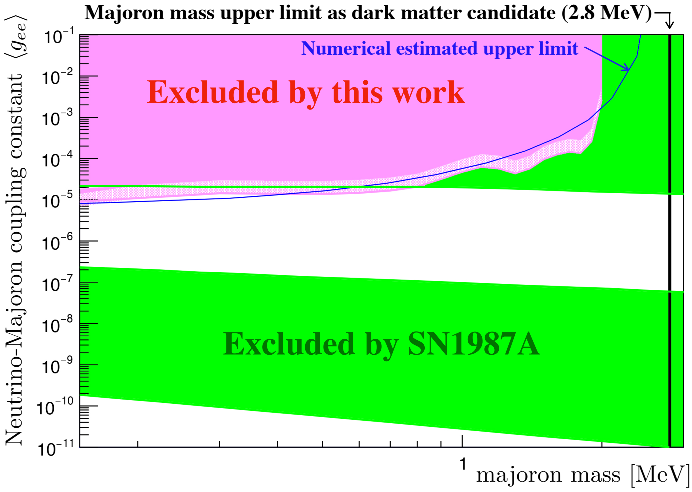

Fig. 3: Constraints on $\langle g_{ee} \rangle$ and majoron mass

Reference

[1] Tim Brune and Heinrich Päs, Phys. Rev. **99**, 096005 (2019).

[2] KamLAND-Zen Collaboration, A. Gando *et al.*, Phys. Rev. C **86** 021601 (2012).

[3] KamLAND-Zen Collaboration, Y. Gando *et al.*, JINST **16** P08023 (2021).