Prospects for searching new Double Beta Decay physics with KamLAND-Zen 800

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Abstract. Two-neutrino double beta decay ($2\nu\beta\beta$) is a rare second-order weak radioactive decay process. It has been observed in neutrinoless double beta decay ($0\nu\beta\beta$) search experiments. Precise observation of $2\nu\beta\beta$ is essential to reduce the theoretical uncertainty in the calculation of nuclear matrix elements required to obtain the effective Majorana mass from a lifetime of $0\nu\beta\beta$. Also, $2\nu\beta\beta$ itself is interesting because new physics could be hiding in the energy spectrum, such as for example, Majoron emission mode $0\nu\beta\beta$ and $2\nu\beta\beta$ with neutrino self-interaction. KamLAND-Zen 800 is an experiment to search for $0\nu\beta\beta$ of ^{136}Xe with a large ultra-pure liquid scintillator detector, KamLAND. KamLAND-Zen 800 has been observing 745 kg of xenon gas at 91% enriched in ^{136}Xe since 2019, providing a high statistics $2\nu\beta\beta$ decay sample. We describe the potential for new physics searches in $2\nu\beta\beta$ with KamLAND-Zen 800.

1. Introduction

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, loaded with xenon gas 91% enriched in ^{136}Xe into KamLAND to perform the KamLAND-Zen experiment. KamLAND-Zen is one of the experiments to search neutrinoless double beta decay ($0\nu\beta\beta$) in the world.

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. The amount of xenon was doubled, and the background level of the Inner Balloon was reduced to 1/10[1].

KamLAND-Zen 400 set the most stringent limit on the $0\nu\beta\beta$ half-life of ^{136}Xe $T^{0\nu}_{1/2}$ $>1.07\times10^{26}$ yr(90% C.L.) with effective Majorana neutrino mass bounds of (61 - 165) meV[2]. KamLAND-Zen 800 is currently running, and the KamLAND-Zen collaboration will soon update the results.

2. Double Beta Decay

Two-neutrino double beta decay ($2\nu\beta\beta$) is a particular β-decay in which two neutrons in a nucleus transform into two protons under the emission of two electrons and two neutrinos. There are several tens of known isotopes capable of $2\nu\beta\beta$. $2\nu\beta\beta$ of some isotopes has been observed by $0\nu\beta\beta$ experiments. $2\nu\beta\beta$ of ^{136}Xe is one of the best studied. $0\nu\beta\beta$ is a hypothetical process that has never been observed. In this process, only electrons are emitted. While $2\nu\beta\beta$ produces a continuous energy spectrum, $0\nu\beta\beta$ produces a peak at the Q-value. The observation of $0\nu\beta\beta$ is attractive as it is the only realistic way to verify the Majorana nature of neutrinos[3]. Then many experiments search for $0\nu\beta\beta$ with various isotopes all over the world. Usually, $2\nu\beta\beta$ is an irreducible background for the $0\nu\beta\beta$ search because a tail of $2\nu\beta\beta$ blends into the signal due to detector energy resolution. However, $2\nu\beta\beta$ is not only a hindrance but also its observation can provide information. Precise observation of $2\nu\beta\beta$ is essential to reduce the theoretical uncertainty in calculating nuclear matrix elements(NME) required to obtain the effective Majorana neutrino mass from a half-life of $0\nu\beta\beta$. Also, $2\nu\beta\beta$ itself is interesting because new physics could be hiding in the energy spectrum. These are introduced in the following section.

2.1. A half-life of $2\nu\beta\beta$

As mentioned earlier, a precise observation of $2\nu\beta\beta$ is essential to reduce the theoretical uncertainty in calculating NME. Obtaining the effective Majorana neutrino mass from a half-life of $0\nu\beta\beta$ requires the phase-space factor(PSF) and NME. The PSF can be calculated precisely, but the NME depends on model-based approximations. It is challenging to quantify the uncertainties, and there are significant uncertainties from different models. If we know the exact half-life of $2\nu\beta\beta$, we can constrain the parameters of each model, thus reducing the uncertainty[4, 5]. Here is the half-life of $2\nu\beta\beta$ that KamLAND-Zen has reported so far and obtained by EXO-200 for reference,

$$T_{1/2}^{0\nu\beta\beta} = [2.30 \pm 0.02(\text{stat.}) \pm 0.12(\text{syst.})] \times 10^{21}\text{yr}(\text{KamLAND} - \text{Zen400}[2]), \tag{1}$$

$$T_{1/2}^{0\nu\beta\beta} = [2.165 \pm 0.016(\text{stat.}) \pm 0.059(\text{syst.})] \times 10^{21}\text{yr}(\text{EXO} - 200[6]). \tag{2}$$

In both experiments, a systematic error remains as a large uncertainty. The significant factors that make this large uncertainty include the following. In EXO-200, there are 1.6% and 1.77% uncertainties in partial event reconstruction and fiducial volume cut, respectively[6]. There is a 3% uncertainty in fiducial volume cut in KamLAND-Zen (See Table. 1). We aim to reduce this uncertainty.

Table 1. Systematic errors for the measurement of the $2\nu\beta\beta$ half life in KamLAND-Zen[7].

Fiducial volume	3.0%
Xe Enrichment	0.09%
Xe amount	0.8%
Detector energy scale	0.3%
Detection efficiency	0.2%
Total	3.1%

3. Majoron emitting $0\nu\beta\beta$

Majorons are hypothetical Nambu-Goldstone bosons associated with the lepton number violation. $0\nu\beta\beta$ is the process that breaks the lepton number by two units. Then Majoron emitting $0\nu\beta\beta$ can occur. The Majoron emitting mode is accompanied by one or two Majorons:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \chi^0 \ (+\chi^0), \tag{3}$$

where χ^0 denotes a Majoron. Here, a Majoron is a massless or light boson, which is coupled to the neutrino in the broad sense of the word. The type of Majoron depends on the model. Some models propose Majorons that are not Nambu-Goldstone boson. The energy spectrum of Majoron emitting $0\nu\beta\beta$ becomes a continuous spectrum like $2\nu\beta\beta$. This shape is different depending on only the spectral index n. The spectral index n is defined from the PSF $G \sim (Q_{\beta\beta} - K)^n$, where $Q_{\beta\beta}$ is Q-value of $0\nu\beta\beta$, and K is the total energy of the two electrons.

KamLAND-Zen 400 has already set stringent limits on half-lives of Majoron emitting $0\nu\beta\beta$ and the effective coupling constant with the spectral index $n = 1, 2, 3$, and 7[8]. The limit of $n = 1$ is shown as a representative; $T_{1/2}^{0\nu\beta\beta\chi^0} > 2.6 \times 10^{24}$ yr, $\langle g_{ee} \rangle < (0.8 - 1.6) \times 10^{-5}$. The energy spectrum of selected Majoron emitting $0\nu\beta\beta$ candidate events from 0.5 to 4.8 MeV is shown in Fig. 1.

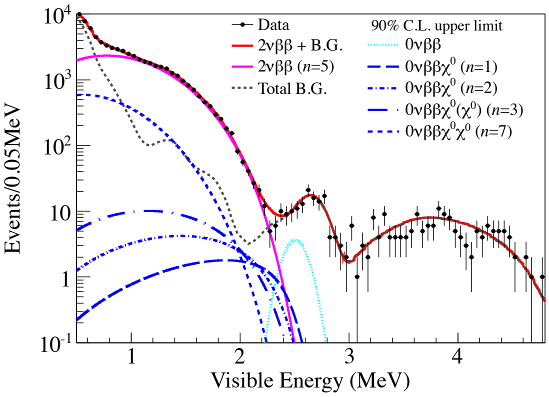

Figure 1. Best-fit energy spectrum for selected candidates[8] in KamLAND-Zen 400 Phase-I. Dots represent data, gray dashed line represents the background, purple line represents the $2\nu\beta\beta$ spectrum, blue lines represent the Majoron emitting $0\nu\beta\beta$ and sky-blue line represents $0\nu\beta\beta$.

This result is based on an exposure of 112.3 days with 125 kg of ^{136}Xe in KamLAND-Zen 400 Phase-I using 1.2-m radius reconstructed vertices events at the detector center. KamLAND-Zen 400 Phase-I had an unexpected background from ^{110m}Ag in the $0\nu\beta\beta$ region of interest(ROI). While the live-time of KamLAND-Zen 800 is already more than three times the live-time of KamLAND-Zen 400 Phase-I, backgrounds were also successfully reduced. The fiducial volume as a sensitive region was expanded to about three times larger owing to the Inner-Balloon renewal. We can update our limit several times by rough estimation considering the live-time increase and the background reduction.

Additionally, the massive Majoron model is getting much attention. The search for dark matter particles is currently being conducted, but the search for dark matter remains unsuccessful. Therefore, a massive Majoron is interesting as a dark matter candidate[9]. KamLAND-Zen 800 has the potential to search for dark matter candidates by massive Majoron emitting $0\nu\beta\beta$ search. We will search for massive Majoron emitting $0\nu\beta\beta$ up to a Majoron mass of 2.46 MeV because Majoron, which has a mass greater than Q-value of ^{136}Xe(2.46 MeV), cannot be searched for in KamLAND-Zen 800. Supernova SN1987A data set constrain for $\sim 10^{-10} < \langle g_{ee} \rangle \sim 10^{-7}$ of the effective Majoron-neutrino coupling$\langle g_{ee} \rangle$[9]. A constrain of massive Majoron emitting $0\nu\beta\beta$ was calculated from the EXO-200 massless Majoron emitting mode search. However, there is a gap of about two orders of a magnitude between constrains of massive Majoron emitting $0\nu\beta\beta$ and the Supernova result. We aim to close this gap. The energy spectra of every 0.2 MeV mass considered detector responses are shown in Fig. 2 by a solid line. The energy spectra are normalized by the PSF ratio $G(m_\chi)/G(0)$ because the decay width is reduced due to the mass depended PSF. The phase space suppresion is calculated as $G(m_\chi)/G(0)$. The energy fitting using each spectrum will be performed.

4. Neutrino self-interaction induced $2\nu\beta\beta$

In astrophysics, there is a problem that late and early time measurements of the Hubble expansion rate are different by about 4 σ. This problem is called the Hubble tension problem. One of the solutions for this problem is to introduce neutrino self-interactions(nSI) beyond the Standard Model. The nSI change cosmological neutrino properties and also explain the Hubble tension. Such interactions can affect $2\nu\beta\beta$, which is observed as a distortion of the $2\nu\beta\beta$ energy spectrum[10]. According to [10], the ^{136}Xe lifetime of nSI induced $2\nu\beta\beta$ can be calculated to be 1.55×10^{19} yr under various assumptions. This excluded the coupling constant favored by cosmological data. KamLAND-Zen 800 can experimentally verify the ^{136}Xe lifetime of nSI induced $2\nu\beta\beta$ and search for the unknown nSI by an exact measurement of the $2\nu\beta\beta$ energy spectrum shape. The energy spectra considered detector responses are shown in Fig. 2 by a bold black dotted line.

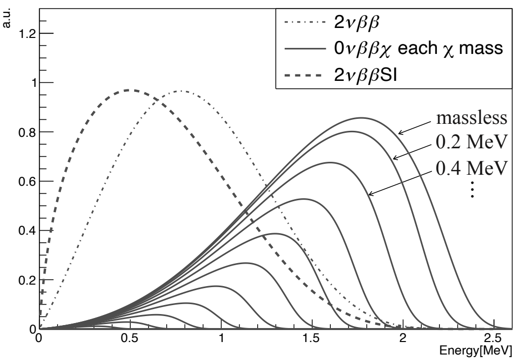

Figure 2. Energy spectra for Majoron emitting modes $0\nu\beta\beta$ and self-interaction induced $2\nu\beta\beta$. Spectra of $0\nu\beta\beta\chi$ are drawn every 0.2 MeV and nomalized by the PSF ratio $G(m_\chi)/G(0)$.

5. Summary

The KamLAND-Zen is a very sensitive experiment to search for $0\nu\beta\beta$ in ^{136}Xe. KamLAND-Zen 800 has been running with 745 kg of xenon from 2019. The new physics could be hiding in the $2\nu\beta\beta$ energy spectrum, such as for example, $0\nu\beta\beta\chi^0$ and nSI induced $2\nu\beta\beta$. KamLAND-Zen has the potential for these searches using a high statistics $2\nu\beta\beta$ decay sample.

Acknowledgments

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