Simulation study of cosmic-ray muon backgrounds for KamLAND-Zen experiment

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Abstract. Neutrino is a major candidate of Majorana particle and the neutrinoless double beta \((0\nu\beta\beta)\) decay is the key physics to prove it. In 2019, KamLAND-Zen experiment have started data taking to search for \(0\nu\beta\beta\) decay with 745 kg of \(^{136}\text{Xe}\) as the source. The sensitivity is restricted by the statistics of backgrounds and the most critical ones are induced by spallation reactions of cosmic-ray muons. Physics process and statistics are studied with FLUKA which is widely used simulation tool. The most critical background is the decay of \(^{10}\text{C}\), while FLUKA predicts that heavy isotopes such as \(^{137}\text{Xe}\) can be a potential background. We apply delayed coincidence method to quantify those backgrounds and also have been developing new tools focused on space and charge features, pulse shape discrimination and particle identification.

1. Introduction
KamLAND-Zen experiment is a search for \(0\nu\beta\beta\) decay using decay of \(^{136}\text{Xe}\). The points at issue are low background, good energy resolution of detector and the amount of decaying isotope. Our detector is located under the peak of mountain with 2700 m water equivalent overburden to limit cosmic-ray muon backgrounds. It has 1 kton of ultra-pure liquid scintillator (LS) and 1879 photomultiplier tubes [1]. The xenon dissolved LS is contained in mini-balloon which is suspended in the center of the detector. KamLAND-Zen have started data acquisition in Jan. 2019 with 745 kg of \(^{136}\text{Xe}\), that is about twice as large when compared with our previous observation [2].

The backgrounds can be divided into ones originating from impurities and others. Cosmic-ray muons generate latter backgrounds by spallation reactions on LS. In the following, spallation backgrounds and tagging method are described.

2. Cosmic-ray muon backgrounds
Cosmic-ray muons hit the LS components and produce many kinds of unstable isotopes which decay to make serious backgrounds in the energy region of interest. The measured rate of muons crossing the inner detector of KamLAND is approximately 0.2 Hz [1]. The LS is the mixture of 80 % of dodecane (\(\text{C}_{12}\text{H}_{26}\)), 20 % of pseudocumene (\(\text{C}_{9}\text{H}_{12}\)) in the volume ratio, and PPO (2, 5-Diphenyloxazole) whose density is 1.36 g/L. The main component of LS are carbon and hydrogen, and xenon is also present in the LS inside the mini-balloon.

Since the Q-value of \(^{136}\text{Xe}\) decay is 2.46 MeV and our ROI is 2.35~2.7 MeV, the isotopes with Q-value of more than 2.7 MeV are the problem. It is also important to consider the statistics and lifetime. If residual isotopes have short lifetime, they could be effectively suppressed by...
vetoing the detector. We should investigate long-lived isotopes in order to find and prepare for unexpected backgrounds.

3. Simulation
FLUKA is a well studied Monte Carlo simulation tool reliable for modeling hadronic interactions [3]. We present predicted feature of backgrounds related to physics process and spacial distribution that would help finding isotopes of interest more effectively. The version of FLUKA used is “FLUKA 2011.2” and important physics models activated in this study are DEFAULTS of PRECISIO(n), PHOTONUC and MUPHOTON.

The energy and angular distribution of cosmic-ray muons are input from MUSIC/MUSUN simulation which well agree with the data. Reproducibilities were checked with the charge and track distribution of muons. Neutron capture time is another good benchmark with high statistics. The measured mean capture time and MC are 207.5 ± 2.8 µsec and 207.4 ± 3.6 µsec, respectively.

3.1. Tagging method
Short-lived isotopes (τ_{1/2} < 180 s) are mainly produced by spallation of ^{12}C. Most critical ones are listed in Tab. 1. The highest production yield in the ROI comes from ^{10}C and veto is not enough to deal with. Primary process of ^{10}C production is ^{12}C(n, 3n)^{10}C. Since more than 99% of ^{10}C are generated with neutrons, we apply three-fold tagging, that identifies the muon, neutron captures on ^{1}H and ^{10}C decay.

For the further improvement of tagging efficiency, we have been developing likelihood function. The strong point is that it can adapt regardless of neutrons. The probability density function is adjusted with the distance between the muon track and ^{10}C, and the charge distribution projected on the muon track. As shown in Fig. 1, spallation would influence the local charge distribution.

We note that source particles make difference in space distribution of produced isotopes and it is known that sources of spallation are not cosmic-ray muons but rather secondary particles. For example, neutrons can travel further than pions since it takes longer for neutrons to be captured. The main sources of ^{10}C are neutrons and pions, while most of ^{12}B are produced by neutrons so that ^{10}C is more closely distributed around the muon track compared with ^{12}B (see Fig. 2).

![Figure 1](image1.png)  
**Figure 1.** Charge distribution along with the muon track. The position of ^{10}C is indicated by green line.

![Figure 2](image2.png)  
**Figure 2.** Transverse distance between muon track and background isotopes. Green circle and blue triangle represent ^{10}C and ^{12}B.
### Table 1. Short-lived isotopes

| Isotope | Lifetime | Q-value [MeV] |
|---------|----------|--------------|
| $^{10}$C | 27.78 s  | 3.65         |
| $^{6}$He | 1.16 s   | 3.51         |
| $^{8}$Li | 1.21 s   | 16.00        |
| $^{12}$B | 29.1 ms  | 13.37        |
| $^{9}$Li | 257.2 ms | 13.61        |

### 3.2. Potential backgrounds

Long-lived isotopes ($\tau_{1/2} > 180$ s) are generated by spallation of $^{136}$Xe and potential backgrounds are shown in Tab. 2. Probability to observe heavy isotope becomes higher with increased amount of $^{136}$Xe and the simulation predicts that our next critical background would be $^{137}$Xe. It was not found in the earlier phase of the experiment, however candidate events were found in the current phase. It is discriminated by another set of delayed coincidence, that is the muon, the neutron capture on $^{136}$Xe and $^{137}$Xe decay.

### Table 2. Long-lived isotopes

| Isotope | Lifetime | Q-value [MeV] |
|---------|----------|--------------|
| $^{137}$Xe | 5.51 m  | 4.17         |
| $^{132}$I | 199 m   | 3.58         |
| $^{130}$I | 0.74 d  | 2.95         |
| $^{108}$In | 83.7 m | 5.15         |
| $^{120}$I | 117 m   | 5.62         |

### 4. Summary

KamLAND-Zen experiment is searching for $0\nu 2\beta$ decay of $^{136}$Xe. Cosmic-ray muons generate one of the most critical backgrounds and we apply delayed coincidence tagging method to identify it. The simulation indicates that the space and charge distribution of muons are correlated with the background production, so that likelihood function have been adjusted to enhance these features. In addition, we are preparing background removing techniques such as pulse shape discrimination, particle identification and hardware upgrade to raise the tagging efficiency. Another useful aspect of the simulation is a search for potential backgrounds. We implemented delayed coincidence optimized for $^{137}$Xe and continue detail investigation.

### References

[1] Abe S et al (KamLAND Collaboration) 2010 *Phys. Rev. C* **81** 025807
[2] Gando A et al (KamLAND-Zen Collaboration) 2016 *Phys. Rev. Lett.* **117** 082503
[3] Ferrari A, Sala P R, Fasso A and Ranft J 2005 *FLUKA: A Multi-Particle Transport Code*, CERN-2005-10, INFN/TC_05/11, SLAC-R-773
[4] Bellini G et al JCAP08(2013)049