Improvment of Energy Estimator for KamLAND-Zen 800

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Abstract. KamLAND-Zen 800 explores neutrinoless double beta decay ($0\nu\beta\beta$) of $^{136}$Xe. The experiment was started in January 2019 and data acquisition is going well. In the latest result of KamLAND-Zen 800 the most dominant background is $2\nu\beta\beta$ decay, which can be reduced by improvement of the detector energy resolution. In this study we aim to improve the energy resolution by optimizing the energy reconstruction method and reduce the $2\nu\beta\beta$ background by a factor of $\sim 2/3$.

1. Introduction
In KamLAND-Zen 800, $2\nu\beta\beta$ decays are the largest background source due to the limited energy resolution. There is an increasing number of degraded amplification PMTs (low gain PMTs) in KamLAND due to the long-term detector operation. At present, we exclude such PMTs from analysis, because they cannot correctly evaluate hit timing and charge and increase systematic uncertainties. Increase in the number of unusable PMTs directly leads to degradation of the energy resolution and it is therefore important to develop a reconstruction method which utilizes low gain PMTs.

It is known that we can estimate the amount of $2\nu\beta\beta$ events in region of interest (ROI) of $0\nu\beta\beta$ analysis by $N_{2\nu\beta\beta} \propto (\Delta E/E)^{5.8}$[1]. Currently observed resolution is $7.2\%/\sqrt{E[\text{MeV}]}$ and if we achieve resolution of $6.6\%/\sqrt{E[\text{MeV}]}$ observed around the year 2011, the number of $2\nu\beta\beta$ events in the ROI can be reduced by about $2/3$.

2. Energy Reconstruction
2.1. Formulation of Likelihood
In this study, the maximum likelihood method is used for energy estimation. The likelihood function is composed of hit and no-hit probabilities for each PMTs, and it is sufficient if one of them is formulated, because we can calculate hit probability by subtracting no-hit probability from 1. The likelihood function is obtained by multiplying hit probability for a PMT that observed a hit and no-hit probability for a PMT that didn’t observe a hit for all PMTs as follows:

$$L = \prod_{i \in \text{hit}} (1 - p_i) \times \prod_{i \in \text{no-hit}} p_i,$$

where index $i$ means PMT cable number and $p_i$ represents no-hit probability of the $i$-th PMT. We will use Eq.(1) throughout this report, but we know this formulation works well only in
lower energy region ($\lesssim 1$ MeV). It is effective to weight hit probabilities using hit timing and charge information as follows:

$$L = \prod_{i \in \text{hit}} (1 - p_i) \rho_i \tau_i \times \prod_{i \in \text{no-hit}} p_i,$$

(2)

where $\rho_i$ and $\tau_i$ are probabilistic weight functions composed of charge and hit timing. The current energy estimation without low gain PMTs is based on the maximum likelihood of Eq.(2), but this study used Eq.(1) as a first attempt in incorporating all available PMTs.

2.2. Formulation of no-hit probability

We assume that the photo-electron (p.e.) count of each PMT follows a Poisson distribution. The probability that the $i$-th PMT detects $n$ p.e. in expected light intensity $\mu$ is expressed as

$$\kappa_i(n; \mu) = (\frac{\mu^ne^{-\mu}}{n!}).$$

(3)

Considering only this assumption, the no-hit probability is understood as probability of observing zero p.e.’s, that is, we can simply represent no-hit probability as $p_i = \kappa_i(0; \mu_i)$. However we have to consider the effect of trigger threshold. To suppress electronics noise, various thresholds are set for each PMT typically at $\sim 0.15$ p.e., so there is a small loss of the p.e. detection efficiencies for physics events. Especially, low gain PMTs have a non-negligible loss of the p.e. efficiencies. Thus, the no-hit probability of the $i$-th PMT is expressed as follows:

$$p_i(\mu) = \kappa_i(0; \mu_i) + \sum_{n=1}^{\infty} \epsilon_n \kappa_i(n; \mu_i),$$

(4)

where $\epsilon_n$ is the detection inefficiency of $n$ p.e.’s, and $\epsilon_n \kappa_i(n; \mu_i)$ represents the probability that the number of observed p.e.’s falls below the threshold. In Eq.(4), the detection inefficiency $\epsilon_n$ should differ among each p.e. count $n$ because the threshold effect affects mainly low light intensity events: $\epsilon_n$ converges to 0 with large $n$. The probability of observing 0 p.e. as 1 p.e. is ignored.

Our current method uses only the first order of Eq.(4) and fixes $\epsilon_1$ to 0.036. This is why the current method cannot reflect individual differences in PMT in the likelihood function and we have no other way than mask low gain PMTs as long as we use the current energy estimator.

2.3. Parameter Estimation

The detection inefficiency is determined from data up to seventh order in Eq.(4). The fit function is explicitly expressed as follows:

$$p_i(\mu) = \left(1 + \epsilon_1 \mu_i + \epsilon_2 \frac{(\mu_i)^2}{2!} + \cdots + \epsilon_7 \frac{(\mu_i)^7}{7!}\right) e^{-\mu_i}.$$

(5)

Figure 1 shows the fit results. The seven inefficiency parameters obtained here are used for the maximum likelihood fit to estimate the visible energy.

2.4. Performance Check

The performance of this method is checked with source calibration data. The peaks of $^{137}$Cs (0.661 MeV) and $^{60}$Co (2.505 MeV) were fitted with Gaussians and their standard deviation (1$\sigma$) was evaluated. The energy resolution for the old and new estimator are summarized in Table 1. The new method achieves better resolution in $^{137}$Cs. This is because the new method
3. Summary

A new energy reconstruction method has been developed to utilize the information from the low gain PMTs, and the effectiveness of the method has been confirmed in the low energy region (~ 0.6 MeV). The next task is to incorporate weighting factors based on charge and hit timing information into the likelihood function according to Eq. (2), which is expected to achieve good performance even in the ROI of the $0\nu\beta\beta$ analysis (~ 2.5 MeV).

Acknowledgement

This work was supported by Graduate Program on Physics for the Universe (GP-PU), Tohoku University.

References

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