Neutron rejection performance of the upgraded KOTO CsI calorimeter

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Abstract. We are searching for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay at the J-PARC KOTO experiment. The signature of the signal events is two photons from a $\pi^0$ decay and no other detectable particles. One of the main backgrounds is caused by neutrons in the beam halo. If a beam halo neutron produces a hadronic shower in the calorimeter and a secondary neutron interacts at a different position in the calorimeter, it can mimic the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay. To suppress this hadron-cluster background, we installed MPPCs (silicon photo sensor) on the upstream surface of the CsI calorimeter in 2018. Neutrons and photons can be distinguished by using the timing difference between the MPPC signal from upstream and the PMT signal from downstream. The hadron-cluster background is suppressed to a 2.2% level retaining the 90% signal efficiency.

1. The KOTO experiment
We study the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at the J-PARC KOTO experiment. This decay mode is highly suppressed in the Standard Model and its branching ratio is predicted to be $(3.0 \pm 0.3) \times 10^{-11}$ with small theoretical uncertainties [1]. The signature is two gammas from a $\pi^0$ and two undetectable neutrinos. The two gammas are detected with the calorimeter composed of undoped cesium iodide (CsI) crystals. Each crystal is read out with a PMT attached on the rear side.

We set the best upper limit on the branching ratio of $3.0 \times 10^{-9}$ for this decay mode at the 90% confidence level using the data taken in 2015 [2].

One of the main backgrounds is caused by neutrons in the beam halo. If a beam halo neutron produces a hadronic shower in the calorimeter and a secondary neutron interacts at a different positions in the calorimeter, it can mimic the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay ("hadron-cluster background"). In the 2015 analysis, the number of the estimated background events was $0.24 \pm 0.17$. The contribution of the hadron-cluster background was $0.24 \pm 0.17$.

By improving the existing cuts, the number of the hadron-cluster background events can be reduced by a factor 4. To reach the Standard Model sensitivity, we should suppress the background events further by another factor of 10.

2. Both-end readout
To suppress the hadron-cluster background, we developed a new method using the depth of the interaction. The concept is shown in Fig. 1. With the radiation length of CsI (2 cm), gammas make shallow showers. With the interaction length of CsI (40 cm), neutrons can make deep showers. Thus, a measurement of the depth of the interaction can distinguish gammas and neutrons. For the hadron-cluster background, secondary neutrons tend to go downstream. Therefore, by using the depth of secondary clusters, we can reduce the background further.
Figure 1. Concept of the both-end readout

We attached MPPCs on the front-face of the crystals in the autumn of 2018, and took the data during the beam time in 2019. The time difference between the MPPC and the PMT, $\Delta T = T_{\text{MPPC}} - T_{\text{PMT}}$, reflects the depth of the interaction.

3. Control samples

To collect a pure gamma sample, we used the $K_L \rightarrow 3\pi^0$ decay. A pair of gammas from a $\pi^0$ is used for the control sample. Figure 2 shows the distribution of the cluster energy. Black points represent the MC simulation of the $K_L \rightarrow 3\pi^0$ decay and the green line represents the data of the $K_L \rightarrow 3\pi^0$ decay.

Figure 2. Distributions of the cluster energy of the $K_L$ decays

We performed a special run to collect a control sample for the hadron-cluster background. During this special run, a 3mm-thick aluminum plate was placed into the beam line to enhance the scattered neutrons. We collect two clusters events ("hadron-cluster control sample") and estimate the reduction performance of the hadron-cluster background.

4. Performance

Figure 3 shows the $\Delta T$ distribution of two clusters for the hadron-cluster control sample and for the gammas from the $K_L \rightarrow 3\pi^0$ decay. Both clusters of gammas have a shallow distribution and the smaller $\Delta T$ time because gammas interact in the upstream region of the calorimeter. On the other hand, neutrons interact broadly in the depth of the calorimeter, and thus the $\Delta T$ distribution is wide. The $\Delta T$ distribution of the hadron-cluster control sample has two peaks because the secondary neutrons tend to go downstream (the later peak) compared to primary neutrons (the former peak). We thus decided to use the larger $\Delta T$ value out of two clusters to suppress the hadron-cluster background.

We fitted the $\Delta T$ distributions with the Gaussian function, and used the fitted $\sigma$ as the timing resolution. As shown in Fig. 4, the resolution of the $\Delta T$ is better for higher cluster
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Figure 3. Distributions of $\Delta T$ for two clusters of the gammas from $K_L \to 3\pi^0$ and the hadron-cluster control sample.

Figure 4. Timing resolution of the $\Delta T$ distribution vs energy deposit.

energy. The $\Delta T$ distribution of the $K_L \to \pi^0\nu\bar{\nu}$ was obtained by weighting the $\Delta T$ distribution of $K_L \to 3\pi^0$ according to the cluster energy (Fig 2).

Figure 5 shows the distributions of the larger $\Delta T$ out of the two clusters for the hadron-cluster control signal. If we set the threshold of $\Delta T$ at the 90% gamma efficiency, the hadron-cluster background is suppressed down to 2.2%.

5. Summary
We succeeded in the CsI calorimeter upgrade. We evaluated the neutron rejection performance using the data taken in 2019. The hadron-cluster background is suppressed to 2.2% with the 90% gamma efficiency.

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References
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