Calorimeter Upgrade of the KOTO experiment with both-end readout of CsI crystals with MPPCs

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Abstract. We are searching for the decay $K_L \rightarrow \pi^0\nu\bar{\nu}$ in the KOTO experiment at J-PARC. The signal is identified by detecting two photons from the $\pi^0$ decay with a calorimeter composed of undoped CsI crystals. The main background “hadron cluster background” is caused by a neutron hitting the calorimeter to form two clusters: a neutron in the beam halo hits the calorimeter to generate the first cluster, and a secondary neutron generated in the interaction creates the second separated cluster. In order to reduce this background, we upgraded the calorimeter to have both-end readout by attaching MPPCs on the upstream face of each CsI crystal in addition to the original PMT attached on the downstream face. The background can be rejected exploiting the timing difference between the MPPC and PMT, since neutrons tend to interact deeper inside the crystals. We installed the MPPCs in 2018, and evaluated the performance with data taken in 2019. The principle in the calorimeter upgrade and the performance of the background reduction are reported.

1. Introduction
The KOTO experiment [1] at J-PARC is dedicated to studying the decay $K_L \rightarrow \pi^0\nu\bar{\nu}$. This decay is rare ($\mathcal{B} = 3 \times 10^{-11}$) and CP-violating in the Standard Model (SM), and is sensitive to new physics beyond the SM. The best direct upper limit on the branching fraction of $K_L \rightarrow \pi^0\nu\bar{\nu}$, $3 \times 10^{-9}$ (90% CL), was obtained in the analysis of data taken in 2015, where the single event sensitivity (SES) was $1.3 \times 10^{-9}$ [2].

The 30-GeV protons hit the production target and generate $K_L$. The $K_L$’s are collimated and guided to the KOTO detector (Fig. 1). The $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay is identified with the following two conditions. Two photons from a $\pi^0$ decay are detected with an electromagnetic calorimeter (“CSI” in Fig. 1). No other particles are detected in the hermetic detector system. The electromagnetic calorimeter is composed of 50-cm-long undoped CsI crystals: 2240 2.5-cm-square crystals in the inner region, and 470 5-cm-square ones in the outer region.

The main background in the analysis of the 2015 data is named “hadron cluster background”, in which two calorimeter clusters are generated from neutrons in the halo of the $K_L$ beam (halo neutron). A halo neutron hits the calorimeter, and generates the first cluster. Another neutron generated in the interaction travels and interacts in the calorimeter, and generates the second cluster. The estimated number of the hadron cluster background events is 0.24 in the analysis of 2015 data, after applying cuts on cluster shapes and pulse shapes of the recorded waveforms. Further background reduction with the two shapes is obtained in the analysis of data taken in 2016-2018. The number of this background is estimated to be 0.02 where the SES is $6.9 \times 10^{-10}$.
Figure 1. Cross-sectional side view of the KOTO detector.

in preliminary [3]. This should be further reduced by one order of magnitude toward the SM sensitivity.

2. Upgrade of the calorimeter
We upgraded the calorimeter to suppress the hadron cluster background [4, 5, 6]. The second cluster tends to have hits in the downstream region of the crystals. The depth information of the hits in the crystal can be used to reduce the background. In order to get such information, we attached new photo-sensors, multi-pixel photon counters (MPPCs), on the upstream face of the crystal in addition to the existing PMT on the downstream face. The depth information can be obtained from the timing difference between the MPPC and the PMT to detect scintillation photons propagating in the crystal. We defined the timing difference $\Delta T = T_{\text{MPPC}} - T_{\text{PMT}}$, where $T_{\text{MPPC}}$ and $T_{\text{PMT}}$ are the timings measured with the MPPCs and the PMT, respectively.

A MPPC is adopted for the new photo-sensor for the following reasons: sensitivity to 310-nm UV light of CsI scintillation, sensitive area of 6 mm $\times$ 6 mm to have enough light yield, high gain of $1.7 \times 10^6$, compact size to fit the available gap space of 23 mm for the installation, small material of 0.004 radiation lengths allowable in front of the calorimeter, and low cost.

We tested the both-end readout scheme with a 50-cm-long 5-cm-square crystal. Four MPPCs were attached on one face, and a PMT was attached on the other face. Cosmic rays were triggered and the incident position was defined with plastic scintillators on the top and bottom of the crystal. Fig. 2 shows a good linearity in the correlation between $\Delta T$ and the incident position. The depth information can be obtained from $\Delta T$ with the propagation time of 7.4 (ns/m).

Figure 2. Correlation of $\Delta T$ and the incident position measured with cosmic rays.

Figure 3. Photo of the MPPCs with a circuit board attached on the upstream faces of the crystals.
For the calorimeter upgrade, we used one MPPC for the 2.5-cm-square crystal, and four MPPCs for the 5-cm-square crystals. The number of MPPCs is 4080 in total. In order to reduce the number of readout channels, the signals from 16 MPPCs are summed up into one readout channel; Four MPPCs are connected with a passive circuit, and the signal is transmitted with a 3.5-m-long thin coaxial cable. The signals from the four cables are summed up with op-amps. Finally the waveforms are recorded with 125-MHz sampling ADCs.

We glued the MPPCs on the surface of the crystals as shown in Fig. 3. A 0.5-mm-thick quartz plate was glued on the MPPC photo-sensitive side to make a flat surface beforehand. It can be attached on the vertical flat surface of the crystal with minimum amount of the glue.

3. Performance of the upgraded calorimeter

We collected data from February to April 2019 with the upgraded calorimeter. First, we aligned \( \Delta T \) for each readout channel with the photon cluster since photon makes a sharp \( \Delta T \) distribution in the smaller \( \Delta T \) region due to the short radiation lengths of CsI (1.86 cm). After the timing calibration of the PMT readouts, the timing of MPPCs were aligned using data selected with 6 clusters in the calorimeter. Pure photon clusters from \( K_L \rightarrow 3\pi^0 \) was selected with a constraint of the nominal mass of \( K_L \).

A distribution of \( \Delta T \) for two photons from a \( \pi^0 \) (“photon sample”) was obtained with the pure photon sample from the \( K_L \rightarrow 3\pi^0 \). Three pairs of photons from \( \pi^0 \) were selected assuming the decay vertex on the beam axis, and assuming the nominal \( \pi^0 \) mass for the two photons.

A \( \Delta T \) distribution for the hadron cluster background was obtained with a special control sample prepared as follows. An aluminum plate was inserted in the beam core at the upstream of the KOTO detector. A large number of core neutrons scattered in the aluminum plate, and hit the calorimeter. Large statistics of the events emulating the hadron cluster background was obtained (“neutron sample”) when events with two clusters in the calorimeter were selected.

We also prepared a MC simulation for the \( \Delta T \) for the photon sample. The propagation time and pulse height of MPPCs as a function of the hit depth was obtained separately from the data taken with cosmic rays. The hit depth was analyzed by tracking the cosmic ray with plastic scintillator strips above and below the calorimeter. Events with \( K_L \rightarrow 3\pi^0 \) were simulated, and the energy deposit in the crystal was obtained as a function of the depth. Waveforms were generated according to the measured propagation time and pulse height as a function of the depth.

We selected the larger \( \Delta T \) among the two clusters from the photon and neutron samples. Fig. 4 shows the \( \Delta T \) distributions for the photon and neutron samples, and for the simulated photon sample. The simulation is well tuned and reproduces the distribution of the photon sample.

The cluster energy of the photon sample is lower than that from the \( K_L \rightarrow \pi^0 \nu\bar{\nu} \) decay. The distribution was reweighted as in Fig. 5 to have the same cluster energy distribution. The hadron cluster background can be reduced to 2% with the photon selection efficiency of 90%.

4. Conclusion

We successfully upgraded the KOTO calorimeter with the both-end readout. The depth of the interaction in the calorimeter can be obtained from the timing difference of the both ends. The photon sample was prepared with the \( K_L \rightarrow 3\pi^0 \) decay. The neutron sample to emulate the hadron cluster background was prepared with a special run inserting an aluminum plate in the beam core. We evaluated the performance of the upgraded calorimeter with the photon and neutron samples. We reduced the hadron cluster background to 2% with a 90% efficiency for the signal. It enables us to search for the \( K_L \rightarrow \pi^0 \nu\bar{\nu} \) decay toward the SM sensitivity with a negligible contribution from the hadron cluster background. This also offers a new handle to
Figure 4. Distributions of $\Delta T$ for the photon and neutron samples, and a simulation for the photon sample.

Figure 5. Distributions of $\Delta T$ for $K_L \to \pi^0\nu\bar{\nu}$ (black) where the photon distribution was reweighted according to the cluster energy, and for the neutron sample (blue).

study backgrounds, a new way to search for new physics, and a new freedom in the design of future experiments.

Acknowledgment

We would like to express our gratitude to all members of the J-PARC Accelerator and Hadron Experimental Facility groups for their support. We also thank the KEK Computing Research Center for KEKCC. This work was supported by the JSPS KAKENHI Grant Numbers JP16H06343 and JP16H02184.

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