Front-end electronics for MPPCs for the KOTO CsI calorimeter upgrade

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(Received March 19, 2019)

The aim of the J-PARC KOTO experiment is to search for new physics beyond the standard model (SM) by measuring the rare kaon decay $K_L \to \pi^0 \nu \bar{\nu}$. This decay is highly suppressed in the SM; the branching ratio of this decay is predicted to be $3.0 \times 10^{-11}$ [1].

1. The KOTO experiment

The aim of the J-PARC KOTO experiment is to search for new physics beyond the Standard Model (SM) by measuring the rare kaon decay $K_L \to \pi^0 \nu \bar{\nu}$. This decay is highly suppressed in the SM; the branching ratio of this decay is predicted to be $3.0 \times 10^{-11}$ [1].

Fig. 1. Sectional side view of the KOTO detector.

The signature of the decay $K_L \to \pi^0 \nu \bar{\nu}$ in the detector is two photons plus nothing else, and the reconstructed $\pi^0$ should have a finite transverse momentum. To detect this signal, the KOTO detector consists of an electromagnetic calorimeter and hermetic veto counters as shown in Fig. 1. Figure 2 shows the KOTO calorimeter, which is made of undoped cesium
iodide (CsI) crystals. The central area of the calorimeter consists of 2240 small crystals \((25 \times 25 \times 500 \text{ mm}^3)\), and the surrounding area is populated with 476 large crystals \((50 \times 50 \times 500 \text{ mm}^3)\). The scintillation light from a crystal is detected with a photomultiplier tube (PMT), which is attached on the downstream side of the crystal. The waveforms of the PMT signals are recorded by 125 MS/s 14-bit ADCs.

One of the main background in the data taken in 2015 [2] are beam-halo neutrons. These neutrons produced two hadronic clusters in the calorimeter as shown in Fig. 3. To reach the sensitivity of the SM prediction, we need to suppress the neutron background to 1/40. This background will be reduced to a quarter with improved analysis methods. To reduce the background by another factor of ten, we upgraded the CsI calorimeter by reading out both ends of the crystals.

![Fig. 2. Sectional view of the CsI calorimeter.](image1)

![Fig. 3. Sketch of a halo-neutron background event.](image2)

2. Both-end readout system of the CsI calorimeter

Figure 4 shows the concept of the both-end readout system. In addition to the PMTs on the downstream surface of the crystals, we attached Multi Pixel Photon Counters (MPPCs), Hamamatsu S13360-6050CS, on the upstream surface. Using timing informations of the PMTs and MPPCs, we can measure the depths of the interaction points. Photons interact closer to the upstream surface of the CsI crystal. Neutrons can make showers in a deeper region. Neutrons, on the other hand, typically penetrate deeper into the crystal. We can thus distinguish neutrons from photons.

We attached four MPPCs on each large crystal \((50 \times 50 \text{ mm}^2)\), and one MPPC on each small crystal \((25 \times 25 \text{ mm}^2)\). In total, we installed 4080 MPPCs.

![Fig. 4. Concept of the both-end readout system.](image3)
3. Radiation damage at the KOTO experiment

From simulation, we estimated that the MPPCs would be exposed to $1.5 \times 10^9 \text{n}_{1\text{MeV}}/\text{cm}^2$ in the KOTO detector. We radiated some MPPCs with that dose and evaluated their characteristics such as breakdown voltage and relative gain of irradiated MPPCs. Figure 5 shows comparisons of the characteristics measured before and after irradiation. The breakdown voltage became lower by 2.3%, and the relative gain did not vary. Although the variation of the breakdown voltage will affect the pulse height, it is small enough within the sensitivity of our measurement.

![Comparison of breakdown voltage and relative gain before and after irradiation.](image)

Fig. 5. Comparisons of (a) breakdown voltage and (b) relative gain before and after the irradiation.

4. Front-end electronics for the MPPCs

We developed front-end electronics to read out signals and monitor the operation of the MPPCs. In the electronics, we reduced the number of channels with two methods: Connecting MPPCs in series and adding the MPPC signals with a summing amplifier.

Groups of four MPPCs are connected as shown in Fig. 6(a) [3]. This circuit acts as a series connection of the MPPCs for the readout of the signals, and as a parallel connection for the purpose of supplying the bias voltage. The series connection of the MPPCs reduces the load capacitance, which results in faster signals. Even if the dark current of the MPPCs increases due to radiation damage, the parallel connection of the bias supply results in a constant bias voltage for each MPPC.

The signals from four connected MPPCs are, furthermore, summed up with the amplifier circuit shown in Fig. 6(b). By summing the signals from four groups of the MPPCs, the number of readout channels is reduced from 4080 to 256. A group of 16 MPPCs covers a $100 \times 100 \text{ mm}^2$ region of the calorimeter. The summed signals are converted to differential signals, which are then sampled with 125MS/s 14-bit ADCs.

There had been some problems in the readout circuit designed in a previous study [4]. One of the problems was that electronics distorted the waveforms depending on the amplitude of the input signal. Figure 7(a) shows output waveforms measured with various input pulse heights. We mitigated the distortion by changing the op-amp used in the summing amplifier to a faster response op-amp. Figure 7(b) shows normalized output signals of the new op-amp. We also solved a cross-talk problem between neighboring channels.

5. Conclusion

We attached 4080 MPPCs on the upstream surface of the CsI calorimeter in order to reduce the halo-neutron background by an additional factor of ten. In the both-end readout
Fig. 6. (a) Scheme of MPPC connection. (b) Circuits of the summing amplifier and the differential buffer.

Fig. 7. Output waveforms with (a) old op-amp (AD8033) and (b) new op-amp (AD8065) measured with various input pulse heights. Each waveform is normalized with the output pulse height.

method, we can measure the depths of the interaction, and distinguish neutrons from photons. Although MPPCs will be exposed to $1.5 \times 10^9$ $n_{1\text{MeV}}/\text{cm}^2$ doses in the KOTO detector, that radiation damage would not affect the operation of the MPPCs in the experiment.

We developed the front-end electronics for the MPPCs. All of the front-end electronics achieved the required performance and were installed in the KOTO detector. From February 2019, we take data with the upgraded CsI calorimeter and these front-end electronics.

References
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