Upgrade of the CsI calorimeter for the KOTO experiment

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Abstract. The aim of the KOTO experiment is to study new physics beyond the standard model via a search for the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$. The KOTO detector consists of the electromagnetic calorimeter and hermetic veto counters. To reach the Standard Model sensitivity, we need to reject the neutron-induced backgrounds by a factor of ten. In the summer of 2018, we will start to instrument the front surface of the CsI calorimeter with 4096 multi pixel photon counters (MPPCs) to measure the arrival-time difference between the signals at MPPCs and at photomultiplier tubes connected to the rear surface of the calorimeter. The depth of energy deposition in the shower is measured through the timing difference, which in turn helps to discriminate neutrons and photons. To manage the large number of MPPCs, we have developed an electronics to reduce the number of channels down to 256. The method of gluing between the MPPC and the CsI crystals has been also developed. Using a quartz plate as a medium, the condition of flatness is assured in advance and a stable gluing can be performed. By developing a dedicated method to glue the MPPC with the quartz plate, the glue joint gets to be able to endure the decrease of temperature down to -20 °. The functionality of the developed hardwares were confirmed by two beam tests.

1. KOTO experiment
The primary goal of the KOTO experiment is to study new physics via a search for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay. The Standard Model (SM) prediction of its branching ratio is highly suppressed because the decay violates the $CP$ invariance and the tree-level flavor changing neutral transition ($s \rightarrow d$) is forbidden in the SM; the SM predicts $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ [1].

The experiment is being carried out at the Hadron Experimental Facility of J-PARC, Ibaraki Japan, using the high intensity 30 GeV proton synchrotron. The long-lived neutral kaons, $K_L$’s, are produced by the incident protons on the target made of Au and transported to the KOTO detector. The intense $K_L$ beam (the flux is $4.6 \times 10^7$ per $2 \times 10^{14}$ protons on target at the entrance of the detector) enables us to study rare decays.

The experimental signature of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is two photons + nothing; a $\pi^0$ is reconstructed from two photons in the final state and any other extra particles should not be observed at the same time. The KOTO detector consists of an electromagnetic calorimeter and hermetic veto counters around the decay volume. Figure 1 shows the sectional side view of the KOTO detector. The decay volume is kept in vacuum ($< 10^{-4}$ Pa) and surrounded by barrel veto counters and several collar veto counters. The energy and timing of photons produced by $K_L$ decays are measured with the CsI calorimeter in the downstream. For more detail, see Ref. [2].
The energy resolution is \( \sigma_E/E = 0.99\% \pm 1.74\%/\sqrt{E} \) (energy in GeV) and the timing resolution is \( \sigma_t = 1 \) ns. The details of the KOTO CsI calorimeter are described elsewhere [4].
Figure 3: (a) Sectional view of the KOTO CsI calorimeter; (b) Photograph of the CsI calorimeter.

Figure 4: Concept of the both-end readout of a crystal. A photon makes a shallow shower while a neutron deposits energy in a deeper region. The depth of energy deposition is measured thorough the timing difference observed with an MPPC and a PMT.

3. Upgrade of the CsI calorimeter

To reject the neutron-induced backgrounds further by a factor of ten, we plan to upgrade the CsI calorimeter. An incident photon makes an electromagnetic shower in the shallow region of the crystals, while a neutron deposits energies in a deeper region of a crystal, and thus a measurement of the depth of energy deposition can distinguish neutrons and photons. As mentioned in Sec. 1, the mechanism that the halo neutron mimics two photons from a $\pi^0$ is a neutron scattering inside CsI. The arrival time of signal at the PMT attached in the rear end of a crystal is a sum of propagation time of scintillation light and the incident timing, thus the single side readout does not precisely deliver the information on the location of energy deposition.

The idea of our both-end readout of the CsI crystal for neutron rejection is illustrated in Fig. 4. We will attach multi-pixel photon counters (MPPCs) of Hamamatsu S13360-6050CS, with the 6 mm × 6 mm sensitive area and 14400 pixels, in the front surface of the crystals. The difference of the arrival time between the MPPC and the PMT in a crystal, $\Delta t$, is used to locate the shower depth. The small/large value of $\Delta t$ implies an energy deposit at upstream/downstream side. In our analysis, we will use a constant fraction time which is the time when the pulse crossed the half of a peak value.

We evaluated the performance of the discrimination power based on a Monte Carlo (MC) calculation. We generated the halo-neutron and $K_L \rightarrow \pi^0\nu\bar{\nu}$ events and simulated the detector response using GEANT4 [5]. In addition, a library to simulate the propagation of scintillation light in the crystal was developed. Since the halo-neutron event mimics a signal by producing successive two clusters in the calorimeter, their correlation should be properly taken into account. The second neutron cluster tends to deposit energy deeper than the initial one, thus the larger of $\Delta t$ is the better discriminator to separate neutrons and photons. Figure 5 shows the distributions of the larger and the smaller ones of $\Delta t$ out of two photon clusters ($\Delta t_{\text{larger}}$ and $\Delta t_{\text{smaller}}$).
Figure 5: Simulated distribution of the larger one (red) and the smaller one (blue) of the timing differences for (a) neutrons and (b) photons.

respectively) for the halo neutron clusters and photon clusters. The events were selected by imposing vetoes and kinematic selection criteria which were to be used for the $K_L \rightarrow \pi^0\nu\bar{\nu}$ analysis. The cut position of $\Delta t_{\text{larger}}$ was determined to satisfy the signal ($K_L \rightarrow \pi^0\nu\bar{\nu}$) acceptance to be 90%, and halo neutron events were reduced by a factor of 19. However, we should take into account a correlation with other discriminators. After the discrimination with shower shape, the rejection power of neutrons was worsened to 11, while under the discrimination with pulse shape, the rejection power did not change.

4. Development of front-end electronics

Taking into account the number of readout channels, we decided to place four MPPCs in the large ($50 \times 50 \times 500 \text{ mm}^3$) crystal and one MPPC for the small ($25 \times 25 \times 500 \text{ mm}^3$) crystal at the front-end of the calorimeter. The number of MPPCs is still large (4096 in total) and it is difficult to realize an instrumentation of their separate readout. Thus, the granularity is reduced by the following two steps.

First, we integrate four MPPCs at the stage of the bias connection. Figure 6 shows the circuits for three different schemes being considered for the MPPC connections, and Fig. 7 shows the waveforms of the signals from these schemes. The series connection exhibits the small time constant (70 ns) because the effective capacitance becomes small. However, this connection requires a large bias voltage (220 V) and, more problematically, it is expected to have a poor tolerance on the radiation damage. The position dependence of dose rate can cause the different increase of the dark current among the integrated MPPCs, and accordingly, the radiation damage results in an instability of bias voltage for each MPPC. Using an MC simulation, we estimated that the difference of the amount of dose will reach up to 30% among neighboring MPPCs (displaced by 25 mm) and this would break down the balance of gain by 10%. The second option is a parallel connection, in which the application of the bias voltage and the readout are operated in parallel. The capacitor shortens the time constant. This scheme neither requires the (four times) larger bias voltage nor has the poor tolerance towards the radiation damage. Furthermore, the simple connection enables us to reduce the number of cables. However, the time constant is significantly larger than the series connection (150 ns), as shown in Fig. 7, and in turn the timing resolution gets worse. The last option is so called the hybrid connection, which was originally developed for the MEG II upgrade [6]. The high-
Figure 6: Three schemes being considered to apply the bias voltage to MPPCs: (a) series (b) parallel and (c) hybrid.

Figure 7: Comparison of the waveforms of the signal for three different schemes in Fig. 6.

frequency pulse is connected in series and the bias voltage is applied in parallel. Though the connection becomes more complex than the first and second options, this scheme has pros: the small time constant, the low bias voltage, and the stability towards the radiation damage. The waveform has a small time constant as that of the series connection, and the timing resolution is also sufficiently good. We thus decided to adopt the hybrid connection.

In the second step, to further reduce the number of channels, the signals from the four-hybrid connections are summed together as shown in Fig. 8. Sixteen MPPCs are simultaneously read out, thus the total number of channels is down to a manageable number, 256.

5. Development of the method to install MPPCs

There were several issues to be considered in the installation of MPPCs. First, we have to attach MPPCs onto the vertical surface of the already-stacked CsI crystals. Second, we cannot inspect the joint after the installation because the downstream side of the crystal is already covered by the PMT. Finally, the surface of MPPC is concave (see the schematic view in Fig. 9a), and it is therefore necessary to fill the space with a material to keep the reflective index as constant.

Based on the requirements, we decided to use a 0.5 mm-thick quartz plate as a medium between the MPPC and CsI crystal. We select the quartz plate (instead of a cheaper glass...
Figure 8: Circuit of the front-end. The four diodes enclosed by a circle represent the MPPCs integrated by the hybrid connection. The pulses from the four hybrid sets are mixed by a sum amplifier followed by a differential signal generator.

Figure 9: (a) Schematic view of the joint of an MPPC and a CsI crystal. (b) Gap appeared when the temperature becomes low.

plate) that has a high transmittance (\(\sim 100\%\)) at the 310 nm wavelength and the reflective index of 1.5 close to those of CsI (\(n = 1.8\)) and silicone (\(n = 1.4\)). By combining the MPPC and quartz plate using silicone polymer, the flatness and the soundness of joint are assured in advance so that the procedures of the installation become easier. However, we found that the boundary between the silicone and quartz surfaces had a poor tolerance on the low temperature. Figure 9b shows the boundary when the glued MPPC was cooled down to 5 \(^\circ\)C. The silicone has a larger thermal coefficient than the MPPC enclosure and the quartz plate, and thus produced the gap. Such gaps decrease the photon yield down to 80\%. We thus lifted the quartz plate 0.2 mm above the MPPCs with the silicone filled between them, and after the silicone is hardened, applied a pressure on the MPPC and fixed it with an epoxy glue on the edge of the MPPC (see Fig. 10). With this treatment, the silicone has a high enough internal pressure to compensate for a shrinkage down to \(-20\%\).

6. Performance tests
To verify the development, we did two beam tests. The first test was carried out at Research Center for Nuclear Physics (RCNP) of Osaka University to evaluate the separation capability between photons and neutrons. The second test was carried out at Research Center for Electron
The energies of both particles distributed continuously and reached up to 400 MeV. A prototype, in which eight large crystals surrounding four small crystals were stacked, was placed at 30 m downstream of the target. The incident particles, neutron or photon, were identified by time-of-flight. Figure 11 shows the timing difference between the MPPC and the PMT ($\Delta t$) for neutron and photon candidates. The two-peak structure in the $\Delta t$ distribution can be explained by the propagation of scintillated light; the CsI crystal was made by gluing two crystals in the middle and the light attenuation at the glue-joint changes the PMT pulse shape depending on the scintillation position. Photons scintillated in the downstream half reach the PMT both directly and indirectly. In the latter case, photons produced towards the upstream are reflected in the front surface and then reach the PMT attenuated at joint twice. Such delayed photons flatten the observed pulse shape and cause $\Delta t$ to be large. Meanwhile photons scintillated in the upstream half pass the joint only once, and thus the deformation of the pulse shape is relatively small. This is the mechanism why there is a difference between the two regions. Its quantitative explanation is under investigation. The cut position on $\Delta t$ was selected to have 90% photon efficiency. With this cut, neutron events were suppressed to 34%.

### 6.2. The resolution of timing difference

The ELPH synchrotron accelerates electrons to 1.3 GeV and its synchrotron radiation is injected to a metal plate. The produced positrons were selected by a magnet field and its monochromatic...
beams (200 MeV, 400 MeV, 600 MeV, and 800 MeV) were injected to the CsI crystals, whose setup was similar to the one used at RCNP. Moreover, after the evaluation of the performance of ordinary MPPCs, we swapped them with the ones which were irradiated in advance by placing them in the $K_L$ beam for KOTO. Assuming three-years operation at 100 kW proton-beam power, the MPPCs were irradiated by $2.4 \times 10^8$ 1 MeV equivalent neutrons per cm$^2$. Moreover, the front-end circuits and the MPPCs glued with quartz plates, described in the previous section, were fully tested.

Figure 12 shows the resolution of $\Delta t$ as a function of the incident beam energies. In spite of an increase of the dark current of the MPPC by a factor of 100 due to irradiation, we confirmed that the irradiation of the MPPC does not affect the measurement of timing difference.

7. Conclusion

The KOTO collaboration studies new physics via the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$. To observe an event in the SM sensitivity without the contamination of the halo neutron backgrounds, it is required to suppress neutron backgrounds by a factor of ten. This will be achieved by the measurement of the depth of energy deposition inside the CsI crystal. We plan to install MPPCs in the front surface of our CsI crystals, so that the depth will be measured as a timing difference between arrival signals at the MPPCs and PMTs. By a MC simulation, a suppression of neutron events by a factor of 11 can be achieved while retaining an efficiency of the signal event by 90%.

The design of the front-end electronics and the procedures of the installation of MPPCs have been developed. We carried out two beam tests to validate our ideas and the functionalities of the hardware, and demonstrated that the performance of the upgrade of CsI calorimeter was robust. In the summer of 2018, we will start the upgrade.

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