Construction of the double-side readout calorimeter for $K_L \rightarrow \pi^0 \nu \bar{\nu}$ search

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Abstract. We study the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at the KOTO experiment at J-PARC. To detect two photons from the $\pi^0$, the KOTO detector consists of a cesium iodide (CsI) calorimeter and hermetrical veto counters. The calorimeter is made of 50 cm-long CsI crystals stacked in a cylinder of 1.9 m diameter. Each crystal is read out with a PMT on its rear side. One of the major backgrounds is caused by a neutron generating two clusters in the calorimeter. To reject such events, we have upgraded the calorimeter to distinguish photon clusters from neutron clusters by measuring the time difference of the scintillation light at the front and rear ends of the crystals. We established the methods to install 4080 silicone photomultipliers on the front surface of crystals for this purpose.

1. Introduction
We upgraded the KOTO CsI calorimeter (CSI) for the study of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC in the autumn of 2018 [1]. The signature of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is only two $\gamma$ clusters on the CSI, and the reconstructed $\pi^0$ should have a transverse momentum balancing with the unobservable neutrino pair [2]. To separate such signals from a type of background due to a neutron generating two clusters in the CSI, we installed 4080 of silicon-photomultipliers (SiPMs) on the front surface of the CsI crystals in addition to the PMTs already on the rear surface. The timing difference between the pulses from the SiPM and the PMT helps to distinguish between neutrons and photons. Electromagnetic showers start in shallow regions in the crystals whereas the depths of neutron-induced hadron showers have a wider distribution.

The upgrade was successful, and the performance was better than expected [3]. We will describe the methods that we developed to glue the SiPMs on the CsI calorimeter.

2. Requirements
The CSI consists of 2240 small-size crystals surrounded by 476 large-size crystals as illustrated in Fig.1. The lateral dimension is $2.5 \times 2.5$ cm$^2$ for the small crystals and $5.0 \times 5.0$ cm$^2$ for the large crystals. Their length is 50 cm.

The requirements on the upgrade are as follows:

(i) SiPM should be sensitive to the 310 nm scintillation light from the CSI.

Figure 1. Event display of the CsI calorimeter with six shower clusters.
(ii) Materials between SiPM and crystals should also be transparent to the 310 nm scintillation light.

(iii) The mechanical strength of the adhesive product should withstand the shear and tensile strengths of 5 N equivalent to the guaranteed strengths of the cable’s connector.

(iv) The 5 N strength should be maintained in the temperature range between -5 and 45°C,

(v) be maintained in the vacuum of 0.1 Pa, and

(vi) be maintained in irradiation equivalent to $3 \times 10^{10}$ of 1 MeV neutrons/cm$^2$.

(vii) All materials inside the vacuum region of the detector should be free from outgas which reduces the UV transparency of the silicone pad between CsI crystals and PMTs.

(viii) The SiPMs should be protected from the pressure between CsI crystals and the CSI cover placed in front of the CSI. The CSI cover prevents crystals from moving during earthquakes.

(ix) The installation should be done without disassembling the CSI.

3. Methods

3.1. Quartz plate between SiPM and crystal

We used MPPCs S13360-6050CS supplied by Hamamatsu KK as SiPMs. This SiPM has a silicone window to keep the sensitivity to UV light. The sensitive area is $6 \times 6 \text{ mm}^2$. The concave shape of the silicone window, as illustrated in Fig. 2, makes the gluing process difficult.

We decided to use a quartz plate between each crystal and SiPM(s); for each large crystal we glued four SiPMs. This reduced the difficulty of gluing them on the vertical face of the crystals. The dimensions of quartz plate is $14 \times 14 \times 0.5 \text{ mm}^3$ for the small crystals and $25 \times 25 \times 0.5 \text{ mm}^3$ for the large crystals. Figure 3 shows four SiPMs glued on a quartz plate.

3.2. Adhesives

To glue the quartz plates on the crystals, we used epoxy-type glue “EPO-TEK 305” (EPOTEK). For small crystals, one drop of EPOTEK (12 mg) was applied to let a small amount of EPOTEK protrude all four edges of the quartz plates when the quartz plate was pushed against the crystal. For large crystals two drops (24 mg) was suitable for each quartz plate. The transparency of this amount of EPOTEK and the quartz plate to the 310 nm-light is more than 90%. The cure time of EPOTEK is at least 16 hours.

To glue the SiPMs on the quartz plates, we used “TSE 3032” (TSE). The advantage of TSE is that the silicone pads between crystals and PMTs are made of TSE so that the properties are well known; the transparency of 5 mm thick TSE to 310 nm-light is > 89% after six years at 60 °C. We first tried EPOTEK, but EPOTEK peeled off from the SiPM concave if the temperature was raised to ~35 °C. Although the TSE was more stable than EPOTEK, fine wrinkles of bubble sometimes appeared due to small temperature variance. We considered that this phenomenon is caused by volume variance of adhesive induced by the temperature variance, and

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1 U.FL-2LPHF6-068N2T-A, https://www.hirose.com
2 https://www.hamamatsu.com/resourcespdfs/sds13360_series_kapd1052e.pdf
decided to apply excess inner pressure on the TSE. We tested and confirmed that most types of adhesive confined in a thin closed space had the same phenomena. As shown in Fig. 4, we kept a 200 µm gap between SiPM and the quartz plate when we glued them together with TSE (12 mg/SiPM). After TSE solidified, we applied pressure, and glued the edge of the SiPMs onto the quartz plate with epoxy glue. With this gluing method, the products were stable in the temperature variance from -10 °C to 45 °C.

3.3. Other requirements

We soldered a circuit board [4] on each product made in the previous subsection. After the soldering, all the products were kept under 0.1 Pa for more than 24 hours. None of them was broken nor had an unusual IV curve [4]. One produced sample, glued on a crystal and irradiated with more than $3 \times 10^{11}/\text{cm}^2$ of 1 MeV neutron equivalent, had the strength of more than 35 N to the shear test. All the materials we selected have no outgas which may reduce the UV transparency of the silicone pad for PMTs. This was confirmed by placing the materials and silicone pads in a 55 °C vacuum furnace for 24 hours, and measuring the transparency of silicone pads for the 310 nm light after it.

4. Construction

The construction onsite continued for two months. Two horizontal aluminum beams were set in front of the CSI. Figure 5 shows the tools including such beams for the construction. The procedure for one day of work was the following:

(i) Two aluminum beams indicated with (a) in Fig. 5 were set on a frame held on the CSI cylinder (b). The beams held the jigs illustrated in Fig. 5-4.

(ii) The height of each beam was adjusted to a crystal row using two jacks (d). The CSI has 48 rows of mixtures of small and large crystals and 12 rows of large crystals. Four laser guns were mounted on jigs illustrated in Fig. 5 near the ends of the beams indicated with (c) in Fig. 5. Target films with cross lines (e) were temporarily inserted in front of the crystals. The aluminum beam heights were adjusted so that the laser beams pointed at the centers of the crystals near the ends.

(iii) After fixing the beam positions, the position of each jig was adjusted using again laser guns and the target films.

(iv) During these adjustments, the formulation of EPOTEK, mixing two detergents, and dispensing 12 mg of drop for each quartz plate simultaneously proceeded for all the SiPMs for the day, as shown in Fig. 5.

(v) Each slider (h) holding a SiPM with adhesive was set horizontally on a jig and was pushed toward the crystal by spring (j) keeping 3 N of pushing pressure for 16 hours.

Figure 4. Schematic views and photos showing the procedure to apply inner pressure on the adhesive between SiPM and the quartz plate. 1) Before compression, TSE was cured for 20 hours at 45 °C. 2) After the TSE was cured, the TSE was compressed with 200 N weight. “Araldite (epoxy glue No.2011)” was applied to four edges of the SiPM. The cure time was at least 18 hours in a room temperature. 3) Photo of jig making a 200 µm gap between an SiPM and a quartz plate (g) on ridges (f). 4) Photo showing 44 SiPMs being cured with the 200 N weights (yellow brass cube) for small crystals. The eight jigs in the first row are compressing four SiPMs on a quartz plate for large crystals. a: quartz plate, b: SiPM, c: adhesive (TSE), d: 200 N weight, e: “Araldite” to keep pressure on TSE, f: ridge to keep the 200 µm gap, and g: quartz plate.
Figure 5. Schematic views and photos explaining the system to glue SiPMs on-site. 1) Two aluminized beams set on a frame constructed on the CSI cylinder. 2) A laser light is targeting cross lines on a PET film placed in front of a crystal surface. 3) An SiPM with its circuit board stuck on a foam with its two electrodes. 4) A jig on an aluminum beam. 5) A side view of the jig. 6) A scene of EPOTEK drop applied on the SiPM. a: two aluminum beams holding jigs illustrated in 4), b: cylinder of CSI, c: alignment positions shown in 2), d: four jacks to adjust the heights of the aluminum beams, e: a target for a laser to adjust the position of a beam, f: SiPM on a quartz plate stuck on a foam, g: foam to hold SiPM allowing freedom of direction for SiPM, h: slider keeping SiPM on the jig, i: holder to push and hold the slider, j: spring providing a pressure (∼3 N) to SiPM, and k: screws to tune the position of SiPM.

(vi) After EPOTEK cured, a reflector film made of aluminized polyethylene terephthalate was placed on the front surface of each crystal, avoiding the area of quartz plate.

(vii) Cables to sum four-SiPM signals [4] of small crystals were installed, and output cables to such four-SiPM readout units and individual large crystals were then connected.

(viii) Finally, each crystal was covered with an acrylic cover and rewrapped with the original wrapping film; the lack of wrapping film due to the increase of volume with the acrylic cover was compensated with black insulating tape. The acrylic cover is a box shape having 1 mm smaller lateral size than the crystal surface and 10 mm in height. The thickness of the material is 1 mm. This cover is aimed to protect the SiPM from the pressure generated between the crystal and the CSI cover in an earthquake and to prevent aluminized wrapping film shorting the circuit of SiPM.

5. Summary
We established new methods to glue SiPMs on CsI crystals. The 4080 of SiPMs were successfully glued including cabling by five people in two months.

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