Photon-Veto Counters at the Outer Edge of the Endcap Calorimeter for the KOTO Experiment

T. Matsumura\textsuperscript{a,}\textsuperscript{*}, T. Shinkawa\textsuperscript{a}, H. Yokota\textsuperscript{a}, E. Iwai\textsuperscript{b,1}, T.K. Komatsubara\textsuperscript{c}, J.W. Lee\textsuperscript{b}, G.Y. Lim\textsuperscript{c}, J. Ma\textsuperscript{d}, T. Masuda\textsuperscript{e,2}, H. Nanjo\textsuperscript{f}, T. Nomura\textsuperscript{c}, Y. Odani\textsuperscript{f}, Y.D. Ri\textsuperscript{b}, K. Shiomi\textsuperscript{b}, Y. Sugiyama\textsuperscript{b}, S. Suzuki\textsuperscript{f}, M. Togawa\textsuperscript{b}, Y. Wah\textsuperscript{d}, H. Watanabe\textsuperscript{e}, T. Yamanaka\textsuperscript{b}

\textsuperscript{a}Department of Applied Physics, National Defense Academy, Yokosuka, Kanagawa 239-8686, Japan
\textsuperscript{b}Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
\textsuperscript{c}High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
\textsuperscript{d}Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
\textsuperscript{e}Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\textsuperscript{f}Department of Physics, Saga University, Saga 840-8502, Japan

Abstract

The Outer-Edge Veto (OEV) counter subsystem for extra-photon detection from the backgrounds to the $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ decay is arranged at the outer edge of the endcap CsI calorimeter for the KOTO experiment at J-PARC. The subsystem is composed of 44 counters with different cross-sectional shapes. All counters are consisting of Lead/Scintillator sandwich with the wavelength-shifting fiber readout. In this paper, we discuss the design and performance of the OEV counters that work under the heavy-loaded and vacuum conditions. The average light yield and time resolution are 20.9 photo-electrons/MeV and 1.5 ns for the energy deposit of 1 MeV, respectively, demonstrating that the OEV counters have the capability of vetoing photons with the visible energy as low as 1 MeV. The energy calibration method with cosmic-rays works well.
in monitoring the gain stability with an accuracy of a few percent, though no pronounced peak by minimum ionizing particles is observed in the energy distributions.

Keywords: Lead/scintillator sandwich, Energy calibration, WLS fiber readout, Kaon rare decay, KOTO, J-PARC

1. Introduction

The KOTO experiment is dedicated to observe the \( K_L^0 \rightarrow \pi^0 \nu \bar{\nu} \) decay using the 30-GeV proton beam at Japan Proton Accelerator Research Complex (J-PARC) \([1]\). The \( K_L^0 \rightarrow \pi^0 \nu \bar{\nu} \) decay is a direct CP-violating and flavour-changing neutral current process. The branching ratio (Br) is predicted to be \( 2.43 \times 10^{-11} \) in the Standard Model (SM) \([2]\). The most attractive feature of this decay is the exceptionally-small theoretical uncertainty of only 2-3%. Thus, measurement of the branching ratio of this decay mode is highly sensitive to the CP-violating parameter in the SM and the new physics beyond the SM. Experimentally, the upper limit on the branching ratio was set to be \( 2.6 \times 10^{-8} \) at the 90% confidence level by the E391a experiment at KEK \([3]\). Upgrading from E391a, the KOTO experiment \([4]\) has the sensitivity to reach below \( 10^{-11} \) by utilizing the high intensity beam at J-PARC and with necessary detector upgrades for the improved acceptance and efficient background reduction. The detector construction was finished and the physics data taking started in May 2013 \([5, 6, 7]\).

In the KOTO experiment, the \( K_L^0 \rightarrow \pi^0 \nu \bar{\nu} \) decay is identified by detecting two photons from the \( \pi^0 \) decay with an electromagnetic calorimeter and by ensuring no other particles with hermetic veto counters. The endcap CsI calorimeter located downstream of the decay region (see Fig. 1a) serves the function of detecting the two photons. All the remaining detectors are photon veto and/or charged-particle veto counters to confirm no other particles in the final state of the \( K_L^0 \) decay. The well-collimated \( K_L^0 \) beam at J-PARC \([8]\) enables us to reconstruct the \( \pi^0 \) momentum and decay position from the energies and positions of the two photons measured with the CsI calorimeter. The main background source is expected to be the \( K_L^0 \rightarrow \pi^0 \pi^0 \) decay (Br = \( 8.65 \times 10^{-4} \) \([9]\)), because the decay can mimic a signal candidate if two extra photons from the \( \pi^0 \pi^0 \) decay is missed due to detection inefficiency of the photon veto counters. Thus the photon veto counters, as well as the CsI calorimeter, are crucial for the KOTO experiment in order to achieve its
Figure 1: (a) Schematic side-view of the detector setup of the J-PARC KOTO experiment. Most of the detectors are contained in the cylindrical vacuum vessel of 3.8 m in diameter and 8.7 m in length. The $K^0_L$ beam passes through the center of the setup from the left. The CsI calorimeter is located downstream of the decay region. FB, NCC, MB, OEV, CC03, CC04, CC05, CC06 and BHPV are photon veto counters; HINEMOS, BCV, CV, LCV and BHCV are charged-particle veto counters. The membrane separates the decay region, which is in the vacuum of $10^{-5}$ Pa, from the detector region which is kept at about 0.1 Pa. (b) Enlarged illustration near the outer-edge region of the CsI calorimeter. The main role of the OEV counters is to detect the photons coming from the $K^0_L \rightarrow \pi^0 \pi^0$ background (blue arrow).
The Outer-Edge Veto (OEV) counter subsystem, which is the subject of this paper, is one of the photon veto counter subsystems and is located around the outer edge of the endcap CsI calorimeter. The CsI calorimeter, consisting of 2716 undoped CsI crystals, is stacked in the cylindrical support structure of a vacuum vessel. The OEV counters fill the narrow space between the CsI crystals and the cylindrical support structure. The primary role of the OEV counters is to reject the photons passing through the outer-edge region of the CsI calorimeter before entering the inactive material of the support structure (see Fig. 1b). In particular, the photon from the $K_L^0 \rightarrow \pi^0\pi^0$ decay with the energy around 600 MeV must be eliminated because the other photon from the $\pi^0$ is likely to hit the barrel detector (MB in Fig. 1a) with the energy about 10 MeV, which can be lost with a 20% probability by MB [4]. To keep a short veto time-window under high-rate condition, the time resolution of a few nano-seconds is required for the OEV counters. In addition, they must operate stably in the vacuum and under the heavy load of the CsI crystals.

In consideration of the requirements mentioned above, we adopted a lead-scintillator sandwich with the wavelength shifting (WLS) fiber readout as the OEV counters. This type of the detector is efficient for photons with energy more than 100 MeV [10, 11], and has fast response due to the short decay times of plastic scintillator and WLS fiber.

In this paper, we will firstly describe the design of the OEV counters (Section 2) and the construction process (Section 3) in detail. The following topics on the required performance will be discussed in Section 4: load intensity, discharge characteristic of photomultiplier tubes (PMTs) in the vacuum condition, light yield, and time resolution. Finally, we discuss an energy calibration method with cosmic-rays developed for the OEV counters of KOTO as well as its performance and validity in Section 5.

2. Design

Figure 2 illustrates the upstream view of the endcap part of the KOTO detector. Here, we discuss mainly the three objects: the CsI calorimeter, the cylindrical support structure of the vacuum vessel, and the OEV counters. For the CsI calorimeter two types of undoped CsI crystals are used: 2240 blocks of the small crystal (25 mm × 25 mm) and 476 blocks of the large crystal (50 mm × 50 mm), where the length for both crystals is 500 mm.
PMTs with Cockcroft-Walton (CW) bases \[12\] are used as the readout devices. The CsI crystals are installed in the cylindrical support structure of the vacuum vessel, which is made of 12-mm thick stainless steel with an inner diameter of 1.93 m. The OEV counters, consisting of the 44 lead-scintillator sandwich counters, have different shapes of cross sections in order to fill the space between the CsI crystals and the cylindrical support structure.

We utilized the material resources of the barrel detectors FB and MB, which were originally built and used in the E391a detector \[13\], for the OEV counters since they shared the same components. The first component is the 5-mm thick plastic scintillator sheets, developed for the long barrel detectors,
with an extrusion-molding method. This scintillator is based on MS-resin (polystyrene 80%, polymethyl-methacrylate 20%) \cite{14}. This is suited for scintillators of the OEV counters, which are under heavy weight load of the CsI crystals. The next one is the 1.5 mm-thick lead sheets, which were used for the FB construction. We studied the effect of the lead thickness under the constraint of the same counter size with a simulation program based on Geant4 \cite{15}. The results from the study suggested that there was no difference in the rejection power to the $K_L^0 \rightarrow \pi^0\pi^0$ background between the case of the lead thickness of 1 mm and 2 mm, respectively. Thus, we decided to use the 1.5 mm-thick lead sheets for the OEV counters. The wave-length shifting (WLS) fiber Kuraray Y11(200)M \cite{16} is used to collect scintillation light to the PMTs. These fibers with the diameter of 1 mm were the same as ones used in MB. Readout with the WLS fibers has the advantage of avoiding light-yield non-uniformity originating from the short attenuation length of the extrusion-molding scintillator, which is 45 cm \cite{14}.

Figure 3 shows the exploded views of a typical OEV module located at the bottom of the endcap. The plastic scintillators and the lead sheets of 420 mm in length are alternately stacked in a stainless steel frame. The length of the frame, 500 mm, matches the length of the CsI crystals. The WLS fibers are bent in the remaining space of the frame to a bundle just outside of the
The reflector sheets, Toray Lumirror E60L with the reflectivity of 97%, is 188 $\mu$m thick [17]. They are inserted in a direct contact with the whole surface of the scintillator to achieve a high light-collection efficiency. Note that we selected this particular reflector because of its stable reflection properties under the pressure and our past record of the long-term operation with a large pressure of the 15 tons/m$^2$ in the E391a experiment [13].

Figure 4: OEV counters located at the bottom right section of the endcap. In this figure, each of four counters, OEV-26, 27, 28, and 31, consisted of two modules which was read out with a PMT. The stacking layer direction is horizontal at the bottom and vertical at the side.

The frame structures of the OEV modules are different between the bottom half and the upper half of the endcap. The OEV modules, supporting the weight of the CsI crystals at the bottom part, have a robust frame made of 2 mm-thick stainless steel (see the Fig. 3). By screwing the stacked layers in the frame tightly, warped scintillator plates and/or deformed lead sheets were flattened. This suppresses the deformation under the load caused by the CsI crystals. In contrast, there is no such a load on the OEV modules located in the upper half of the endcap. Hence, the modules are just covered by 1 mm-thick aluminum plates and bound with polyester tape to protect the contents.

Hamamatsu R1924A 1” PMT [18] was used as a readout device for the OEV counters. A total of 44 PMTs were placed about 80 cm behind the end plate of the counters. Some OEV counters which consisted of two modules were connected to one PMT; thus, the total 44 OEV counters actually con-
Figure 5: Cross section of an OEV module (OEV-33) for the bottom center of the endcap. Scintillator plates and lead sheets are stacked in the frame. Green circles in the scintillator plates are the ends of the WLS fibers. The top plate is screwed to the aluminum side bars of the frame in order to press stacked layers in the frame. The module was installed upside down, so that the slope of the top board matches inside of the cylindrical vessel.

sisted of 64 modules with nine different shapes of cross sections (type-0 to type-8 in Fig. 4).

We selected the CW base, Hamamatsu C10344MOD13, as the high-voltage power supply for the PMTs, which operates in the atmospheric pressure or below 0.1 Pa. The power consumption of the base is 30 mW at the maximum, which is one order-of-magnitude less than that of the resistor type dividers. This reduces the amount of the heat generated inside the vacuum vessel. Another big advantage is that the CW base can be operated with the same type of the voltage distributor already developed for the CsI calorimeter without any change.

As illustrated partly in Fig. 4, the direction of the stacked layer is horizontal for the OEV modules located at the top and the bottom region, while the direction is vertical for the side modules. This reduces the azimuthal angle dependence of the effective radiation length for photons emitted from the beam region.

3. Construction

Scintillator plates were cut out from a large scintillator sheet having the area of 5.5 m × 0.68 m. They were then shaped to the desired cross sections
(rectangle or trapezoid, as shown in Fig. 5) with a milling machine and polished with abrasive cloth for optical lenses. After that, grooves for embedding the WLS fibers were machined on one side of each scintillator plate with an interval of 10 mm. The width and the depth of the grooves were 1.2 mm and 1.5 mm, respectively. Note that we set the depth somewhat deeper than the WLS-fiber diameter in order to prevent glue from overflowing.

Ultraviolet curing adhesive, NORAND NOA61 [19], was chosen to glue the WLS fibers to the grooves with good optical contact. The short curing time of the adhesive, about 30 minutes, was well suited to mass production. We developed an automatic gluing system equipped with an X-Y movable stage, Sigma-Koki SGSP46, with a glue dispenser, Nordson EFD Ultra-1400. The control was implemented with a laptop PC via GP-IB communication bus. We applied 0.25 ml of the adhesive to each groove in 10 seconds uniformly without a break. Making a fine adjustment of the air pressure of the dispenser was important to keep the same discharge rate, since the viscosity of the adhesive strongly depended on the temperature and elapsed time from its production date. Visible bubbles were removed with air blowers while the WLS fibers of 145 cm in length were set in the grooves. Finally, we irradiated the glue with ultraviolet light ($\lambda = 365$ nm) with an intensity of 1.5 - 5.5 mW/cm$^2$. It took 30 minutes to deposit the required energy, 3 J/cm$^2$ for full curing. After extra fibers were cut at the front end, the surface was optically polished with a diamond wheel and abrasive cloth.

For the bottom modules, special attention was paid to stack the lead/scintillator layers to reduce extra space inside the OEV modules. A detailed configuration of the layers is illustrated in Fig. 5. The scintillator plate with WLS fibers was sandwiched between two sheets of lead on contact with a reflector sheet. Prior to the stacking, the thicknesses of all scintillator plates and lead sheets were measured with a micrometer with an accuracy of less than 10 $\mu$m. We then prepared special spacers, such as papers (90 $\mu$m) and/or Lummiror sheets (188 $\mu$m), and layered them so that the total thickness of all the layers stacked inside the frame should be fitted to the designed value within 100 $\mu$m. The average thickness of the scintillators and the lead sheets of both the top and bottom OEV modules, $(4.91 \pm 0.07)$ mm and $(1.44 \pm 0.03)$ mm, respectively, were put into the detector simulation code as

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3 The thicknesses of 82% of the scintillators and 100% of the lead sheets were measured, and were taken into account in the average calculation.
Figure 6: Illustration of the WLS fiber bundle and PMT (Hamamatsu R1924A) with CW base (C10344MOD13) for an OEV counter. The WLS fiber bundle is glued to the adapter made of POM. By screwing a PMT holder made of POM to the PMT, the end of the WLS fiber bundle is tightly contacted to the PMT window through a silicone rubber with 2 mm thick (EJ-560). Sleeve of optical fiber is screwed to the adapter of the WLS fiber and optical fiber is hold in the sleeve.

the material and geometry constants. Details of the Monte-Carlo simulation code will be described later.

Both the front and rear edges of the scintillators were painted with reflector, ELJEN EJ-510 [20]. The effect of the reflector at the front end was tested with an type-8 OEV module by measuring the light yield for cosmic rays passing through the center of the module. Three different reflectors were tested: aluminized Mylar (direct attachment), Lumirror E60L (direct attachment) and EJ-510 (painted). The light yields relative to the case without a reflector were 1.08 ± 0.01 for the aluminized mylar, 1.24 ± 0.01 for the Limirror sheet and 1.26 ± 0.03 for EJ-510. Although there was no significant advantage of EJ-510 over Lumirror on the light yield, we selected EJ-510 as the reflector because of the ease of handling and fixed contact.

As shown in Fig. 6 the fiber bundle was optically connected to a PMT with a 2 mm thick transparent silicone rubber, ELJEN EJ-560 [20]. The end of each WLS-fiber bundle was glued to an adapter with optical cement, ELJEN EJ-500 [20], and polished with diamond file and cloth. Figure 6 also shows the mechanism to fix the fiber bundle to the PMT by fastening force through the PMT holder and the adapter. The adapter and folder

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4 Teflon sealing tape was wrapped around the fiber bundle for protection, and the tape was covered with black tape for light shield.

5 For the case in which two modules were read with a PMT, two semi-cylindrical
Figure 7: Illustration of the setup of the load test for an OEV module (type-3) and its photograph. The OEV module placed on the aluminum spacer was pushed by the press machine (20 tons at the maximum load) through the top stainless plate, and the displacement of the plate was measured by the dial gage. The L-type angles, which were clamped to the bottom stainless plate, were used to prevent a transverse slide.

were made of black polyoxymethylene (POM) resin from the consideration of mechanical strength and easiness of machining. For monitoring of the PMT gain, an optical fiber was inserted and fixed to the adapter to which the blue light was flashed continuously at 5 Hz. The light was distributed in common with the CsI calorimeter.

The PMT holder was fixed to the cylindrical support structure. Copper tape (25 mm (wide) and 0.035 mm (thick)) was placed around the CW base to attach to the cylindrical support structure for heat release. A simple calculation shows that the temperature difference is expected to be less than 2 degrees by presuming that the length and the heat conductivity of the copper tape are 2 cm and 400 W/(m·K), respectively.

4. Performance

4.1. Load test

For smooth movement of the CsI blocks during the CsI stacking work, a flat upper surface of the stacked CsI layer is required. The level difference of neighboring CsI blocks is needed to be less than 200 µm. For this reason, the structure of the OEV counters located at the bottom part should be

adapters were used for two bundles.
robust enough to support the weight of the column of CsI crystals above them, 406 kg weight (∼8 tons/m²) at the maximum, without large downward deformation.

To confirm this, we had measured the deformation by applying load with a press machine to the bottom OEV counters. As shown in Fig. 7, the bottom OEV module was fixed with an aluminum spacer that has a slope of the same inclined angle of the module to keep the upper surface horizontal. Each module was pressed uniformly up to 1.2 times the total weight. The displacement of the top surface was measured with a dial gage. Note that, in advance of the measurement, we tried to press one time beforehand to remove the gap between the module and the aluminum spacer. Deformations due to loaded weight were checked in this way.

Figure 8 shows the results of the load test for the sixteen OEV modules which will have over 200 kg weight of CsI crystals stacked above them. Displacements due to the total weight were in the range of 20-120 µm, and were reproducible. The mean and the standard deviation of the displacements were 61 µm and 34 µm, respectively. These results show that the robustness of the OEV counters meets the requirement.
4.2. PMT performance

The $K^0_L$ decay region of the KOTO detector is in a vacuum of $10^{-5}$ Pa to eliminate interactions between beam particles and residual gases. However, the pressure in the endcap region where PMTs and electronics are located is kept at $\sim 0.1$ Pa. We needed to confirm no discharge on the electrodes of the PMTs. Hence, we tested the discharge characteristic of the PMTs used for the OEV counters in the vacuum condition, as well as the general characteristic like the gain-voltage relation.

4.2.1. Gain

We evaluate (1) the voltage dependence of the PMT gain and (2) the gain fluctuation due to the amplification process from the ADC distribution measured by illuminating each PMT with a very weak light source.

In the measurement, a green WLS fiber (Kuraray Y-11) with the length of 10 cm was placed in front of a pair of a PMT and a CW base. The WLS fiber was illuminated with a blue LED (Nichia NSB320BS), where the light intensity was adjusted so that the photo-electron (p.e.) yield was 1-3 p.e./LED pulse (see Fig. 9a). The signal from the PMT was further increased by 63 times with an amplifier (Hamamatsu Photonics C5594), and the output charge was digitized with a 12-bit Charge Sensitive ADC (CS-ADC, REPIC RPC-022). The gate width and the resolution of the ADC were 80 ns and 0.277 pC/ADC count, respectively.

The gain of each PMT ($G$) can be estimated from the output charge initiated with a single photo-electron ($Q$) as $G = Q/e$, where $e$ denotes the electron charge. Figure 9b shows the relation between the PMT gain $G$ and the applied voltage $V$ [kV] from 0.7 kV to 1.2 kV with an interval 0.1 kV for a typical PMT. The line shows a relation of $G = KV^\alpha$ fitted to data points, where $K$ and $\alpha$ are arbitrary constants. The mean values of $K$ and $\alpha$ were $(1.49 \pm 0.15) \times 10^7$ and $7.71 \pm 0.09$, respectively. These parameters can be used for tuning of the PMT gain.

The gain fluctuation due to the amplification process can be obtained from the width of the single photo-electron peak observed in the ADC distribution (see Fig. 9a). The width of the single photo-electron peak was $0.48 \pm 0.05$ p.e., averaged over all the PMTs. This value was utilized for energy smearing in the Monte-Carlo simulation as discussed in Section 5.2.
Figure 9: (a) ADC distribution of a PMT illuminated with weak light from a green WLS fiber. (b) Voltage dependence of the gain for a typical PMT (Hamamatsu R1924A). The straight line shows a fit with the relation $G = KV^\alpha$ (see the text).
Figure 10: Breakdown voltage as a function of the pressure for two randomly selected PMT pairs (circles and squares). There was no indication of discharge in the range 0.5-10 Pa. The dashed line denotes the maximum operating voltage of 1250 V.

4.2.2. Operation in vacuum

The manufacturer randomly selected 5 pairs of a PMT and a CW base, tested them in vacuum at $10^{-3}$ Pa, and found no electric discharge on the CW bases for 48 hours and observed stable output signals from all the PMT pairs. In addition, assuming worse vacuum conditions at the detector commissioning stage, we conducted test at the pressures above 0.5 Pa for two randomly selected PMT pairs. As shown in Fig. 10, we observed continuous discharge above 30 Pa and the breakdown voltage was below the maximum supply voltage of 1250 V. Although we found unstable current occasionally in the range 10-30 Pa, there was no indication of discharge below 10 Pa. These results imply that the PMT pairs applied with the normal operating voltages for the data taking (750-800 V) work safely below the vacuum level of 0.1 Pa, which is the typical vacuum condition around the endcap region.

4.3. Light yield

To detect photons having energies above 100 MeV with sufficiently-low inefficiency ($10^{-4}$), the energy threshold needs to be set to 1 MeV in the visible energy after taking into account the sampling fluctuations and photonuclear interactions [10, 11]. The light yield of the OEV counters is required to be
more than 10 p.e./MeV to obtain a definite timing information. In this section, with cosmic rays, we discuss the light yield and the position dependence along the longitudinal direction.

4.3.1. Setup for the light yield measurement

The schematic setup for the measurement is shown in Fig. 11. Two OEV modules of the same type, with mirror symmetry, were stacked horizontally using aluminum spacers. Three pairs of trigger counters, consisting of 40 mm(length) × 40 mm(width) × 5 mm(thickness) plastic scintillators, defines a cosmic-ray muon passing through the tested OEV modules. The trigger counters were placed at the equal interval of 180 mm in the longitudinal direction to test the position dependence of the light yield. We achieved the light yield measurement with an accuracy of 5% in half a day. The WLS fibers bundle which was connected to the PMT was illuminated with a blue LED (Nichia NSB320BS) as a light intensity monitor.

The signals from the OEV modules were amplified threefold with an amplifier Phillips Scientific 777 [22]. The same voltage of 900 V, which gave the gain of (5.2-8.0) × 10^6, were applied to all PMTs. The output signal from
Figure 12: (a) ADC distribution of an OEV module (type-0) by the LED trigger. The pronounced peaks around 0 and 12 ADC counts correspond to the pedestal and single photo-electron peak, respectively. (b) The same distribution as (a) with the cosmic-ray trigger for 36.7 hours, where the ADC values have been converted to the number of photo-electrons. A function of a Gaussian with an exponential slope was fitted to the data in order to estimate the mean value of the number of photo-electrons.

The amplifier was integrated with a 12-bit Charge Sensitive ADC, REPIC RPV-171, with a gate width of 120 ns. The cosmic-ray trigger was provided by the sum of coincidence signals of the three pairs of the trigger counters. The gains of the PMTs for 1 p.e. were monitored at a frequency of 0.5 Hz with weak light from the blue LED.

4.3.2. Light yield and its position dependence

Figure 12 shows the ADC distributions of an OEV module (OEV-32) collected in coincidence with the LED lighting (Fig. 12a) and with the middle trigger counters (Fig. 12b) for the data collection time of 36.7 hours. The position of the single photo-electron peak in Fig. 12a was estimated to be $12.1 \pm 0.1$ counts by fitting with a convolution function of Poisson and Gaussian distributions. The ADC distribution in Fig. 12b shows a minimum-ionization peak caused by cosmic-ray muons passing through the module, where the horizontal scale has been converted to the number of photo-electrons ($n_{\text{p.e.}}$) using the factor of 12.1 counts/p.e. obtained above.

To obtain the mean value of the light yield, we used the following function.
of a Gaussian with an exponential tail to fit to the ADC distribution,

\[
f(x) = \begin{cases} 
  A \exp \left[ -\frac{(x - x_p)^2}{2\sigma^2} \right] & (x \leq x_b) \\
  B \exp[-\lambda(x - x_b)] & (x > x_b)
\end{cases}
\]

where \( A \) denotes the peak value of the Gaussian at \( x = x_p \) and \( B \) is the value at the boundary of the two functions \( (x_b) \). Note that the parameters \( B \) and \( \lambda \) are determined under the continuity condition of the two functions at the boundary \( x_b \); there are four free parameters, \( A \), \( x_p \), \( x_b \), and \( \sigma \), in the fitting calculation. For the OEV module used in Fig. 12b, the mean value was calculated to be \((129.3 \pm 1.5)\) p.e. from the first moment of the fitted function. In the same time, we estimated the average energy deposit in the plastic scintillators of this module to be 6.24 MeV, assuming that the energy deposit and the average path length of cosmic-rays in the scintillator to be 2.08 MeV/cm and 30.0 mm, respectively. Thus, the mean light yield of this module was \((20.7 \pm 0.2)\) p.e./MeV.

Figure 13a shows the histogram of the mean light yields for all the modules collected with the middle trigger counters. The mean and the standard deviation of the light yield for 64 modules were 20.9 p.e./MeV and 2.8 p.e./MeV, respectively. The minimum light yield among the 64 modules was 16.2 p.e./MeV for a type-2 module, and it is sufficient to detect the energy deposit of 1 MeV.

To check the position dependence along the fiber direction, we plotted the ratios of the light yield at the upstream and the downstream ends to the yield measured at the middle as shown in Fig. 13b and 13c. The dependence shows a similar tendency among all the OEV modules; that is, less light yields near the front face and more yields near the rear side. The differences of the ratios were 5%, corresponding to the effective attenuation length of 350 cm mainly due to the light attenuation in the WLS fibers. The minimum light yield of the three measured points among all the OEV modules was 15.4 p.e./MeV at the upstream for a type-2 module. They are well within the requirement.

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6The energy deposit in the plastic scintillator based on the MS resin, 2.08 MeV/cm, was calculated as a mixture from the \( dE/dx \mid_{\text{min}} \) values of polystyrene and acrylic described in Ref. 8, in which the density of the MS resin was assumed to be 1.075 g/cm³.
Figure 13: (a) Distribution of the mean light yield collected with the cosmic rays passing through the middle trigger counters for all the 64-OEV modules. The mean light yield taken with (b) the upstream and (c) the downstream trigger counters were plotted as the ratio to the middle one. The mean and the root mean square (RMS) of the distributions were calculated.
4.4. Time resolution

In the KOTO experiment, the time resolution of veto counters determines the time window for photon veto, which is directly related to the acceptance loss of the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ signal due to the accidental hits. For example, in order to keep 1% acceptance loss, the time resolution of the OEV counters should be less than 10 ns under an accidental rate of 100 kHz by assuming a veto time window of $\pm 5\sigma$ ($= 100$ ns). In this section, we evaluated the time resolution of the OEV counters and its position dependence with two different conditions: (1) in a bench test: using VME TDCs with the same setup as the light yield measurement, and (2) in the real condition: using 125 MHz waveform digitizers used in the readout of the KOTO experimental setup.

4.4.1. Time resolution evaluated in the bench test

The detector setup in the bench test was the same as the light yield measurement described in Section 4.3.1. One of the output signals was processed with a constant fraction discriminator (CFD) Phillips Scientific 715. We set the CFD threshold to be -150 mV, which corresponds to $17.3 \pm 2.6$ p.e. The time difference between the trigger signal and the output signal from the CFD was digitized with a 12-bit CAEN V775 TDC [23] with a full range of 150 ns. The timing of the trigger signal for each pair of the trigger counters was determined by the bottom ones.

In the data analysis, we obtained the time resolution of each OEV module by fitting a Gaussian to the time-difference distributions between each OEV module and the bottom trigger counters. The contribution from the timing spread due to the three sets of trigger counters were measured to be 0.162 ns (upstream), 0.206 ns (middle) and 0.218 ns (downstream), respectively\footnote{These values were obtained from widths of the time-difference distributions of each pair of the trigger counters by assuming the equal time resolution for the both trigger counters.}, and they were subtracted quadratically.

The scatter plot in Fig. 14 shows the time resolutions of the OEV modules for different light yields with an interval of 10 photo-electrons. The resolutions of all the OEV modules except for the data with low statistical precision ($> 20\%$) were shown. Note that the data points at lower light yields are dominated by the modules having thinner or smaller scintillator layers because the energy deposit in the scintillators depends on the path length of
Figure 14: Time resolution of the 64 OEV modules measured with the middle trigger counters as a function of the number of photo-electrons (open circles). Note that the data having the statistical errors less than 20% are plotted. The weighted-mean values of the time resolutions for different $n_{\text{p.e.}}$ bands are also shown as the closed squares. The dotted curve denotes the fitted function of Eq. 1 in the text, where $a = 6.4 \pm 0.2$ ns/p.e. and $b = 0.49 \pm 0.02$ ns.
Figure 15: Position dependence of the time resolution for three bottom OEV modules. The path length of the cosmic-rays in the scintillators in each type of modules is different from others; thus, the time resolution in this plot is also different. The mean energy deposits in the scintillators are estimated to be 1.7 MeV, 3.6 MeV and 6.3 MeV for the type-2, type-5 and type-8, respectively.

cosmic-rays; the average thickness of the scintillators distributes from 7.7 mm (for type-2) to 33.4 mm (for type-8). The results imply that the resolution is dominated by the statistical fluctuation of the number of photo-electrons. In order to check this, the weighted mean of the resolution among the data with the same light yield bin was calculated, showing a monotonic decrease in the light yield (see the filled squares in Fig. [14]). With Poisson statistics, we fitted the following empirical function to the plot,

$$
\sigma_t = \frac{a}{\sqrt{n_{\text{p.e.}}}} + b,
$$

where $\oplus$ denotes the square root of the quadratic sum and $a$ and $b$ are free parameters. From data shown in Fig. [14] the light yield dependence of the time resolution can be represented by the function with the parameters $a = 6.4 \pm 0.2$ ns/p.e. and $b = 0.49 \pm 0.02$ ns. This relation determines the typical value of the time resolution to be 1.5 ns for the energy deposit of 1 MeV, which is obtained by using the mean light yield 20.9 p.e./MeV described in Section 4.3.2.

The typical longitudinal-position dependence of the time resolution is shown in Fig. [15] for three type of modules (type-2, 5, and 8). We observed

22
that the time resolution was 13% worse at the downstream position although the light yield was 5% larger at this location as discussed in the previous section. This tendency for all the OEV modules originates from the time spread of re-emitted photons from the WLS fibers. In reality, optical path difference in WLS fibers between reflected photons at the front surface of each module and the direct photons toward the PMT is 6 cm, 42 cm and 78 cm at the three positions of the trigger counter. With the propagation velocity of 17.5 cm/ns [13], these cause the time difference of 0.3 ns, 2.4 ns and 4.5 ns, respectively, in the direct and reflected photons. As a result, the photon-detection time spreads with the optical path difference in combination with the decay time of the WLS fiber ($\tau = 6.8$ ns [13]). Although the position dependence of the time resolution is not significantly large, the dependence should be taken into account for the setting of the veto timing window.

4.4.2. Time resolution evaluated in the FADC readout

In the KOTO experiment, the timing information of the OEV counters is extracted with the analysis of the waveforms recorded in the 125 MHz flash ADC (FADC) [21]. Here, we will discuss the time resolution measured with the FADC readout.

The measurement was performed for two OEV counters, OEV-10(top) and OEV-33(bottom) at seven months after the installation of the OEV counters to the endcap in February 2011. Four pairs of trigger counters having the length of 200 cm were set horizontally at the top and bottom of the OEV counters with an interval of about 4 m as shown in Fig. 16. The size of each trigger counter was 10 cm wide and 5 cm thick. By requiring a coincidence in a pair of the top and bottom trigger counters, one can select signals of the cosmic-ray passing vertically through four 10 cm-regions of the OEV counters. The average energy deposits are estimated to be 6.5 MeV and 6.2 MeV for OEV-10 and OEV-33, respectively. We applied the same voltage of 850 V to the PMTs.

In common with the KOTO data acquisition (DAQ) system, analog signals from the OEV counters were digitized with the 125 MHz FADC. A 10-pole low-pass filter with the function of stretching the pulse shapes to a Gaussian form was utilized to accommodate the 8 ns sampling interval. Figure 17 shows the typical pulse shapes of the raw and the filtered signals. The timing was defined as the rising time at half maximum from the fitted Gaussian function to the recorded waveform.

For the time resolution, we obtained the width ($\sigma$) of the time differential
Figure 16: Setup of trigger counters for the time resolution measurement of OEV-10 and OEV-33, which located in the middle of the top and the bottom of the endcap, with cosmic-rays. Four pairs of trigger counters are set horizontally at both sides of the endcap with orthogonal direction to the OEV counters. Each trigger counter, which is made of plastic scintillator (10 cm wide and 5 cm thick and 200 cm long), is read out from both ends with two PMTs. With this setup of the trigger counters, the active length of the OEV counters (42 cm) is divided into four regions.
Figure 17: Typical waveform of a cosmic-ray signal recorded (a) with a 1 GHz digital oscilloscope (Tektronix DPO4104) and (b) with the 125 MHz flash ADC after the 10-pole low-pass filter. The closed squares show 64 sampling points of the flash ADC and the dashed lines are the segmented lines connecting 2 adjacent sampling points.
Figure 18: (a) Time-difference distribution between OEV-10 and OEV-33 at the most upstream region. The curve shows the fitted Gaussian. (b) Position dependence of time resolution of OEV-10 and OEV-33 obtained from the time difference distribution. The line shows the weighted mean of four regions.

ence distribution between the top and bottom OEV counters (see Fig. 18a). Figure 18b shows the time resolution at the four divided regions. They were obtained with $\sigma/\sqrt{2}$ by assuming the equal time resolution for both the OEV counters. Since there is no significant position dependence within this rather large error, we concluded that the time resolution measured with the FADC was $0.62 \pm 0.04$ ns from the weighted mean of the four data points. This result is consistent with the mean time resolutions at the three positions evaluated by the bench test described in the previous section. This implies the readout method with the low-pass filter and the 125 MHz FADC does not worsen the timing performance significantly.

5. Energy calibration with cosmic-ray muons

An energy calibration method with cosmic-ray muons was developed for the data taking period. Because of the trapezoidal shapes and the two dif-
ferent directions of stacking layers of the OEV counters, the path length of
the muon in the scintillators of each counter depends upon the incident po-

tion and angle. Thus, the energy distribution in some OEV counters shows
no peak structure for cosmic-ray muons, and a simple calibration method
with the minimum ionization peak will not work. We tried to establish the
method of obtaining the calibration constants (ADC counts/MeV) for all the
counters by fitting the ADC distribution generated by a Monte-Carlo (MC)
simulation to the experimental data.

5.1. Experimental condition and readout electronics

In the data taking period, calibration data is recorded during the 2 sec-

onds beam-off period out of the 6 seconds acceleration cycle. We analyzed
calibration data of about 3 days taken in May of 2013 with the beam power
of 23.8 kW ($2.98 \times 10^{13}$ protons/pulse). The PMT gains of the OEV counters
were tuned to $2 \times 10^6$. All the PMTs operated stably without any discharge
during the data-taking with the vacuum less than 0.1 Pa. Because of the lim-
ited number of sensors, the temperature was monitored for only two PMTs
(OEV-10 and OEV-22) with thermocouples. The means of the recorded

temperatures were 26.5°C and 32.0°C for OEV-10 and OEV-22, respectively.
Their variations were within ±0.5°C.

The DAQ system for the calibration data was triggered when the to-
tal energy deposit in the CsI calorimeter was greater than 600 MeV. This
rather high-energy threshold requires cosmic-ray muons to have long track
length in the calorimeter (> 77 cm), and reduces backgrounds due to low-
energy showers. (98 ± 1)% of the triggered events were originated from
cosmic-ray muon tracks, which were estimated by a careful eye scan of
event displays. The trigger rate was 40 Hz, and $4.8 \times 10^4$ triggered events
(= 80 triggers/cycle × 600 cycles/h) were accumulated for 1 hour of data
taking.

In the data analysis, we integrated the FADC values of the 64 8-ns sam-

dles (Fig. 19). The pedestal was set by the mean value of the first 10 sampling
points. The black points in Fig. 19 show the integrated ADC distributions

\[8\] The acceleration cycle in the slow-extraction mode at J-PARC consists of a beam-on
period of 2 seconds and a beam-off period of 4 seconds.

\[9\] The temperature for OEV-10 was lower because this counter was just behind a thick
stainless plate, where the heat radiated from many CsI calorimeter PMTs was shielded.
Figure 19: Integrated ADC distributions for 4 typical OEV counters with 10 hours of data taking (black points). The location of each counter is also illustrated in each plot. The red lines show the ADC distributions generated by the Monte-Carlo simulation after the energy to ADC conversion with the calibration constants, which is described in the end of section 5.3. The Monte Carlo distributions are scaled to the data in the range of ADC > 1500 counts, which is indicated by the blue arrows.
for 4 typical OEV counters with 10 hours of calibration data. The distribution for OEV-10, which is located at the top part of the endcap, shows a pronounced peak at around 3500 ADC counts, because the path length of the cosmic muons in the scintillator plates is nearly constant. On the other hand, OEV-2, which is located at the side region, has just a small bump-like structure since the path length has large variation due to triangle shape of the module and the vertical stacking direction.

5.2. Simulation of cosmic-rays

Monte-Carlo simulation code based on Geant4 \cite{15} was used to calculate the energy deposit in each OEV counter. In this code, we implemented geometry and materials of all the detectors for the KOTO experiment shown in Fig. 1. In addition, radiation-shielding concrete blocks (2.3 g/cm$^3$) covering the whole setup was also included. The shield is 1 m or more in thickness with a realistic geometry.\footnote{\textsuperscript{10} The material definition of the concrete was based on the NIST database \cite{24}.} The installation accuracy of the OEV counters is 1 mm originated from the deformation of the cylindrical support structure of the endcap.

In the simulation, the momenta of the cosmic-ray muons ($p_\mu$) and the zenith angles ($\theta$) were generated based on the following distribution of the muon intensity

\[ I(p_\mu, \theta) = \cos^3 \theta \cdot I_V(p_\mu \cos \theta) \] (2)

which reproduces experimental data observed at ground level in the range of $p_\mu > 1$ GeV \cite{25}. Considering the high trigger threshold and energy loss in the shielding concrete (> 390 MeV), we can safely neglect the cosmic-ray muons below 1 GeV. The source positions of the muons were extrapolated to infinite distance so that incident positions at the detector were distributed uniformly in the horizontal plane with an area of 9.0 m (along the beam direction) $\times$ 7.6 m (perpendicular to the beam direction). Thus, the incident muon momenta at the OEV counters were slightly lower than the generated momenta because of the energy loss at the surrounding materials such as the CsI crystals, MB, and the shielding concrete. By limiting the source area, the simulation time can be reduced without a significant loss of primarily generated muons, for shallow incident angle, in particular.
For energy smearing, we generated the number of photo-electrons \(n_{\text{p.e.}}\) in each counter based on the Poisson distribution. Here, the mean value of the distribution \(\langle n_{\text{p.e.}} \rangle\) was obtained from the energy deposit in the scintillators \(E_{\text{dep}}\) and the average light yield of all OEV modules \(Y = 20.9 \text{ p.e./MeV}\) with \(n_{\text{p.e.}} = Y \cdot E_{\text{dep}}\). The number of photo-electrons was smeared again with a Gaussian of width \(\sigma = 0.48 \sqrt{n_{\text{p.e.}}}\) by taking the fluctuation of the dynode amplification of the PMTs into account as described in Section 4.2.1. The energy deposit was finally given by \(n_{\text{p.e.}}/Y\).

5.3. Calibration method

Firstly, we generated the ADC distributions in the MC simulation for each OEV counter assuming various conversion factors of energy deposit to the ADC counts in the range of 400 to 1000 ADC counts/MeV, as shown in Fig. 20. The generated MC distributions were scaled to the experimental distribution in the range above 1500 ADC counts. Note that the threshold value was set to remove accidental noise at low energy. In the example of Fig. 20, the optimum conversion factor is expected to be 550 ADC counts/MeV.

Figure 20: ADC distribution for OEV-33 with 10 hours of calibration data (black points). Three histograms show the ADC distributions generated with different conversion factors. The MC distributions are scaled to the data in the range of ADC > 1500 counts, which is indicated by the blue arrow.
Figure 21: $\chi^2/N_{\text{bin}}$ as function of the conversion factor for the same OEV counters shown in Fig. [19]. The $\chi^2/N_{\text{bin}}$ reduces when the degree of consistency between the data and the MC distributions becomes high, approaching to unity if the distributions are consistent within the errors. The curves show asymmetric parabola functions fitted to each plot around the minimum.

In order to find the best value of the conversion factor, we introduced the following $\chi^2$ value for the histograms,

$$\chi^2 = \sum_{i} \frac{N_{\text{bin}}}{\sigma_{\text{data},i}^2 + \sigma_{\text{MC},i}^2} \frac{(n_{\text{data},i} - n_{\text{MC},i})^2}{n_{\text{data},i} - n_{\text{MC},i}}$$

(3)

where $n_{\text{data},i}$ and $\sigma_{\text{data},i}$ denote the counts and the error of the $i$th bin for the data, and $n_{\text{MC},i}$ and $\sigma_{\text{MC},i}$ are those for the MC distribution, $N_{\text{bin}}$ represents the total number of bins in the summation\textsuperscript{11}. Figure [21] shows the $\chi^2/N_{\text{bin}}$ values as a function of the conversion factor for the same OEV counters shown.

\textsuperscript{11} In the summation, the data points with $n_{\text{data},i} < 4$ were excluded; thus the value of $N_{\text{bin}}$ depends on the statistics of data. Typical $N_{\text{bin}}$ values were 66 for OEV-10 and 42 for OEV-2, with 10 hours data.
in Fig. 19. Asymmetric parabola functions fitted to these plots have the minimum values close to unity at 500-700 ADC counts/MeV, which indicated that good calibration constants were obtained in the calibration method.

5.4. Discussion

With the conversion using the calibration constants obtained above, the ADC distributions generated by the MC simulation were superimposed on the experimental data as shown in Fig. 19. The experimental distributions are in good agreement with the MC distributions. The minimum values of $\chi^2/N_{\text{bin}}$ ranged from 0.7 to 2.0 for all the OEV counters.

The sharpness of the parabola in Fig. 21 represents the precision of estimates for the calibration constant. It depends on both the statistics of the data and the shape of the ADC distribution. A quantitative estimate of the calibration error was the intersection distance at the minimum $\chi^2$ plus 1 (confidence interval of 68%). Figure 22 shows the relative calibration errors for all the counters with different amounts of data-taking period (1, 3, 5, 10
hours). We found that the smallest errors were obtained for OEV-10, 11, 32, 33 (type-0 modules located at the top and bottom part), which showed pronounced peaks in the ADC distributions. On the other hand, large calibration errors were obtained for OEV-2, 3, 19, 24, 42 (counters located near the side region), which showed small bump-like structures in the ADC distributions. The calibration error with 1 hour of data was estimated to be 1% in the best case and 11% in the worst case. Even in the worst case, the error can be easily reduced to be 3% by summing the data for 3 hours. The calibration method works well for various shapes of the ADC distributions with the accuracy of a few percent.

Stability of the light yield can be monitored by checking the time variation of the calibration constant. Figure 23 shows the variation for four OEV counters, showing stable light yield during the data collection period (3 days). This was also true for the other OEV counters (the range of reduced $\chi^2$ was 0.51-1.58). The gain variation of the PMTs was thought to be well below the sensitivity limit of the calibration. For example, the gain variation coming from temperature change is expected to be small ($< 0.2\%$) since the temperature variation was within $\pm 0.5^\circ C$ in this period. On the other hand, other factors of light yield variation, such as aging deterioration of light transmission in the scintillators and/or the WLS fibers could cause longer time degradation. The long-term stability can be monitored with an accuracy of a few percent for all the OEV counters with the accumulation of 3 hours data.

In conclusion, the energy calibration method for the OEV counters described in this section satisfies the purpose of calibrating the light yield variation with a sufficient accuracy during the data-taking of the KOTO experiment.

6. Summary

We built and operated the OEV counter subsystem as a part of the KOTO experiment at J-PARC with an extra-photon detection capability for 1 MeV deposited energy. The subsystem consists of 44 lead-scintillator sandwich type counters (64 modules) with different cross sectional shapes. They were installed between the CsI crystal and the support cylinder in the endcap.

\footnote{The temperature coefficient of the gain is typically $-0.31\%/^\circ C$ for Hamamatsu R1924A.}
Figure 23: Time variation of the calibration constants for the same OEV counters shown in Fig. 19. The larger error bars for OEV-2 and OEV-22 are attributed to the relatively large calibration error among the OEV counters (see Fig. 22). The straight lines show the constant functions fitted to the plots.
We measured the performance of the counters, and confirmed they meet the requirements for the KOTO experiment. Light yield and time resolution were measured for each module with cosmic-rays before the installation. The mean light yield and the standard deviation of 64 modules at the middle of the counter were $20.9 \pm 2.8 \text{ p.e./MeV}$. The minimum light yield in the whole counter area was $15.4 \text{ p.e./MeV}$, which is large enough to detect 1 MeV energy deposit. Position dependence of light yield along the fiber direction was 5% for all the counters. Time resolution dependence on the light yield, $6.4 / \sqrt{n_{\text{p.e.}}}$ $\oplus 0.49 \text{ ns}$ was observed. At the energy deposit of 1 MeV, time resolution was 1.5 ns. The time resolution was measured for a pair of type-0 counters with the KOTO 10-pole low-pass filter 125 MHz waveform digitizer. The results were consistent with those obtained with the constant fraction discriminators and TDCs.

An energy calibration method using cosmic-rays during no-beam period was developed. Stable light yields was observed for all the counters for the physics experiment. We confirmed that the calibration method works well for various shapes of the OEV counters and different stacking directions with accuracy of a few percent.

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