Sampling calorimeter to measure the photon's incident angle

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Abstract. A three-dimensional fine-segmented sampling calorimeter enables us to measure the profiles of generated shower particles along the photon's direction. For a feasibility study, a toy detector was designed via Geant4 simulation. It consists of alternating layers of a 1-mm-thick lead absorber and a 5-mm-thick plastic scintillator. The plastic scintillator is segmented into 15-mm-wide strips, alternately oriented in the vertical and horizontal directions. The energy deposits of each strip are used to train the machine learning algorithm (XGboost) to deduce the given angle, and the resolution of its angle reconstruction is expected to be 1.3 degrees for 1 GeV photon. We fabricate a small sampling calorimeter to validate the simulation results. We use 0.15-mm-thick tungsten strips instead of lead plates and 1mm-square scintillating fibers instead of plastic scintillators for better energy resolution. This updated configuration indicates no significant difference in the angular resolution, while the energy resolution significantly improves. Its performance shows a reasonable agreement between the Monte Carlo expectation and the obtained data with a positron beam. A detailed study is underway to understand the measured data thoroughly.

1 Introduction

The measurement of photon direction in the calorimeter is typically considered optional in accelerator-based experiments, having additional equipment to determine it precisely. Nevertheless, this capability is indispensable in astrophysics experiments for pinpointing the sources of arriving photons[1] [2] [3] [4], as well as in specialized experiments dedicated to specific observations[5] [6].

The KOTO experiment at the Japan Proton Accelerator Research Complex (J-PARC) [7]) is searching for the $K_L \to \pi^0\nu\bar{\nu}$ decay, which could provide insights into the physics beyond the standard model (SM) even if its energy scale is more than 100 TeV. Currently, the experiment's sensitivity is $2.0{\times}10^{-9}$[8], which is still far from the SM expectation of 3×10^{-11}[9]. A follow-up experiment, KOTO-II[10], is under preparation to observe several tens of events based on the SM expectation.

The $K_L \to \pi^0\nu\bar{\nu}$ decay is identified by the two photons measured at the calorimeter and no other accompanying particles confirmed by the hermetic veto system. It is challenging to search for decay due to the substantial background because of its extremely small branching fraction and weak kinematical constraints related to the unique observable being a single neutral particle from the three-body decay. That is, a background rejection is a critical issue in the experiment. A well-reconstructed π^0 defines the signal event, which assumes that the two photons are generated from π^0 decaying on the beam axis. Thus, the K_L beam should be a well-collimated small cross-sectional beam.

However, a tiny amount of K_L enters the detector far from the beam axis due to the scattering by the beamline material. When this halo K_L decays into the two photons ($K_L \to \gamma\gamma$ decay), the current reconstructing method will misidentify this process as a signal. Even though the expected background level of this event is still small at the current experimental sensitivity, a further rejection ability at the KOTO II will be required. When we obtain additional information on the photons (incident angle) directly, we can use consistency between the measurement and calculated result from the reconstruction for the background rejection.

Given that the electromagnetic (EM) shower develops along the photon's direction, we can extract information by examining the shower profile in the calorimeter. The main question is what level of angular resolution can be achieved from this analysis and what critical factors determine the performance. In the context of the KOTO II application, developing a cost-effective method to achieve 1~2 degrees of angular resolution for the 1 GeV photon is crucial.

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We will present a simulation study [11] based on the Geant4 and a package of the machine learning technique, XGBoost (XGB) [12], in section 2. A description of the detector fabrication and performance test for validating the simulation results is in section 3, and a summary is in the concluding section.

2 Feasibility study with simulation

The feasibility of angle measurement is studied with a toy sampling calorimeter, which enables us to consider various designs to obtain three-dimensional information on the EM shower. We start the study with a familiar configuration of alternating sheets of lead and plastic scintillators of 1 mm and 5 mm in thickness, respectively. The angular resolution depends on how precisely we get information on the shower profile and how we connect it to the photon's direction.

2.1 Detector configuration

Figure 1 shows a schematic view of the detector consisting of alternating layers of lead absorber and plastic scintillator. The plastic scintillator is segmented into 15-mm-wide strips, alternately oriented in the vertical and horizontal directions. It has a cross-section of 525 × 525 mm^2 and accommodates 105 alternating layers of 630 mm length, which corresponds to 20 radiation lengths (20 X_o) to contain the EM shower of photons for energies in the range of 0.1 to 2 GeV.

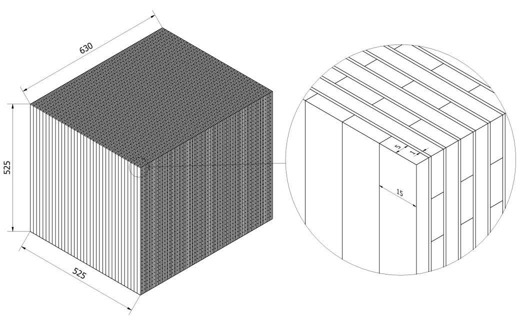

Figure 1. Schematic view of the sampling calorimeter consisting of alternating lead sheets and fine-segment plastic scintillator strips for the feasibility study of the photon's angle measurement.

The Geant4 generates the EM shower in the calorimeter, and the energy deposited into each scintillator strip from the shower particles is recorded. This distribution of energy deposit represents a shower profile indicating the incident angle of the primary photon. The photon direction is defined by the polar angle (θ) with respect to the normal to the front surface of the detector.

2.2 Angle reconstruction

The angle is reconstructed using the XGB, an optimized distributed gradient-boosting library [12]. It maps a feature dataset onto a target variable. Here, the feature dataset and the target variable correspond to the energy deposit in each scintillator strip and the incident angle of a photon, respectively. The feature dataset size is the number of strips; hence, it varies inversely to the strip width to have the same coverage. When the width of the strip becomes narrower, the number of features increases, resulting in a more precise description of the profile. On the other hand, the XGB requires much more training to utilize the increased information.

Fig. 2 represents an example of the angle reconstruction, a distribution of the relative incident angle ($\Delta\theta$) for 1 GeV photons generated at $\theta = 10^0$. The $\Delta\theta$ is calculated with the radial displacement of the reconstructed incident angle relative to the actual direction. The distribution deviates from the Gaussian distribution, and the General Gaussian (GG) function is used to describe it. The GG function is expressed as

$$f(x;\mu,\alpha,\beta) = \frac{\beta}{2\alpha\Gamma(1/\beta)} e^{-(|x-\mu|/\alpha)^\beta}, \quad (1)$$

where μ is the mean value. The parameters α and β determine the scale and shape of the distribution, respectively. The variance in the GG function is given by $\sigma^2 = \alpha^2\Gamma(3/\beta)/\Gamma(1/\beta)$ and the angular resolution is defined as σ that is equivalent to the Gaussian distribution's sigma when β=2.

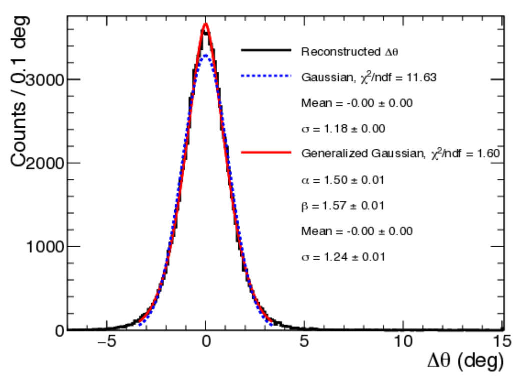

Figure 2. Distribution of relative incident angle ($\Delta\theta$). The data indicates that the generalized Gaussian distribution fits better than the standard Gaussian distribution.

2.3 Expected performance

Figure 3 displays the angular resolution for different widths based on the number of training samples. The width of each curve represents the statistical uncertainty. The narrower strips ultimately provide a better angular resolution when the XGBoost is fully trained with adequate samples. Additionally, there is no significant difference in resolution when using only the front 32 layers compared to all 105 layers, especially with narrow strip widths. It suggests a thin angle measurement detector be placed in front of the main calorimeter. With 32 layers of 15mm wide strips and 10^5 training samples, we could achieve an angular resolution of 1.3 degrees.

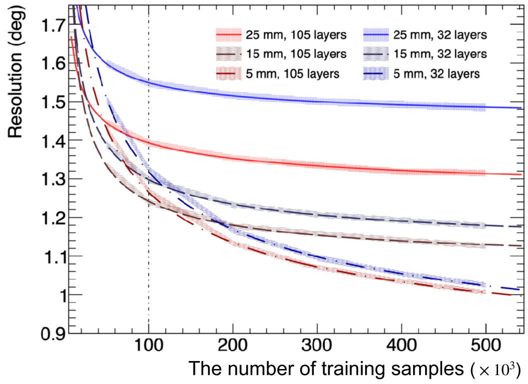

Figure 3. Angular resolution for the different widths of the strips as a function of the number of training samples.

The energy resolution of the sampling calorimeter may degrade due to unavoidable fluctuations in the energy deposit. To address this, the detector should have multiple layers of thin absorbers. Five layers of "1 mm Scintillation Fiber + 0.15 mm Tungsten" can help suppress the sampling fluctuations and improve energy resolution compared to the current method, which uses a single layer of "5 mm Scintillator + 1 mm lead," as shown in Fig 4. Both configurations have similar radiation length and visible ratio. Also, the angular resolution is estimated to be the same.

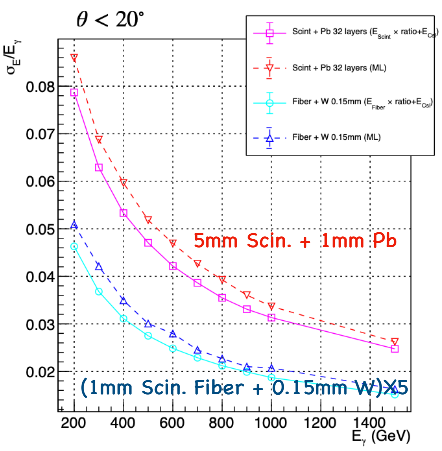

Figure 4. Energy resolution for different thicknesses of absorber layers.

3 Detector for validating the simulation results

A small detector named PAScal (Photon Angle Sampling calorimeter) was fabricated to validate the simulation results, mainly focusing on the angular and energy resolutions. It has 24 layers, each with 16 modules alternatively aligned in the horizontal and vertical directions. The module consists of five layers of alternating 1 mm-square scintillating fibers and 0.15 mm thick tungsten strips, considering the energy resolution mentioned in the previous section. Its width is 14 mm. The total number of modules is 384, and the detector has an effective cross-section of 239 mm×239 mm and a thickness of 167 mm, corresponding to 5.36 radiation lengths.

The detector performance is tested with a positron beam produced by the 1.3 GeV electron synchrotron at the Research Center for Electron Photon Science (ELPH), Tohoku University [13]. By changing the incident momentum and angle of the positron beam, we accumulate more than 10^5 events for each beam condition. The obtained results are understudying with a comparison to those of the Monte Carlo simulation.

3.1 Test module fabrication

Figure 5 shows a process of producing a module. Fourteen scintillation fibers are tightened to a tungsten strip to form a sheet (a). The module is stacked with the five sheets (b) and glued with the optical cement, EJ-500 (c). After polishing with a grit #1500 sandpaper (d), a light guide made of ABS resin is attached to the module (e). The MPPC, Hamamatsu C13360-6050PE, is filled in the rectangular hole of the light guide with a 5 mm air gap between the fiber's edge and the MPPC's surface. 16 MPPCs are aligned in a board (MPPC board) (f), and the same number of modules are attached to be a detector layer. A total of 24 layers are fabricated and stacked to be the PAScal.

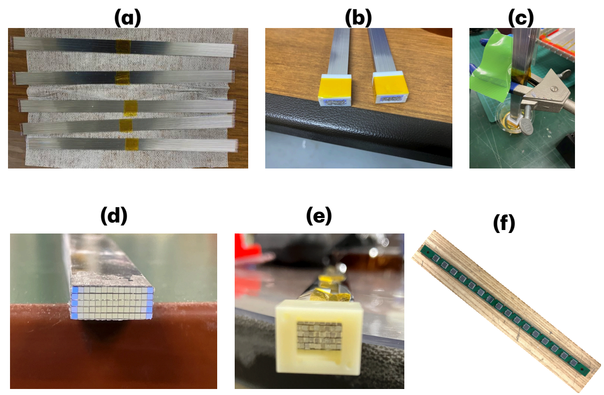

Figure 5. Selected photos showing a process of module production.

The charge produced by the MPPC is converted to the voltage signal with 50 ohms at the MPPC board and handed to the pre-amplification board through flexible flat cables (FFC). 12-pin FFC connects to the 4 MPPCs, and four cables are used between one set of the MPPC board and the pre-amplification board. Two pre-amplification boards connect to one DAQ module to provide the MPPC's operating voltage and record the signal to the 14-bit ADC with a 62.5 MHz digitizer. Each DAQ module communicates with a PC through a USB3 cable for data transmission at a speed of better than 400MB/s for each of the 32 channels.

3.2 Performance test with positron beams

Figure 6 shows the setup of the data taking with a positron beam, placing the PAScal in front of the 5×5 array consisting of CsI crystals of 7 cm × 7 cm × 30 cm(length). The positron beam is defined by the triple coincidence of three plastic scintillators of 1.6 mm×1.6 mm×5 mm(thickness) placed along the beam axis and enters the center of the detector.

The data was taken at four different momenta (200, 400, 600, and 800 MeV/c) and incident angles (0, 10, 20, and 30 degrees). In addition, the data of the CsI array without the PAScal is obtained to study the degradation of energy resolution due to the PAScal.

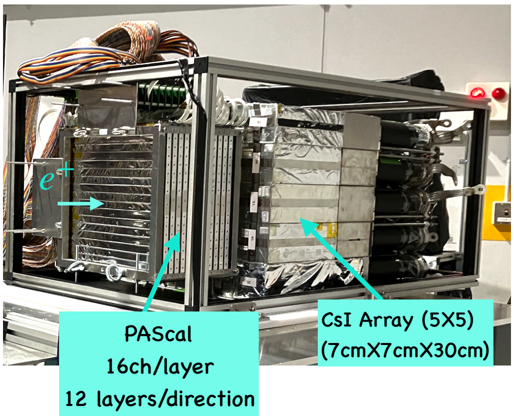

Figure 6. Detector setup for performance test with a positron beam.

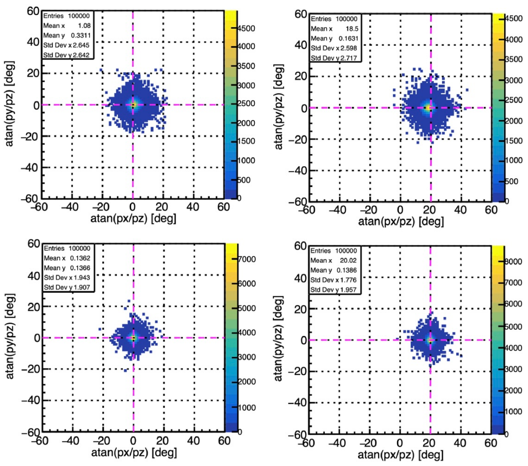

Figure 7. The first glance of obtained data. The detector indicates proper incident directions of 0^0(left) and 20^0(right); however, the obtained angular resolution (top) is worse than the simulated expectation (bottom).

The energy calibration for all channels uses data taken during the beam break at night with cosmic rays. As shown in figure 7, the incident angle is correctly reconstructed for each data set; however, the angular resolution is worse than expected, especially in the low momentum data set. This result is similar to the data from different angles, and a detailed study is being conducted to understand the reason for the differences.

4 Summary

The photon-direction measurement of the calorimeter could be an essential experimental tool for the KOTO searching for the $K_L \to \pi^0\nu\bar{\nu}$ decay. The additional information can provide further rejection power against background events related to the π^0 decays far from the beam axis. A fine-segment sampling calorimeter is a good candidate for the detector. The simulation study with a toy model based on the Geant4 and the XGBoot indicates that the expected angular resolution for a 1 GeV photon is to be 1.3 degrees, which is a green light to apply to the next-generation experiment, KOTO II.

A prototype calorimeter, PAScal, was constructed to verify simulation results on photon-angle measurement. Its performance was evaluated using positron beams ranging from 200 MeV/c to 800 MeV/c at incident angles from 0 to 30 degrees. The measurement data indicates reasonable agreement with the simulation expectations. Further study is ongoing to gain a clearer understanding.

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