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Development on Electromagnetic Calorimeter for COMET/PRISM

T. Tachimoto*, Y. Eguchi, and A. Sato
Depertment of Physics, Osaka University, 1-1 Machikane, Toyonaka, Osaka 560-0043, Japan
E-mail: tachimoto@kuno-g.phys.sci.osaka-u.ac.jp

R&D on an electromagnetic calorimeter system with MPPC readout is underway for the future μ^- - e^- conversion: COMET and PRISM. Design study was performed using a geant4 based simulation with its optical photon package. The required energy resolution was achieved for GSO(Ce) and PWO crystals with MPPC readout.

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*Speaker.

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1. Introduction

A muon is never converted with an observable branching ratio to an electron/positron without neutrinos in the Standard Model of elementary particle physics[1]. Physicists, however, believe that the Standard Model is not perfect theory to describe the Universe. Physics beyond the Standard Model is required. Two experiments, COMET[2] and PRISM[3] , are proposed in Japan to search for coherent neutrino-less conversion of muons to electrons in the presence of a nucleus (μ^- - e^- conversion). This process has been never observed. A discovery of the process indicates the physics beyond the Standard Model. In these experiments, an electromagnetic calorimeter system is installed to trigger signal events using their energy information. The calorimeter is required to work with enough energy resolution under 1 T magnetic field and high radiation environment. Inorganic scintillating crystals readout by MPPCs (Multi Pixel Photon Counter) are studied as a candidate of the calorimeter system. R&D status of this study is described in the following sections.

2. Electromagnetic Calorimeter for COMET/PRISM

Figure 1 shows a schematic layout of the COMET and its calorimeter system. A high intense proton beam hit the pion production target to produce pions and muons. They are collected by a solenoidal magnetic field, and transported to the stopping target. A μ^- - e^- conversion process emit one electron with 105 MeV. The signal particles are transported through the curved superconducting magnet, which works as a spectrometer to select the signal events, then hit the tracking chambers and the calorimeter. All apparatuses are located in the superconducting magnets.

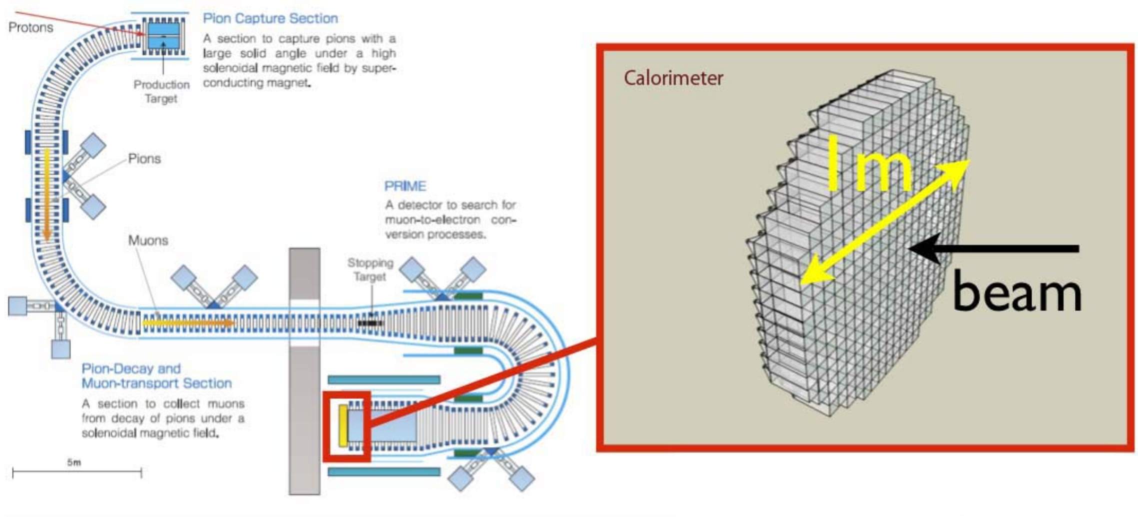

Figure 1: Schematic layout of the COMET and its calorimeter system.

The calorimeter is positioned downstream of the tracking chamber and serves three purposes: to measure the energy of electrons with energy resolution $\sigma_{E_e} < 5\%$ for 105MeV to achieve an efficient trigger efficiency, to provide a timing signal for the trigger, and to provide additional position information on the electron track trajectory correlating the measured energy with the track. Requirements on the calorimeter are summarized in Table 1.

Table 1: Requirements on the COMET calorimeter system.

Energy resolution	< 5 %
Time response	< 100 ns
Position resolution	∼1 cm

A present conceptual design of the COMET calorimeter consists of segments of an inorganic scintillating crystal connected to a photon detector through a light guide, as illustrated in Fig. 2.

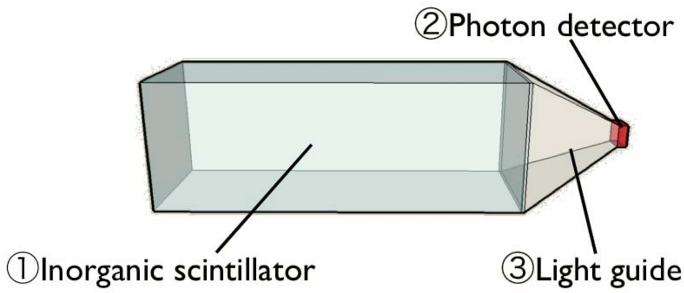

Figure 2: Conceptual design of a segment of the calorimeter.

The crystals need good light yields, fast time response, fast decay time to reduce pile-up, high density, and small Moliere radius, in order to fulfill the above requirements. Table 2 compares various scintillating crystals, which have a large light yield and a small decay constant. GSO(Ce) and LYSO are attractive crystals in view of their performance. In the next section, we describe results using GSO(Ce) crystals.

Table 2: The characteristics of inorganic scintillator crystals. (s: slow component, f: fast component)

	GSO(Ce)	LYSO	PWO	CsI(pure)
Density (g/cm^3)	6.71	7.40	8.3	4.51
Radiation length (cm)	1.38	1.14	0.89	1.86
Moliere radius (cm)	2.23	2.07	2.00	3.57
Decay constant (ns)	600^s,56^f	40	30^s,10^f	35^s,6^f
Wave length (nm)	430	420	425^s,420^f	420^s,310^f
Refraction index	1.85	1.82	2.20	1.95
Light yield (NaI(Tl)=100)	3^s,30^f	83	0.083^s,0.29^f	3.6^s,1.1^f

Segmentation is necessary to reduce pile-up and provide position information. The calorimeter will consist of GSO cells which have a 3×3 cm^2 cross-section and are 11 radiation lengths long (about 15 cm for GSO). If the calorimeter covers the full cross-section of the detector region ($55^2\pi = 9053$ cm^2), then we will use 1056 crystals which is also a hexadecimal unit compatible with the readout architecture (16×66). The total rate in the calorimeter is 9670 kHz which is 92 kHz per crystal if the shower hit multiplicity is 10.

3. Stacked GSO(Ce) Calorimeter as a Prototype and Beam Test

The first prototype of the calorimeter was assembled by stacking small GSO(Ce) crystals, which were produced for Positron Emission Tomography (PET) with a size of $4 \times 6 \times 30$ mm^3. The crystals were cemented using an optical cement (BC-600) to make a stacked calorimeter with a size of $30\times32\times120$ mm^3 as shown in Fig. 3. A light guide shown in Fig. 4 was used to connect a photon detector to the stacked crystals.

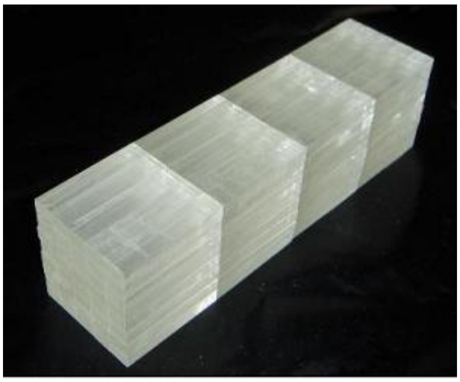

Figure 3: Photograph of stacked crystals for a prototype calorimeter composed of 160 GSO(Ce) crystals of $4\times6\times30$ mm^3.

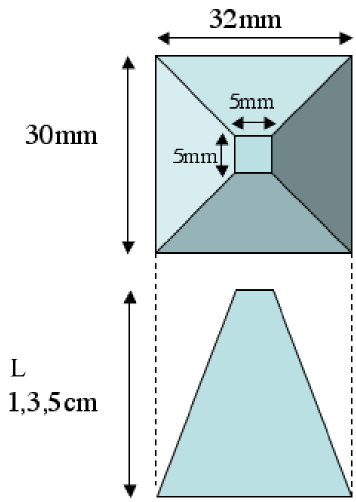

Figure 4: Drawing of the light guides connected to the stacked GSO(Ce) calorimeter.

Design of the calorimeter will be optimized using a simulation code based on geant4 with its optical photon package. A purpose of this prototype calorimeter is to determine parameters in the Monte Carlo simulation described later. Correctness of the optical simulation in the geant4, in particular for the light guide, should be checked.

A beam test was carried out at REFER (Relativistic Electron Facility For Education and Research) of Hiroshima university. In this beam test, a photo multiplier tube (PMT) was used as a photon detector. It was connected to the stacked GSO(Ce) crystal with a light guide. Collimated electron beams with energy of 150 MeV, which is close to the signal electron energy of COMET/PRISM, were injected to the prototype. Changing the injection position and size of the light guide, light yields were measured. As shown in Fig. 5 ,the measured data shows good agreement to the Monte Carlo simulation.

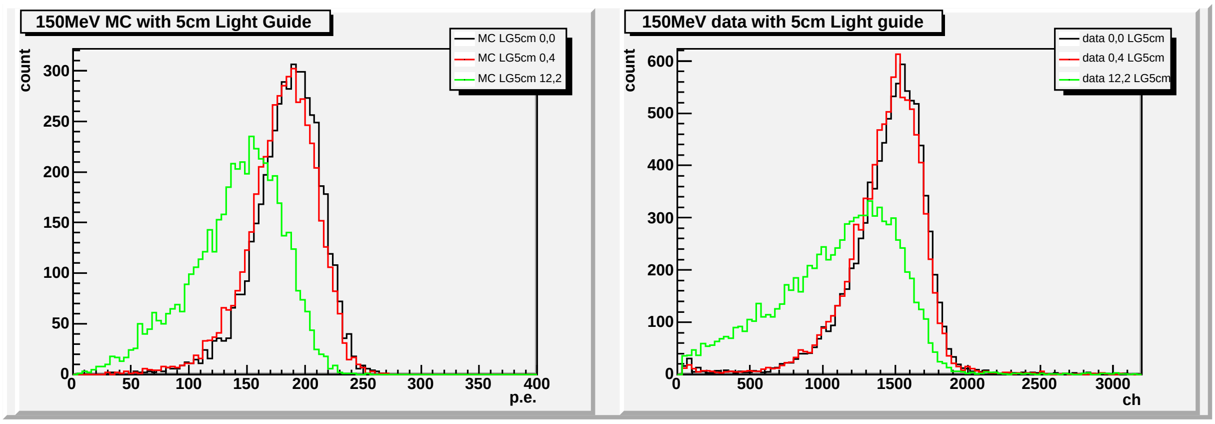

Figure 5: Distribution of the number of photons for 150 MeV elections injected with L=5 cm light guide case: left histograms are by Monte-Carlo simulation and right histograms are from the beam test. Each of three histograms shows injection position of the beam: (x[mm], y[mm])=(0,0),(0,4),(12,2). The position (0,0) means the center of the stacked calorimeter.

4. Performance Estimation by a Simulation Study

Energy resolutions of the calorimeter was studied using Geant4 with Optical Photon Processes. The resolution depends on crystal, light guide, photon detector, and their geometrical configuration. In this section, we discuss dependence of the resolution on the crystals under a possible configuration of the calorimeter. This selection would be a cost effective case for the photon detector, since the ratio of active area of the photon detector to the cross section of the crystal is set to 0.09.

Figure 6 shows a typical event display of this simulation. The calorimeter is a cylinder 1 m in diameter, and consists of 7850 rectangular segments. Figure 7 illustrates a segment of the calorimeter. It consists of a crystal, a light guide, and a photon detector. GSO(Ce), LYSO, PWO were studied in this simulation. The crystal has size of 10 mm$\times$10 mm$\times L$ mm, here L is the length of the crystal, 120 mm for GSO(Ce) and LYSO, and 100 mm for PWO. The material of the light guide is set to acrylic resin with a refractive index of 1.49. The size of the photon detector is 3$\times$3 mm^2, which corresponds the maximum size of MPPC, S10362-33 series of Hamamatsu Photonics K.K., commercially available at the present moment. The light guide is connected using optical cement with a reflective index of 1.46. The crystal and light guide is wrapped by a Teflon sheet to collect photons effectively.

Electrons of 105 MeV emitted from the stopping target disks, then transported to the calorimeter. The energy distribution of electron just before the calorimeter is shown in Fig. 8. In the calorimeter, electrons interact with the material and scintillation photons are emitted. The photons

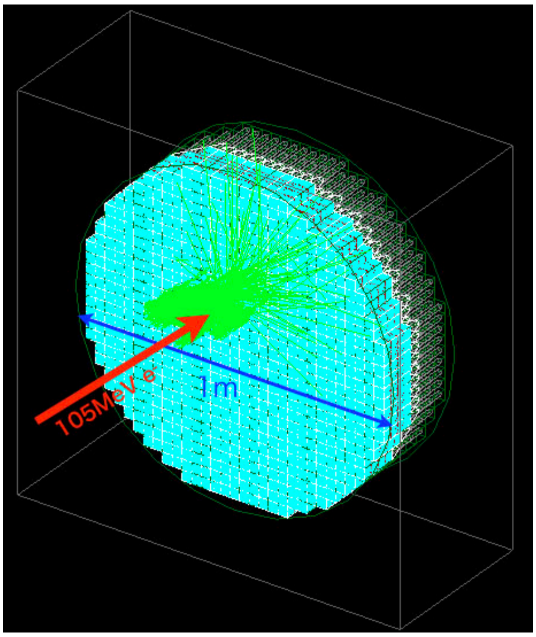

Figure 6: A typical event display of the simulation study of the calorimeter. An electron injected to the calorimeter, then optical photons from scintillation processes are ray-traced to the photon detectors.

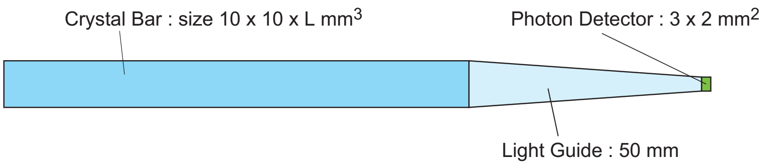

Figure 7: A schematic view of a segment of the calorimeter used in the simulation study.

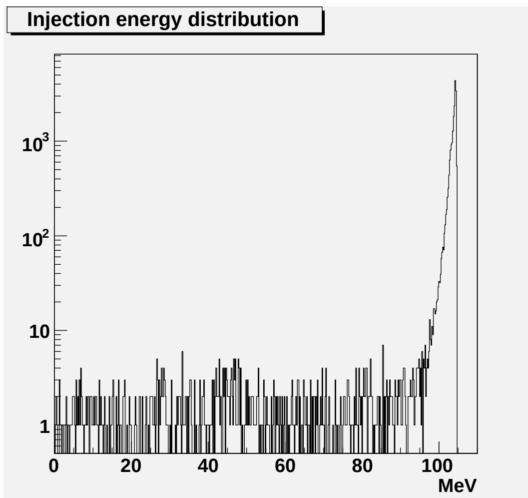

Figure 8: The energy distribution of electrons, which are injected to the calorimeter.

are ray-traced to the surface of the photon detectors. In order to get simulation result in a reasonable computing time, the photon yield of the scintillation process was reduced by factor of 10 for GSO(Ce) and a factor of 36 for LYSO. Figure 9 shows distributions of the number of photons arrived at the photon detectors. We applied a light yield correction considering the light yield factor and a photon detection efficiency (PDE) to estimate the energy resolution.

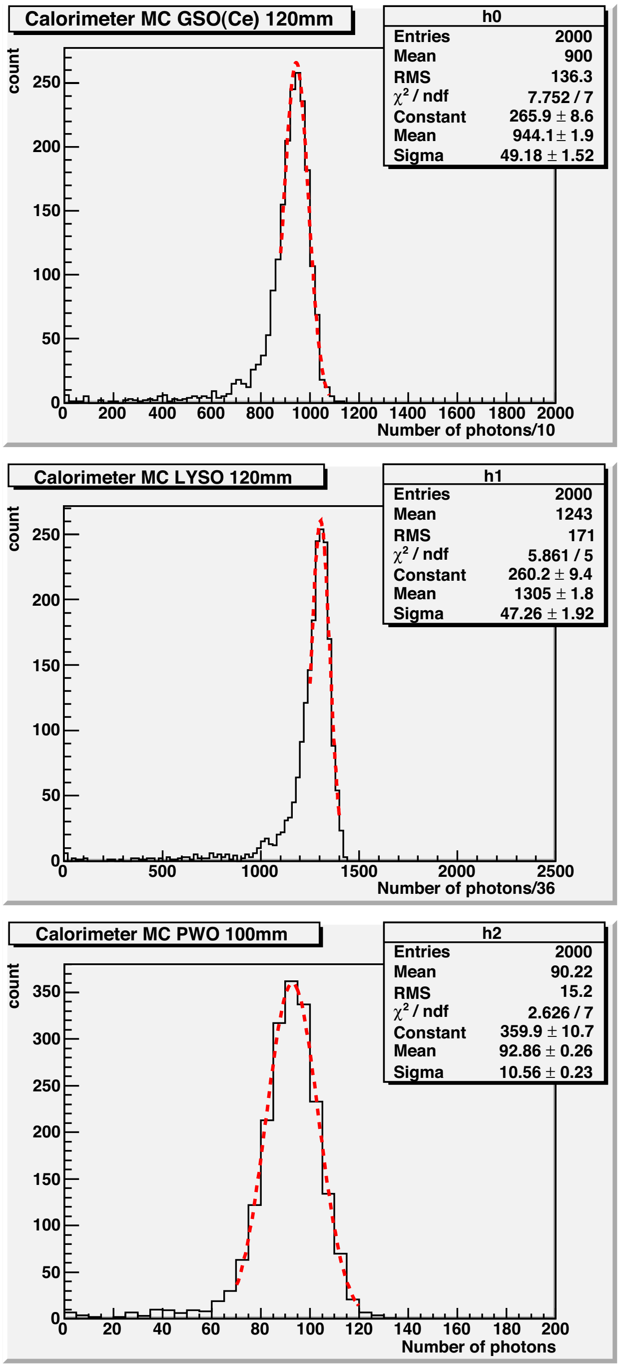

Figure 9: Distributions of the number of photons arrived at the photon detectors for GSO(Ce) (top), LYSO (middle), and PWO (bottom). The number of photons emitted by the scintillation process is reduced by some factors.

The energy resolution obtained from this study are summarized in Table 3 for PDE=0.25. The PDE of the MPPC depends on its pixel size. The typical PDE of MPPCs at 420 nm are 0.73, 0.45, and 0.25 at room temperature for the pixel size of 100 μm, 50 μm, and 25 μm, respectively [4]. The real energy resolution would be worse, since the resolutions in the table do not include the contributions from electronic noise, non-uniformity of the crystals and light collection, and temperature and gain drifts. GSO(Ce) and LYSO can fulfil the requirement of the energy resolution with this configuration. On the other hand, PWO needs larger ratio of the photon detector area.

Table 3: Energy resolutions obtained from this study for PDE=0.25.

		PDE = 0.25
Crystal	Length (mm)	σ_{E_e} (MeV)
GSO(Ce)	120	4.8
LYSO	120	2.6
PWO	100	22.2

5. Summary

R&D programs for an electromagnetic calorimeter are underway. In the present design of the calorimeter uses MPPCs as the photon detector, since the detector needs to work under 1 T magnetic field. The simulation study showed that crystal segmentation with 10×10 mm^2 cross section and 120 mm long can achieve the required energy resolution for the signal electrons, σ_{E_e}<5%, for GSO(Ce) and LYSO crystal. In order to finalize the calorimeter design, a larger prototype which consists of many segment to cover the Moliere radius will be constructed and studied. A beam test with MPPC readout is also planed.

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