Special Issue of the 6th International Congress & Exhibition (APMAS2016), Maslak, Istanbul, Turkey, June 1–3, 2016

Simulation of LYSO Crystal for the TAC-PF Electromagnetic Calorimeter

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In addition to PWO and CsI(Tl) crystals, cerium doped LYSO crystal is considered for the electromagnetic calorimeter part of the Turkish Accelerator Center Particle Factory (TAC-PF) detector, because of its high light yield, fast decay time and good radiation hardness. In this work, LYSO crystals arranged in 3×3 and 5×5 matrices have been simulated against photons in the energy range between 50 MeV and 2 GeV, using Geant4 simulation code. Energy resolutions have been estimated considering the contribution of photoelectron statistics coming from the avalanche and PIN photodiodes.

DOI: 10.12693/APhysPolA.131.527
PACS/topics: 29.40.Mc, 02.70.Uu

1. Introduction

Lutetium-yttrium oxyorthosilicate (LYSO) and lutetium oxyorthosilicate (LSO) crystal scintillators have been initially developed for PET scanners in medical industry. In the last years, LYSO crystals have been also proposed as a candidate material for crystal calorimeters, such as those at SuperB factory [1], Mu2e [2] and the COMET experiment [3]. LYSO crystals have a large stopping power, a fast decay time, a large light yield and a good radiation hardness against gamma rays, neutrons and protons, as seen from Table I [4–7]. Figure 1 shows the emission and the transmittance spectra of the LYSO crystal. The crystal emits light in the wavelength region of 360 nm to 600 nm, peaking at around 402 nm. Due to these properties, the LYSO crystals may also be considered for the electromagnetic calorimeter (ECAL) part of the proposed Turkish Accelerator Center-Particle Factory (TAC-PF) detector, in addition to PWO and CsI(Tl) crystals [8, 9].

TABLE I

Some properties of the most common crystal scintillators used in particle physics experiments [10].

Crystal	NaI(Tl)	CsI(Tl)	PWO	LYSO
Density [g/cm^3]	3.67	4.51	8.30	7.40
Radiation length [cm]	2.59	1.86	0.89	1.14
Moliére radius [cm]	4.13	3.57	2.00	2.07
Light yield	100	165	0.3/0.077	85
λ_{peak} [nm]	410	560	420	402
Decay time [ns]	245	1220	30/10	40

The scintillation photons generated by the incident particles in the crystal could be detected by a pair of Hamamatsu S2744-08 PIN photodiodes or Hamamatsu S8664-55 (S8148) avalanche photodiodes (APD), which are used in many high energy physics experiments as the photodetectors [11–14]. The aim of this paper is to investigate the possible effects of the LYSO crystal-photodetector pairs on the calorimetric energy resolution.

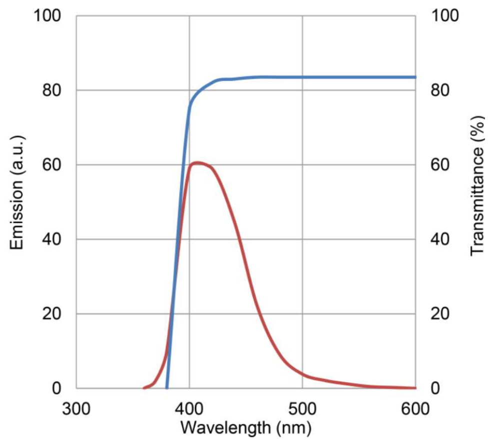

Fig. 1. Emission (red) and transmittance (blue) spectra of LYSO crystal [15].

2. Calorimetric energy resolution

The energy resolution of a calorimeter is parameterized as $\sigma_E/E = a/\sqrt{E}\oplus b\oplus c/E$, where a is the stochastic term, b is the constant term, c is the noise term, E is the incident particle energy in GeV and $\oplus$ represents addition in quadrature. The stochastic term of the energy resolution for crystal-photodiode combination is composed of a contribution from event to event fluctuations in the lateral shower containment a_{lateral} and a contribution from photoelectron statistics a_{pe}, given as $a = a_{\text{lateral}} \oplus a_{\text{pe}}$. The photoelectron statistics contribution, which is related with fluctuations in the photodetector signal, is given as $a_{\text{pe}} = \sqrt{\bar{F}/N_{\text{pe}}}$ [16]. Here, $\bar{F}$ is the emission-weighted excess noise factor coming from the fluctuations in the avalanche gain process. N_{pe} is the number of primary photoelectrons resulted from photoabsorption in the photodiode and calculated from $N_{\text{pe}} = N_{\text{ph}}\overline{QE}$. Here, N_{ph} is

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the number of incident photons collected by the photodiode, which is related to the number of photons leaving at the end of the crystal and $\overline{QE}$ is the emission-weighted quantum efficiency [9, 10, 17].

3. Simulation and results

Geant4 simulation code [18] was used to simulate photons of different energies passing through the crystal, arranged in a 5×5 matrix. The LYSO crystal has a length of 20 cm with a cross section of 25×25 mm^2 ($17.5 X_0$). Photons in the energy region from 50 MeV to 2 GeV have been injected into the center of central crystal of the matrix. The energy of the incident particle is deposited in the crystals. As the energy deposition spectra have a Gaussian form, with an asymmetric tail towards lower energies, they have been fitted using Novosibirsk function to obtain energy resolution. Novosibirsk function is defined by [19]:

$$f(E)=A_s \exp(-0.5 \ln^2 [1+\Lambda\tau(E-E_0)] / \tau^2+\tau^2), \quad (1)$$

where $\Lambda = \sinh(\tau\sqrt{\ln 4})/(\sigma\tau\sqrt{\ln 4})$, E_0 is the peak position, σ is the width, and τ is the tail parameter. Figure 2 shows the energy deposition spectra in the LYSO crystal matrix, at 1 GeV, as an example, obtained in the nine crystals and in the twenty five crystals. As a result of fits, the energy resolutions have been determined as 2.18% for the 3×3 crystal matrix and 1.59% for the 5×5 crystal matrix, at 1 GeV incident photon energy.

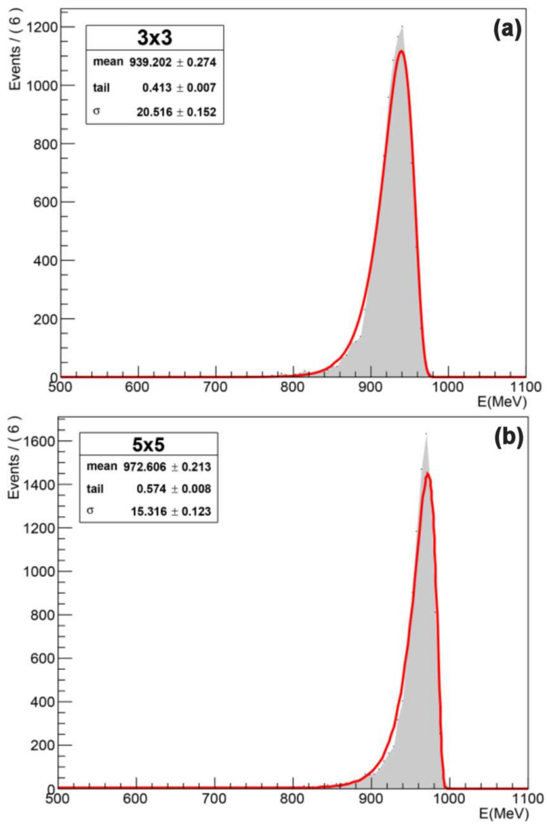

Fig. 2. Energy spectra of LYSO crystal matrices for 1 GeV photons injected into the crystal. Solid curves are the results of the fits with a Novosibirsk function.

Figure 3a presents the simulated energy resolution obtained with the 3×3 and 5×5 crystal matrices, as a function of incident photon energy. The increasing number of crystals decreases the fluctuations on the energy deposition, thus improving the energy resolution. The shower leakages in the transverse directions outside the crystal matrix contribute mostly to stochastic term, while the shower leakages from back of the crystals contribute to constant term. The simulated energy resolutions have been fitted using the function $\sigma_E/E = a/\sqrt{E} \oplus b$, and the parameters $a = 0.46\%$ and $b = 1.49\%$ were found for the 5×5 crystal matrix. The energy resolution values obtained from the simulation are consistent with [20].

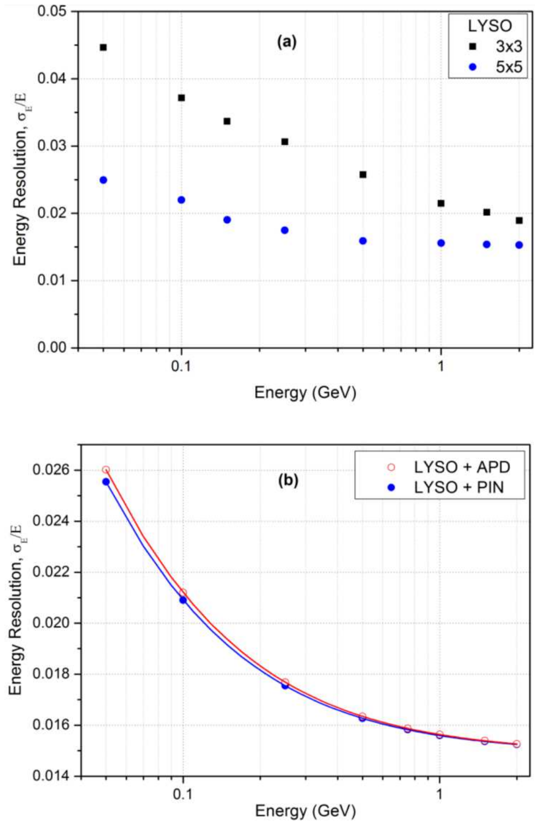

Fig. 3. (a) Energy resolution as a function of incident photon energies for the 3×3 and 5×5 LYSO crystal matrices. (b) Energy resolution as a function of incident photon energies for the crystal-photodiode combinations for the 5×5 LYSO crystal matrix. Solid lines are the results of fits.

To estimate the other major contribution in the stochastic term we need to know the emission-weighted excess noise for the crystal-APD combination and the number of primary photoelectrons. As the PIN diodes have no internal amplification, the emission-weighted excess noise is equal to 1 for the crystal-PIN combination. Emission-weighted APD excess noise factor has been calculated as 2.12 at a constant gain value of 50 for the LYSO emission spectrum. Here, the wavelength-dependent APD excess noise values were obtained from [21].

Average number of collected photons at the rear end of the crystal is determined by using the transmittance spectra given in Fig. 1 and the light yield (32 000 photons/MeV) of the crystal [22]. Number of the primary photoelectrons in the photodetector can be calculated by considering back face cross section of the crystal, active area of a pair photodetectors and the quantum efficiency. Active areas of the APD and the PIN diode are 5×5 mm^2 and 1×2 cm^2, respectively. The emission-weighted APD and PIN quantum efficiencies have been calculated as 78% and 58% for the LYSO emission spectrum. The calculated emission-weighted quantum efficiency values for the crystal-photodiode systems are compatible with the results of experimental measurements, given in [23]. For instance, considering a coverage of 8% of the crystal end-face by the active area of the APD and the APD quantum efficiency of 78%, the number of photoelectrons has been obtained as 1597 pe/MeV and this value is consistent with the experiment [23]. Thus, the photoelectron statistics contribution to the stochastic term has been calculated as 0.115% for LYSO-APD and 0.032% for LYSO-PIN combinations. Thus, the energy resolutions have been obtained by adding the photostatistics contributions to the intrinsic resolutions and the results are presented in Fig. 3b. The energy-dependent resolutions are parametrized as:

$\sigma_E/E = 0.48\%/\sqrt{E} \oplus 1.49\%$, for the LYSO-APD and

$\sigma_E/E = 0.46\%/\sqrt{E} \oplus 1.49\%$, for the LYSO-PIN pairs.

4. Conclusions

The Monte Carlo simulation has been performed for a LYSO crystal calorimeter intended for the TAC-PF detector, considering the incident photon energies from 50 MeV to 2 GeV. Photostatistics contributions to the energy resolution have been obtained as 0.115% and 0.032% for the LYSO crystal coupled to APD and LYSO crystal coupled to PIN pairs, respectively. The final energy resolutions of the LYSO crystal-photodiode pairs give approximately same results for the incident photon energies, because of the high light yield of the LYSO crystal. In comparison with the previous work [9], the energy resolutions of the LYSO and the CsI(Tl) crystals are better than that of PWO crystals for the incident photon energies below 1 GeV.

Acknowledgments

This work was supported by Scientific Research Projects Unit of Uludag University.

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