Light output simulation of LYSO single crystal

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Abstract

We used the Geant4 simulation toolkit to estimate the light collection in a LYSO crystal by using cosmic muons and E=105 MeV electrons. The light output as a function of the crystal length is studied. Significant influence of the crystal wrapping in the reflective paper and optical grease coupling to the photodetectors on the light output is demonstrated.

1 Introduction

The role of the experiments searching for the lepton flavor violation to constrain the models of new physics has increased over two years of the LHC operation: any indications of new physics are still beyond the grasp of experiments. Flavor changing by all neutral current interactions is strongly suppressed in the Standard Model (SM). The new physics scenarios beyond the SM (supersymmetry, extra dimensions, little Higgs, quark compositeness) naturally allow and predict the charged lepton flavor violation at some level (see, e.g.,[1]).

The aim of the $\mu \to e$ conversion experiments is to search for the coherent conversion of the muons from muonic atoms to the electrons in the field of a nucleus through some new lepton flavor violation interactions. The conceptual designs[2, 3] of the $\mu \to e$ conversion experiments include the calorimeter able to measure the energy of the electrons with the resolution $<5\%$ for 105 MeV and the time resolution $\sim 1\,\text{ns}$ to provide the trigger signal and measure track positions in addition to the tracking chambers. The calorimeter will consist of the $3\times3\,\text{cm}^2$ dense crystals and are $>10$ radiation lengths long. Several factors

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affect the accuracy of the energy and time measurements using the scintillator-light detector. The energy resolution of a photopeak at energy $E$ can be expressed in terms of various contributions\cite{4, 5}:

$$R_{tot}^2 = R_{ph}^2 + R_{sc}^2 + R_{en}^2,$$

where $R_{tot}$ is the full width at half maximum energy resolution, $R_{ph}$ represents the contribution from the photon statistics, $R_{sc}$ represents the influence from the nonideal nature of the crystal (inhomogeneities, nonproportionality), variance in the light-collection efficiency, and $R_{en}$ represents the contribution of electronic noise. The nature of the reflective wrapping around the crystal and the interface between the crystal and the light detector must also be considered as the factors affecting the quality of measurements: the former leads to the increase and the later to the loss of the scintillation photons collection. For an ideal scintillator and ideal readout electronics $R_{sc} = R_{en} = 0$ and for $N_{ph}$ photoelectrons

$$R_{tot} = R_{ph} = 2.35/\sqrt{N_{ph}}.$$ 

The quantity $N_{ph}$ can be expressed in terms of the mean number of scintillation photons, $N_\gamma$, produced by the scintillator due to the absorption of energy, the collection efficiency of the detector system for scintillation photons, $\epsilon_\gamma$, the collection efficiency for the photoelectrons, $\epsilon_e$, the quantum efficiency of the associated photon detectors, $q_{eff}$, and the total gain of the light detector, $g_t$,

$$N_{ph} = N_\gamma \epsilon_\gamma \epsilon_e q_{eff} g_t.$$ 

The analysis of different contributions to the energy resolution for some crystals was performed, e.g., in\cite{6, 7}.

The reliable Monte-Carlo simulation plays an important role in the crystal selection and the calorimeter configuration, minimizing the systematic uncertainties in the physics analysis. Without knowing certain detector properties and neglecting the effects of crystal inhomogeneity, we restricted this work to the simulation of the number of photons in the LYSO crystal. The next section gives a brief description of the LYSO crystal choice advantages. Section 3 describes the cosmic muon simulation and the strategy of simulating optical photons in a crystal using Geant4 toolkit. In Section 4 we give the light output results. The dependence of the photon number on the size of the crystal and influence of the crystal wrapping is studied. In this section we also show the energy deposition in the crystal when
cosmic muons and E=105 MeV electrons are used. We end with the conclusions in Section 5.

2 Inorganic crystal for the calorimeter

Recently\textsuperscript{8} we have performed the comparative analysis of three dense crystals for using in the $\mu \to e$ conversion experiment. Several superior characteristics — high stopping power (radiation length $X_0=1.14\,\text{cm}$, $R_{\text{Moliere}}=2.07\,\text{cm}$), fast decay time ($\tau=40\,\text{ns}$), bright scintillation (light yield $\geq 26\,\text{photons/keV}$) relative to many other crystals used in high energy physics, nonhygroscopic nature, and radiation hardness — make cerium-doped lutetium and lutetium-yttrium oxyorthosilicats (LSO:Ce and LYSO:Ce) major candidates for being used in trigger calorimeters in the $\mu \to e$-conversion experiments\textsuperscript{1}.

The commonly used optical photon detectors have high $q_{eff}$ at the peak emission wavelength, 420 nm, of LSO/LYSO crystals. For example, the $e_{eff}$ values for the Photonis XP2254B photomultiplier tube and the Hamamatsu S8664 avalanche photodiode are $7.2 \pm 0.4\%$ and $75 \pm 4\%$\textsuperscript{9}, respectively. Luminescence properties and compatibility of the LYSO:Ce crystal to many currently employed optical photon detectors are discussed in more detail in\textsuperscript{10}.

3 Cosmic muons and optical photons simulations

The accurate simulation of the processes in the scintillator was performed using optical and scintillation models of Geant4\textsuperscript{11} version 9.6.p01. The Geant4 low-

\footnote{The unpleasant factors are the natural radioactivity and a high price of LSO/LYSO crystals in relation to commonly used scintillators, which may be significantly reduced if they are mass produced for high-energy physics needs.}
energy electromagnetic libraries were employed in that simulation. The studied crystal is LYSO:Ce with the dimensions 3x3x13 cm$^3$. The yttrium content of LYSO:Ce is 4%, the cerium doping level is 0.02%. The refractive index of LYSO:Ce was set as a function of the optical photon wavelength\cite{12}. We assumed the intrinsic light output of the LYSO:Ce crystal to be 26 scintillation photons per keV (see, e.g.,\cite{13}). The photon absorption length in whole interval of wavelengths was put to 20 cm\cite{14, 15}.

The crystal is polished on all surfaces. From one of the readout ends (3x3 cm$^2$) we collected the photons. The opposite surface of the crystal is covered by non-reflective black paper. Four lateral layers of the crystal were wrapped in highly reflective (R=97%) Tyvek paper to collect photons effectively. Reflection of photons from the surfaces between two dielectric materials was simulated using the UNIFIED model\cite{11}. We used the polished and ground types of the surfaces. We also performed simulation without wrapping the crystal.

The minimal tracking step in the simulation was set to 10 µm, which corresponded to the energy cuts of $\sim 3.2$ keV for the photons and $\sim 51.9(50.8)$ keV for the electrons(positrons) for the LYSO:Ce crystals.

The cosmic muons were generated according to the energy spectrum\cite{16} and injected perpendicularly to the 3x13 cm$^2$ surface of the crystal at a random point.
Figure 3: The number of photons in the nine areas into which the 3x3 cm$^2$ crystal surface is divided. The E=105 MeV electrons penetrate the center of the crystal on the opposite side in the perpendicular direction.

The azimuthal angular distributions and energy spectrum of the simulated cosmic muons are shown in Fig. 1. In the range 0.3-1000 GeV $<E_{\text{cosm}}>$=9.79 GeV.

4 Results

In this study the light from the single LYSO:Ce crystal is collected (1) from the whole 3x3 cm$^2$ surface divided into nine 1x1 cm$^2$ areas and (2) from two 1x1 cm$^2$ areas arranged symmetrically about the vertical axis of the crystal at a distance of 0.5 cm from each other. The lateral surfaces of the crystal was covered with Tyvek paper without a thin air gap.

Figure 2 compares the number of photons collected from whole crystal surface and two 1x1 cm$^2$ areas for the naked and wrapped LYSO:Ce crystal with different
Figure 4: The number of photons collected from the whole 3x3 cm$^2$ surface when 105 MeV electrons penetrate the center of the opposite surface of the crystal in the perpendicular directions. The influence of wrapping in Tyvek paper and optical grease are demonstrated.

lengths. The cosmic muons were injected perpendicularly to the upper 3x13 cm$^2$ side of the crystal at a random point. Note that Tyvek wrapping increases the light collection by a factor of more than 2. The number of photons decreases by a factor of $\sim 1.4$ when the length of the crystal increases from 5 to 10 cm. We have found that the use of the previous Geant4 version (9.5.p01) leads to a decrease in the number of photons by 3.7% and 2.2% for the crystal lengths 5 and 13 cm, respectively.

In Fig. 3 we present the number of photons collected from the whole 3x3 cm$^2$ surface of the LYSO:Ce crystal divided into nine 1x1 cm$^2$ areas. The E=105 MeV electrons are injected into the center of the opposite 3x3 cm$^2$ surface. The maximal number of photons is collected in the central part of the crystal, and the minimal number was collected in its corners. The same behavior is observed if the cosmic muons are injected perpendicularly to the upper surface of the crystal at a random point. The ratio $\sigma/E$ for the central cell corresponding to the Gaussian fit is $\sim 0.29$ (see Fig. 3).

In Fig. 4 we show the number of photons collected from the 13-cm-long naked and wrapped LYSO:Ce crystals using 105 MeV electrons. The electrons were injected perpendicularly into the center of the 3x3 cm$^2$ surface of the crystal and the photons were collected from the whole opposite surface of the crystal. The
influence of 0.1 mm optical grease is also demonstrated in the figure. The optical grease (polidimethilsiloxane, C$_2$H$_6$OSi, $\rho=0.97$ g/cm$^3$, reflective index $R=1.4$) is used for attaching the photodetectors to the crystal and transmitting light to the photodetector. From the Gaussian fit, the mean of photon numbers corresponding to the wrapped crystal, wrapped crystal with optical grease, and naked crystal are in the ratio 1:0.57:0.42. Note that between the reflective paper and the crystal there is no thin air gap and without grease the light is collected just after crystal.

Finally in Fig. 5 we demonstrate the energy deposition in the LYSO:Ce crystal by cosmic muons and E=105 MeV electrons. The cosmic muons and electrons penetrate the crystal as described above. The Gaussian fit curves and parameters are also demonstrated in the figure. The ratio $\sigma/E$ for these distributions is 0.091 and 0.061 for the cosmic muons and electrons, respectively.

5 Conclusions

In this paper we focused our attention on the light output of LYSO:Ce crystals neglecting their nonproportionality and inhomogeneity and light detector response. The simulation of the crystal is based on the Geant4 simulation toolkit. The light output was studied using cosmic muons and E=105 MeV electrons. Significant influence of the size and wrapping in reflective paper on the light output is demonstrated. The optical grease used for attaching the photodetectors to the crystal leads to a decrease in the light output. The central region of the crystal

Figure 5: The energy deposition in the LYSO:Ce crystal when cosmic muons penetrate the 3x13 cm$^2$ surface in the perpendicular direction at a random point (left) and when 105 MeV electrons penetrate the center of the 3x3 cm$^2$ surface (right).
on the end surface is the most predominant area for photon collection.

To validate the simulation, these results should be benchmarked with experimental measurements of LYSO:Ce crystals. Such comparisons should lead to the correct considerations of nonproportionality of the scintillator response below 300 keV and crystal inhomogeneity in the simulation. The experimental data on the light spectra and photon numbers for LSO:Ce and LYSO:Ce crystals obtained with different light detectors also are necessary for correct simulation.

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