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INVESTIGATION OF LYSO AND GSO CRYSTALS AND SIMULATION OF THE CALORIMETER FOR COMET EXPERIMENT

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The research results of parameters of LYSO and GSO crystals — candidates for being used in an electronic calorimeter for the COMET experiment — are described. The research has been made at the specially created high-precision measuring setup. Measurements of uniformity of LYSO and GSO crystals along the crystal length were made. The energy resolution of the crystals, their light output and processing speed were measured. The energy calibration of the crystals was also performed. The research results were used for GEANT4 simulation of the calorimeter for the COMET experiment. As a result of simulation of the calorimeter on the collimated 105 MeV electrons source with the use of real optical parameters, an energy resolution of 5.0% was obtained for a calorimeter on GSO crystals and 2.5% for a calorimeter on LYSO crystals.

Описаны результаты исследования параметров кристаллов LYSO и GSO, являющихся кандидатами для создания электронного калориметра в эксперименте COMET. Исследования проводились на специально созданном прецизионном измерительном стенде. Были проведены измерения однородности кристаллов LYSO и GSO по длине. Также были измерены энергетическое разрешение кристаллов, их световыход и быстродействие. Проведена энергетическая калибровка кристаллов. Результаты исследования были использованы для GEANT4 моделирования электронного калориметра эксперимента COMET. В результате моделирования калориметра на коллимированном 105-МэВ источнике электронов с использованием реальных оптических параметров было получено энергетическое разрешение 5,0 % для калориметра на GSO-кристаллах и 2,5 % для калориметра на LYSO-кристаллах.

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INTRDUCTION

Lepton flavor violation is predicted by many theories beyond the Standard Model (SM). In the muon sector such a violation entails, for example, the conversion process $\mu^- - e^-$. COMET (Coherent Muon to Electron Transition) experiment is the one that will search for neutrinoless $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$ conversions with a single-event sensitivity of $3 \cdot 10^{-17}$. This sensitivity is a factor of 10,000 better than achieved by the SUNDRUM-II experiment which set the current world's best limit for $\mu - e$ conversions ($R_{\mu e} \leqslant 7 \cdot 10^{-13}$) [1]. The experiment will be realized on a proton beam of the Japanese Research Accelerator Complex (J-PARC, Tokyo).

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The main task of realization of the COMET experiment is creation of an electron calorimeter. The electron calorimeter should serve three purposes:

1) to measure the energy of electrons, where good energy resolution is necessary to produce an efficient trigger and add redundancy to the energy measurement;

2) to provide a timing signal, i.e., a trigger, with respect to which the electron events are referenced;

3) to provide addition position information on the electron track trajectory correlating the measured energy with track.

Calorimeter should well discriminate among electrons, neutrons and low-energy gamma and it should have good timing resolution because the total rate in the calorimeter is 9760 kHz, which is 92 kHz per crystal.

The energy resolution of the calorimeter is determined by the optical parameters of crystals. So, the crystals of the calorimeter should have the minimum possible Moliere radius and the minimum radiation length, which is achieved by increasing the density of the scintillation material. The crystals should have good light output, fast time of response and short decay time. In addition, the crystals should be relatively inexpensive; they should have thermal and radiation resistance and uniformity. Among the properties listed above, the light output is the most important, as it effects both the efficiency and resolution of the detector.

Proceeding from these requirements, two currently available candidates for use in a calorimeter are crystals GSO:Ce and LYSO:Ce. These crystals have suitable values of radius of Moliere, radiation length, density, time-stable parameters of temperature and radiation resistance. The main disadvantage of GSO:Ce crystal is the large value of slow component of decay time. The main disadvantage of LYSO:Ce crystal is intrinsic radioactivity.

The aim of the work was to define some important properties of these crystals and study their influence on the energy resolution of the calorimeter.

In the first part of this paper we present an experimental study of some properties for polished GSO:Ce crystal of dimensions $20 \times 20 \times 120$ mm produced by Hitachi Chemical Co in Japan and for polished LYSO:Ce crystal of equal size, produced by Saint-Gobain Crystals Inc. For measurements the crystals were wrapped with Teflon tape.

In the second part of the paper we present simulation of the COMET calorimeter by using real optical parameters we obtained from the research of crystals.

1. EXPERIMENTAL SETUP

For carrying out investigations of GSO and LYSO crystals a precision measuring setup has been created. The setup consists of:

- an optical measuring system that was executed on fast PMT HAMAMATSU H1949-50 with divider H1949-50;
- a precision mechanical system for moving the radiation source with accuracy 1 micron on the basis of the precision step-motor;
- a precision measuring system on base of the 14 digit 5-GHz digitizer;
- a trigger system of selection which was made on the NIM modules;
- a calibrated sources of radioactive radiation ^{22}Na, ^{60}Co, ^{137}Cs, ^{133}Ba.

The setup work is based on a correlation method for measurements of the signals from PMT located at both ends of the crystal. This allows one to reduce the noise and the

contribution of the intrinsic radioactivity of LYSO crystal, more precisely to organize a trigger for a given energy on the statistics set.

Radioactive radiation source (^{22}Na, ^{60}Co, ^{137}Cs, ^{133}Ba) is installed in a lead collimator with an aperture of 1 mm and, by using the precision mechanical system, can move to the desired position along the surface of the crystal with very high accuracy. This ensures the identity of all measuring parameters of the setup for investigation of properties of calibration crystals.

Table 1. **Parameters of radioactive radiation sources [2]**

Radiation source		Intensity of radiation, kBq	Error ($P = 0.95\%$)
Type	No.		
^{22}Na	7084	94	3
^{60}Co	7112	106	3
^{137}Cs	7763	103	3

All work on the set of statistics, the movement of source to the desired position with the required accuracy along the surface of the crystal was automated. For these purposes, special windows applications were written by using Visual Studio C^{++} 2010. In addition, special programs for making histograms of measurement results were written by using C^{++}. For these researches calibrated radiation sources were used whose parameters are given in Table 1.

2. MEASUREMENT OF OPTICAL PARAMETERS OF LYSO AND GSO CRYSTALS

2.1. Measurement of Energy Resolution of LYSO Crystal. The energy resolution of a crystal is one of the key parameters on which the selection of candidates for use in electronic calorimeter will be made. In this study, we measured the optical parameters of LYSO and GSO crystals of equal size.

These crystals have similar values of the energy resolution (8% for GSO and 10–11% for LYSO), but different values of light output. The light output of LYSO crystal is 3–4 times higher than that of the GSO crystal [3, 4]. In addition, the energy resolution of real crystals GSO [5] and LYSO depends on the percentage of cerium [3, 6], the uniformity of its distribution along the length of the crystal, the availability of its intrinsic radioactivity and the value of slow component of decay time. Determining the impact of these factors on the energy resolution was just the main objective of this research.

At first we carried out comparative measurements of the energy resolution of crystals by using different types of radiation sources and their different location with respect to the crystal. The LYSO crystal has intrinsic radioactive radiation with energies of 401, 307, 201 and 82 keV [7, 8], so we measured the spectrum of intrinsic radioactivity that can be taken into account in simulation of the COMET calorimeter on LYSO crystals.

The measured spectrum of LYSO crystal intrinsic radioactivity is shown in Fig. 1. Since the energy of this radiation is large enough, it distorts the measured spectrum and the distortion will be more noticeable when the energy of intrinsic radioactivity radiation and the source energy have close values. The energy spectrum of LYSO crystal measured on ^{60}Co source that was located at the end of the crystal is shown in Fig. 2. The energy spectrum of LYSO crystal that was measured by using two sources, when the ^{137}Cs source was located at the end of the crystal and the ^{133}Ba source was located at the center of crystal, is shown in Fig. 3.

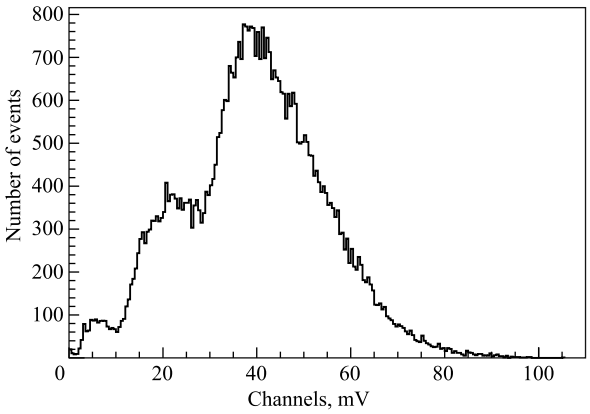

Fig. 1. Spectrum of LYSO crystal intrinsic radioactivity

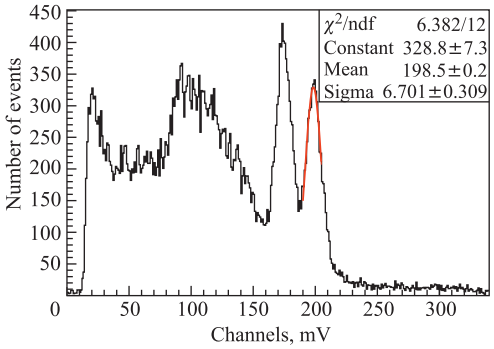

Fig. 2. Energy spectrum of LYSO crystal on ^{60}Co source

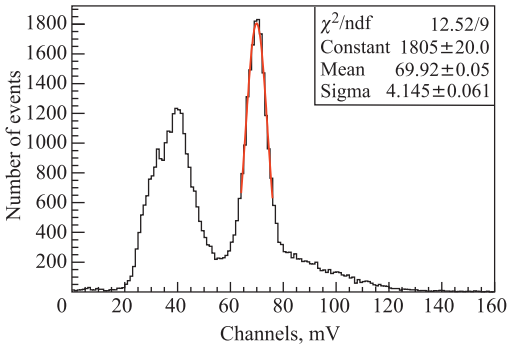

Fig. 3. Energy spectrum of LYSO crystal on ^{137}Cs and ^{133}Ba sources

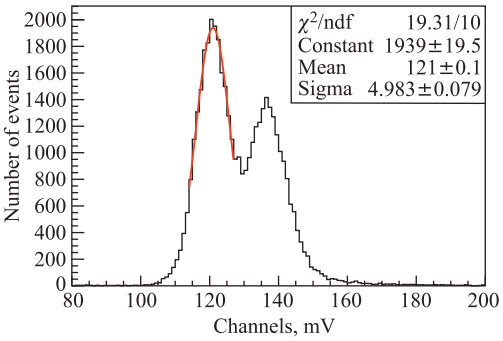

Fig. 4. Energy spectrum of LYSO crystal on a collimated ^{60}Co source

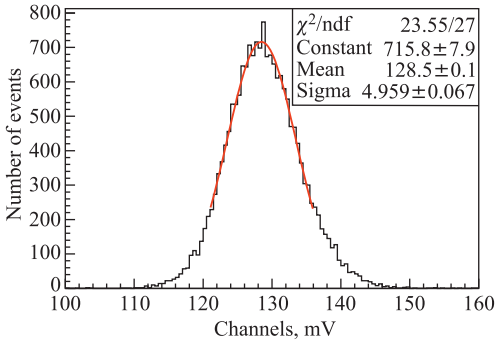

Fig. 5. Energy spectrum of LYSO crystal on a collimated ^{22}Na source

The energy spectrum of LYSO crystal that was measured by using the collimated ^{60}Co source with the diameter of aperture 1 mm is shown in Fig. 4. The source was located at the middle of the length of the crystal at the 5 mm distance from the surface. A similar energy

spectrum of LYSO crystal that was measured by using the collimated ^{22}Na source is shown in Fig. 5.

From these measurements of LYSO crystal it is clear that the spectral estimation (σ) is 4.1%, and the energy resolution calculated as $\Delta E/E$ (FWHM) is equal to 13.9% at the energy 662 keV (^{137}Cs). The spectral estimation of 4.96% and the energy resolution of 9.1% were obtained for LYSO crystal at the energy 1274.5 keV (^{22}Na). The spectral estimation of 6.7% and the energy resolution of 7.9% were obtained for LYSO crystal at the energy 1332.5 keV (^{60}Co). Thus, the spectrum of LYSO crystal intrinsic radioactivity makes worse the energy resolution, especially for energies close to the energies of its intrinsic radioactivity, and it produces a shift in the center of the spectral estimate in the region of larger values.

These results closely match the results obtained by Novotny, who researched LYSO crystal of the same size. He obtained a similar value of LYSO crystal spectral estimate, 4.6%, on the ^{22}Na source. In the measuring setup he used a special trigger system for the suppression of radiation spectrum of the crystal to reduce the impact of intrinsic radioactivity [7].

It should be noted that in our research all spectra were the result of direct measurement, i.e., without mathematical data handling. The correlation algorithm for selection was used in the trigger system to reduce the impact of intrinsic radioactive radiation on the energy resolution of LYSO crystal.

2.2. Measurement of Energy Resolution of GSO Crystal. The GSO crystal does not have intrinsic radioactivity, but the light output of this crystal is not great and besides it consists of fast and slow components. Duration of the slow component of decay time depends on percentage of cerium in a crystal and this value can make from 70 ns, at concentration of cerium 5%, to 1200 ns, at concentration of cerium 0.1% [5]. The light output also strongly depends on concentration of cerium and can make from 100 photons/cm^3 at concentration of cerium 5% to 340 photons/cm^3 at concentration of cerium of 1% [5].

The long duration of slow component of decay time significantly reduces the energy resolution of GSO crystal, and, therefore, it is required to increase the concentration of cerium. However, the increase of concentration leads to a decrease of the light output, which is also a critical parameter, especially for the large length of the crystal. In this context, the effect of the intensity of the energy source on the value of the energy resolution of GSO crystal was studied.

Since most of the literature on optical properties of crystals is given at the energy 662 keV, so at first we made the measurement of the energy spectrum for different intensities of the ^{137}Cs source.

Three types of collimators were used for this study. The first two collimators had a diameter of aperture of 2 and 1 mm and a thickness of 2.5 mm, the third had a diameter of 0.5 mm and a thickness of 7 mm. The ^{137}Cs source has an intensity of 103 kHz without collimator (Table 1), and using these collimators we can reduce its intensity about 100, 200 and 600 times, respectively.

The spectrum of GSO crystal on the uncollimated ^{137}Cs source (source located on the surface of the middle length of the crystal) is shown in Fig. 6, and the spectrum of the same crystal on the collimated source with an aperture of 2 mm is shown in Fig. 7.

The spectrum of GSO crystal on the ^{137}Cs source with a collimator with an aperture of 0.5 mm and a thickness of 7 mm is shown in Fig. 8, and the spectrum of GSO crystal on the ^{22}Na source with a collimator with an aperture of 1 mm and 2 mm thick is shown in Fig. 9.

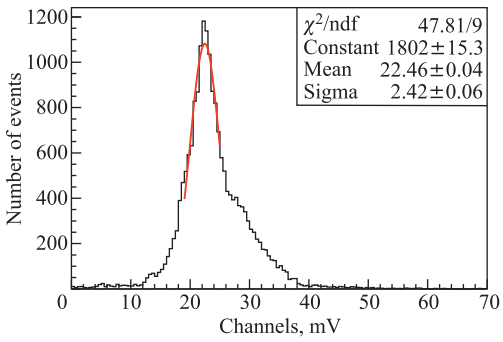

Fig. 6. Signal spectrum of GSO crystal on ^{137}Cs source without a collimator

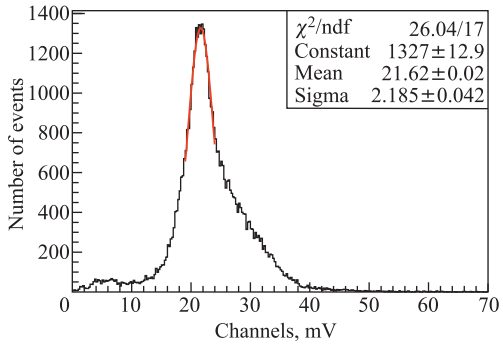

Fig. 7. Signal spectrum of GSO crystal on ^{137}Cs source with a collimator with an aperture of 2 mm

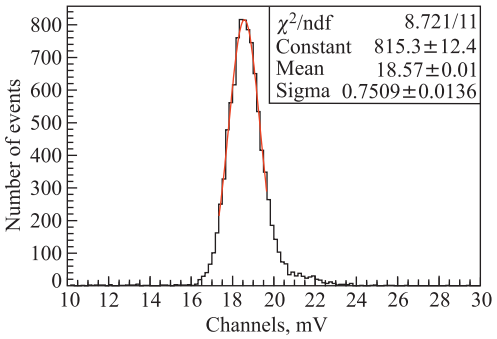

Fig. 8. Spectrum of signal of GSO crystal on the ^{137}Cs source with a collimator with an aperture of 0.5 mm

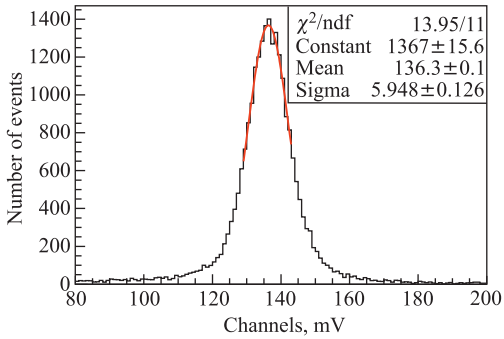

Fig. 9. Spectrum of signal of GSO crystal on the ^{22}Na source with a collimator with an aperture of 1 mm

From measurements we obtained that the energy resolution of GSO crystal on the source with an energy of 662 keV (^{137}Cs), calculated as the FWHM, without collimator is equal to 25.3%, with a collimator of 2 mm aperture is equal to 23.7%, and with a collimator of 0.5 mm aperture is equal to 9.5%. The energy resolution of GSO crystal on the collimated source with a diameter of aperture of 1 mm, and on the 1274.5 keV (^{22}Na) source is equal to 10.3%. Spectra in Figs. 4 and 5 show that the presence of the slow component of decay time makes worse the energy resolution of the crystal and it shifts the spectrum of crystal into the region of higher energies due to crystal illumination.

2.3. Energy Calibration of Crystals. Energy calibrations of LYSO and GSO crystals were measured with the use of the sources of ^{133}Ba, ^{137}Cs, ^{60}Co with corresponding energies 356, 662, 1173.2 and 1332.5 keV. The energy calibration of GSO (Fig. 10) and LYSO (Fig. 11) crystals were made by using ^{133}Ba, ^{137}Cs, ^{60}Co sources.

Analysis of Fig. 12 shows that the presence of the slow component of GSO crystal shifts the calibration point at an energy of 356 keV into the region of higher energies. This is explained by the crystal illumination arising from the slow component of decay time. For LYSO crystals one also observes calibration points offset at an energy of 662 keV (Fig. 13). This effect is connected with the intrinsic radioactivity of the crystal, which is close to this energy (307, 401 keV).

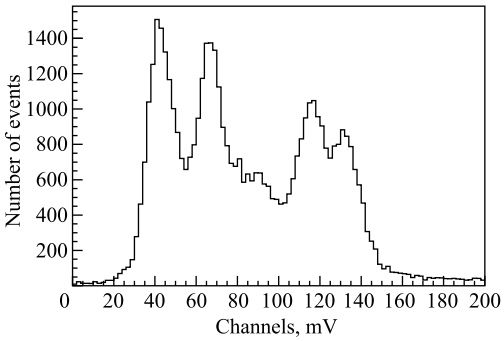

Fig. 10. Energy spectrum of GSO crystal on the ^{133}Ba, ^{137}Cs, ^{60}Co sources

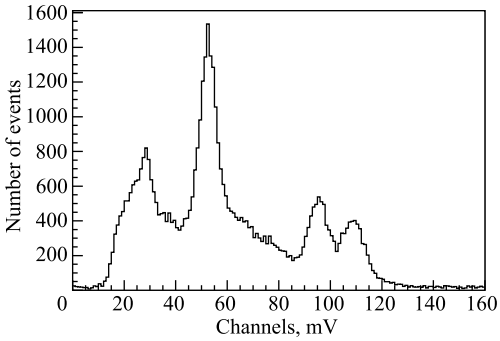

Fig. 11. Energy spectrum of LYSO crystal on the ^{133}Ba, ^{137}Cs, ^{60}Co sources

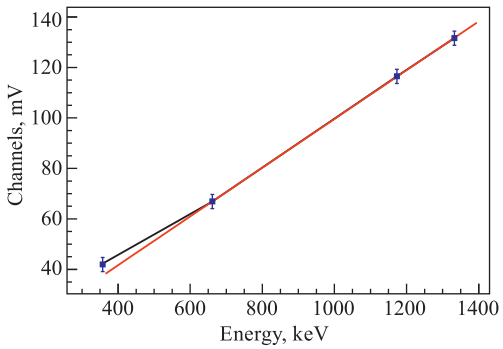

Fig. 12. Energy calibration of GSO crystal on the ^{133}Ba, ^{137}Cs, ^{60}Co sources

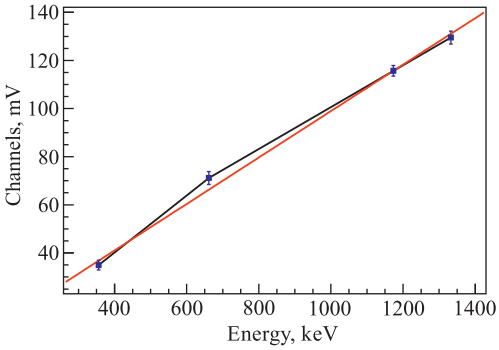

Fig. 13. Energy calibration of LYSO crystal on the ^{133}Ba, ^{137}Cs, ^{60}Co sources

2.4. Measurement of Homogeneity or Loss of Light Output along the Crystal Length. Measurement of uniformity along the crystals length, i.e., light output losses depending on the position of the source, was made on the ^{22}Na source. The study of uniformity was conducted with the help of a high-precision mechanical system. The collimated source with a diameter of the aperture of 1 mm moved along the surface of the crystal in steps of 5 mm. The obtained histograms were used to determine the centers of distributions and then their values were used to define the uniformity of crystals (see Fig. 8).

Losses of light output in a crystal and its uniformity depend on the distribution of cerium along the crystal length during the manufacturing. Besides, for the big crystals the magnitude of light output losses depends on the general concentration of cerium along length.

These two factors lead to heterogeneity of the crystal and light output losses. As seen from Figs. 14 and 15, the heterogeneity of light output losses of GSO crystal is a little worse than that of LYSO crystal. The heterogeneity of light output losses of GSO along the length is approximately 3.3%, and of LYSO crystal is approximately 2.5%.

2.5. Measurement of Light Output. For determination of the light output of GSO and LYSO crystals, precise measurements of their energy spectrum at an energy of 662 keV (^{137}Cs) were carried out by using constant parameters of the measuring system, namely,

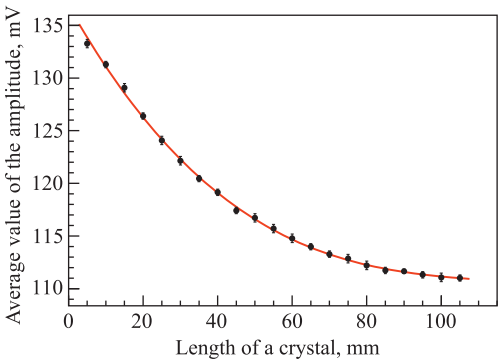

Fig. 14. Distribution of uniformity of GSO crystal

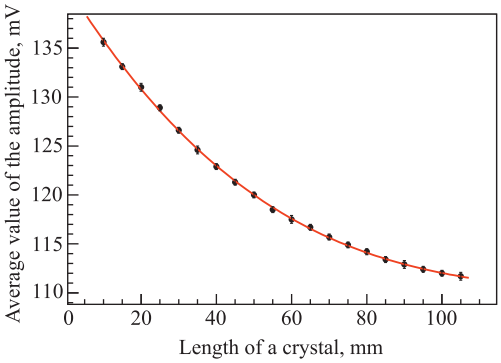

Fig. 15. Distribution of uniformity of LYSO crystal

the measurements in the same position of the crystal, with the same values of the gains of measurement system, at the same position of the collimator.

Spectrum of LYSO and GSO crystals on the ^{137}Cs source at constant parameters of the measuring system is shown in Fig. 16. The center of spectrum for GSO crystal lies at (17.64 ± 0.02) mV and for LYSO at (65.01 ± 0.08) mV. Thus, the ratio of the light output is LYSO/GSO $= 3.69$.

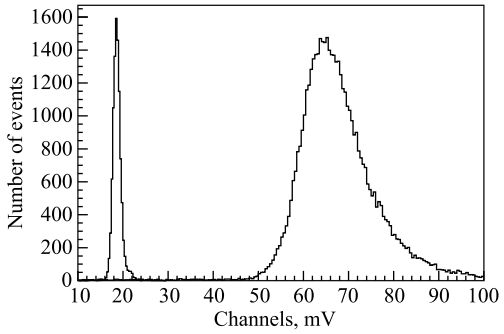

Fig. 16. Spectrum of LYSO and GSO crystals on the ^{137}Cs source at constant parameters of the measuring system

The value of the light yield of GSO crystal can be determined from the slow component of decay time. The time range of signal at the GSO crystal is shown in Fig. 17.

The slow component of time decay is equal to about 420 ns, which corresponds to the concentration of cerium of about 1.3%, and the value of light output at such a concentration is about 350 photons/cm^3 [5].

As the position of radiation source was in the center of crystal in our measurements, the photons were highlighted from volume 24 cm^3, the magnitude of light output of GSO crystal is approximately 8400 photons. Thus, the value of light output for LYSO is $8400 \cdot 3.69 = 30957$, i.e., approximately 31000 photons, which corresponds to the data presented in the literature [5]. Using the timing signal of GSO crystal (see Fig. 17), it is also possible to define a percentage of slow component in the light output value of GSO crystal. The value of slow component

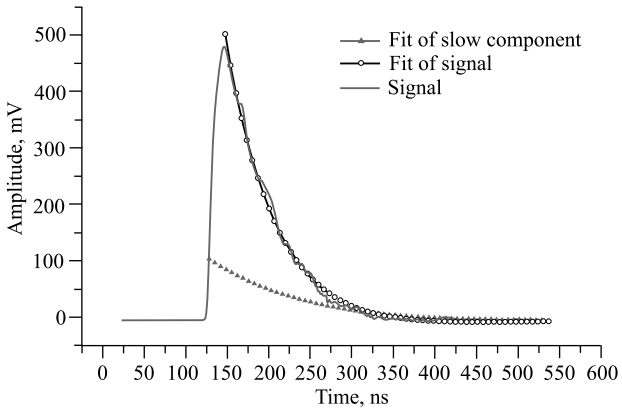

Fig. 17. Timing signal of GSO crystal on the ^{137}Cs source with constant parameters of the measuring system

obtained by minimization is equal to about 12.5% of the total value of the timing signal. This value closely coincides with the data given in [3, 4].

These real parameters, i.e., the real value of light output for LYSO and GSO crystals, the value of decay-time slow component and its percentage and percentage of cerium for GSO crystal, have been used for the simulation of the COMET calorimeter.

3. CALORIMETER SIMULATION FOR THE COMET EXPERIMENT

3.1. The Simulation of the COMET Calorimeter on the basis of LYSO and GSO Crystals Using Real Optical Parameters. We simulated single crystals GSO:Ce and LYSO:Ce and the COMET calorimeter by using the Geant4 simulation code [9]. Both crystals had the same size: $20 \times 20 \times 120$ mm. The crystals were wrapped with Teflon tape. In the simulation, the boundary processes of all crystal surfaces follow the rules of the UNIFIELD model.

Such optical properties of the materials as light output, time decay, the percentage of cerium for GSO crystal, the ratio of slow and fast components in per cent for the GSO crystal, involved in the simulation, were obtained as a result of our research. The other optical parameters needed for simulation were taken from literature [3, 4].

The optical model of simulation included the following processes: optical absorption, Rayleigh optical scattering reflection, reflection on the interaction between surfaces. These processes required the definition of main optical material properties.

The LYSO:Ce crystal properties comprise light yield (31000 photons/MeV), time decay constant (47 ns), radiation length (1.14 cm), Moliére radius (2.03 cm) and wavelength of emission max (420 nm), density (7.4 g/cm^3), the index of refraction (1.81).

The GSO:Ce crystal properties comprise light yield (8400 photons/MeV), time decay constant (fast component is 56 ns (87.5%) and slow component is 420 ns (12.5%)), radiation length (1.38 cm), Moliére radius (2.3 cm) and wavelength of emission max (440 nm), density (6.71 g/cm^3), the index of refraction (1.85).

For the simulation of the PMT, borosilicate window with an index of refraction 1.53 was used, which corresponds to optical photon wavelength in crystal 400–450 nm. We

Table 2. **Parameters of the simulation**

Parameters	GSO(Ce)		LYSO(Ce)	
	From literature	From the investigation	From literature	From the investigation
Density, g/cm^3	6.71	—	7.4	—
Decay time τ, ns (fast/slow components)	40–60/300–600	60/420	40–60	47
Number Z_{eff}	59	—	66	—
Refraction index	1.85	—	1.81	—
Wavelength of emission max, nm	440	—	420	—
Scintillation yield (662 keV), photons/MeV	8000–11500	8400	25000–32000	31000
Interaction length, cm	1.0	—	1.15	—
Attenuation length, cm	20.8	—	30.3	—

used GLISUR optical model, usually recommended to simulate a dielectric–metal surface like photocathode of a PMT.

The particles involved in our simulation were photons, electrons and positrons; thus, the physical processes describing their interactions were entirely electromagnetic. The selected physical processes for the simulation were photoelectric effect, Compton and multiple scattering, gamma conversion, bremsstrahlung, and annihilation for positrons and electrons. The intrinsic radioactivity of LYSO:Ce crystals was taken into account as energy cut (500 keV) in the simulation. The basic parameters of crystals GSO:Ce and LYSO:Ce used for the simulation are shown in Table 2.

3.2. Results of the Simulation. We simulated the COMET calorimeter by using the 105-MeV collimated electron source. The calorimeter consists of 1224 crystals, which create a cylinder of diameter 800 mm. Figure 18 shows geometry of real COMET calorimeter.

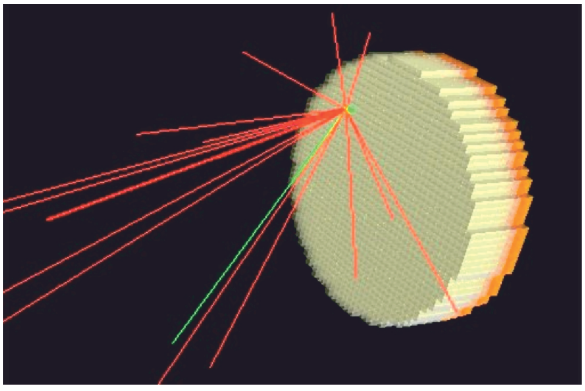

Fig. 18. Geometry of real COMET calorimeter

We made the simulation of optical photons spectra of real calorimeter on GSO:Ce and LYSO:Ce crystals for 105-MeV collimated electron source in the case when a uniform magnetic field is present. The magnetic field was directed perpendicular to the direction of the particles of the source. The source was collimated and was located along the axis of the calorimeter. The optical photon spectrum recorded at the 105-MeV collimated electron beam in the GSO:Ce calorimeter with real geometry is shown in Fig. 19. The optical photon spectrum recorded at 105-MeV collimated electron beam in the LYSO:Ce calorimeter with real geometry is shown in Fig. 20.

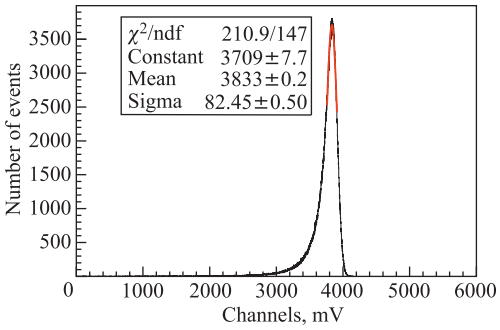

Fig. 19. Simulated optical spectrum on the 105-MeV electron source for the COMET calorimeter on GSO crystals

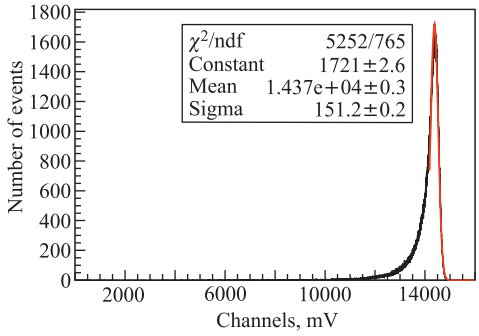

Fig. 20. Simulated optical spectrum on the 105-MeV electron source for the COMET calorimeter on LYSO crystals

As a result of simulation of the calorimeter on the collimated 105-MeV electron source with the use of real optical parameters, we obtained an energy resolution of 5.0% (HWFM) for a calorimeter on GSO crystals and 2.5% (HWFM) for a calorimeter on LYSO crystals.

Arrival time spectrum of photons for the COMET calorimeter on GSO and LYSO crystals, i.e., the time during which the photons reached PMT from electromagnetic shower, which is formed from the beam of 105-MeV electrons, is shown in Figs. 21 and 22. Figure 22 shows

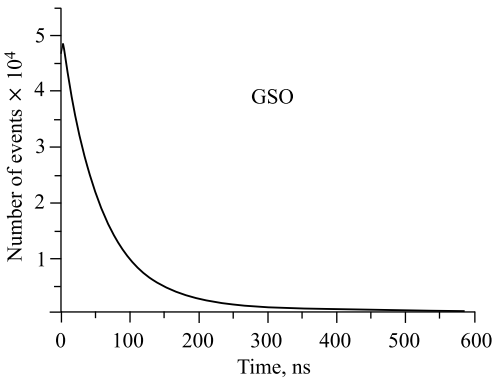

Fig. 21. Arrival time spectrum of photons for calorimeter on GSO crystals

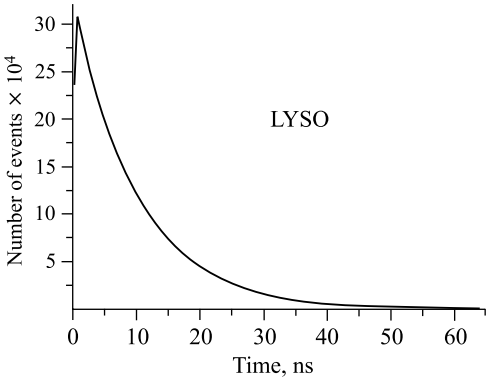

Fig. 22. Arrival time spectrum of photons for calorimeter on LYSO crystals

that the arrival time spectrum for the calorimeter on LYSO crystals slightly differs from the arrival time spectrum of a single crystal (about 17 ns). Figure 21 shows that the arrival time spectrum for the calorimeter on GSO crystals is very different from the arrival time spectrum of a single crystal (about 130 ns).

CONCLUSIONS

In the paper, some properties of LYSO and GSO crystals have been studied. The research has been made at the specially created high-precision measuring setup. All the work on the set of statistics, the movement of the source to the desired position with the required accuracy along the surface of the crystal was automated. In our investigation, all spectra were the result of direct measurement, i.e., without mathematical data handling. The correlation algorithm for selection was used in the trigger system to reduce the impact of intrinsic radioactive radiation on the energy resolution of LYSO crystal.

Measurements of uniformity of crystals LYSO and GSO along the crystal length, and the energy calibrations of crystals were made. We obtained the energy resolution of GSO and LYSO crystals on different radioactive sources. For example, an energy resolution of 10.3% for GSO crystal and 9.1% for LYSO crystal on the ^{22}Na source was obtained. We calculated the light output of 8400 photons/MeV for GSO crystal and 31000 photons/MeV for LYSO crystal on the ^{137}Cs source by using the measured data. We also calculated percentage of cerium (about 1.3%) and value of the slow component of light output (12.5%) for GSO crystal. We obtained the spectrum of the intrinsic radioactivity for LYSO crystal. As a result of GEANT4 simulation of the calorimeter on the collimated 105-MeV electron source, with the use of real optical parameters we obtained an energy resolution of 5.0% for a calorimeter on GSO crystals and 2.5% for calorimeter on LYSO crystals.

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