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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

RESPONSE OF LYSO:Ce SCINTILLATION CRYSTALS TO LOW-ENERGY GAMMA RAYS

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The LYSO crystals of dimensions $30 \times 30 \times 130$ mm and $10 \times 10 \times 10$ mm are tested with different gamma sources. Energy resolutions and linearity of the energy responses in the energy range of 511–1333 keV are measured. It is found that crystals have good linearity of the energy response in the entire tested energy range. Longitudinal light response nonuniformity of the long crystal is found to be less than 3.2% within the 35–120 mm range along the crystal axis.

С использованием различных гамма-источников исследовались кристаллы LYSO, имеющие размеры $30 \times 30 \times 130$ мм и $10 \times 10 \times 10$ мм. Измерены энергетическое разрешение и линейность отклика в диапазоне энергий 511–1333 кэВ. Показано, что кристаллы имеют высокую линейность отклика в этом диапазоне энергий. Измеренная продольная неоднородность световыхода вдоль оси длинного кристалла не превышает 3,2 % на расстоянии 35–120 мм от торца кристалла.

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INTRODUCTION

Cerium-doped Lutetium Yttrium Oxyorthosilicate crystal $Lu_{2x}Y_{2-2x}SiO_5$:Ce (LYSO:Ce or LYSO) is one of the candidates for being used in the electromagnetic calorimeter of the Mu2e experiment proposed at Fermilab [1]. The LYSO has density of 7.1 $g \cdot cm^{-3}$, high light yield $\sim$ 25000 photons/MeV, which is about 75% of that of NaI(Tl), radiation length of 1.14 cm, and decay time $\sim 40-45$ ns [2]. These LYSO parameters satisfy the Mu2e electromagnetic calorimeter requirements, i.e., time resolution better than 1 ns and energy resolution better than 2% at 100 MeV/c electron momentum [1, 3]. Crystals from different producers planned to be considered and compared before the final selection are made. In this paper, we present test results of Saint-Gobain [4] LYSO crystals with dimensions of $30 \times 30 \times 130$ mm and $10 \times 10 \times 10$ mm.

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1. SETUPS TO ANALYZE THE LYSO CRYSTALS PERFORMANCE

Energy resolutions and linearity of energy response of both $30 \times 30 \times 130$ mm and $10 \times 10 \times 10$ mm crystals and longitudinal light response uniformity of the longer crystal were measured using different setups.

The block diagram of the setup for measuring the $30 \times 30 \times 130$ mm LYSO crystal energy resolution and linearity of the energy response is shown in Fig. 1. The EMI 9813B photomultiplier tube (PMT) was employed for these measurements. The crystal was attached to the photocathode by means of optical grease and the opposite end was irradiated by gamma sources. The crystal was wrapped up in TYVEK diffuse paper. Signals from the PMT were sent to splitter, and then to the ADC input via delay line DL and to discriminator D and the coincidence circuit CC to generate an ADC gate and to trigger the data acquisition system (DAQ). The ADC gate width was 300 ns. Data were taken either in the self-triggering or the coincidence mode. An additional H5783 PMT with the $10 \times 10 \times 10$ mm crystal (placed over the $30 \times 30 \times 130$ mm LYSO crystal) was used in the latter case. The gate generator GG produced a "veto" signal to block the DAQ during the signal conversion.

The setup for measuring the longitudinal light response uniformity of the LYSO crystal is presented in Fig. 2. Measurements were done using the Philips XP2020 PMT. Signals were amplified by the shaping amplifier (shaping time 1 μs) and sent to the spectrometric ORTEC Trump-2k multichannel analyzer. The collimated ^{22}Na γ source was placed in a holder sliding along the crystal axis. The LYSO crystal was wrapped up in TYVEK diffuse reflective paper.

Signals from the $10 \times 10 \times 10$ mm LYSO crystal were read out with the S8664-1010 Hamamatsu silicon avalanche photodiode (APD) (active area size 10×10 mm). Signals from the APD were amplified by the low-noise charge sensitive preamplifier. The integration time of the preamplifier was 300 ns. The signals were then amplified and shaped by the external shaping amplifier and digitized by the Polon 712 10-bit ADC. The start of digitization was controlled by the internal peak detector of the ADC. The digitized data from the ADC were read out by the PC. Data were taken in the self-triggering mode. The diagram of the

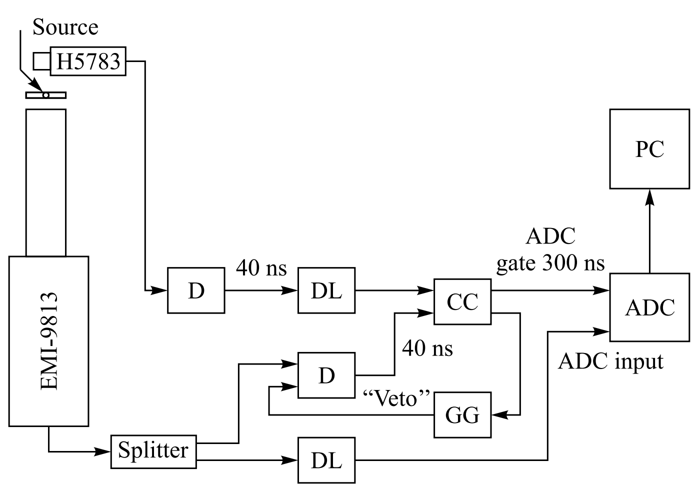

Fig. 1. The block diagram of the setup for measuring the $30 \times 30 \times 130$ mm LYSO crystal energy resolution

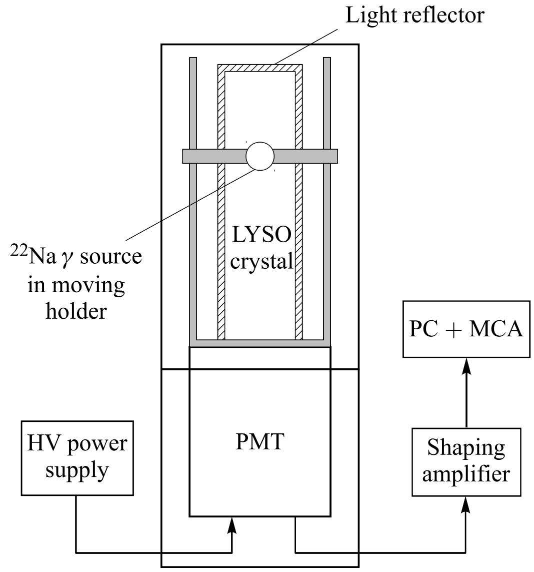

Fig. 2. The block diagram of the setup for measuring the $30 \times 30 \times 130$ mm LYSO crystal light response uniformity

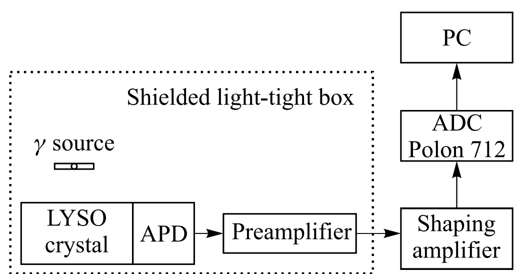

Fig. 3. The block diagram of the setup for measuring the $10 \times 10 \times 10$ mm LYSO crystal energy resolution

experimental setup is shown in Fig. 3. During the measurements the LYSO crystal, APD, and preamplifier were placed in a shielded light-tight black box together with a gamma source. The LYSO crystal was wrapped up in diffuse reflective paper. The APD was coupled to the LYSO crystal with optical grease. The measurements were done at room temperature.

2. TESTS OF THE CRYSTALS: RESULTS AND DISCUSSIONS

2.1. Tests of the $30 \times 30 \times 130$ **mm Crystal.** *2.1.1. Energy Resolution.* The LYSO crystals feature intrinsic radioactivity due to lutetium β decay with a maximum electron energy of 596 keV ^{176}Lu $\rightarrow$ ^{176}Hf followed by emission of three prompt gammas with energies of 88, 202 and 307 keV. The total counting rate of the tested crystal due to intrinsic radioactivity is found to be (31970 ± 179) s^{-1} or (272.9 ± 1.5) s$^{-1} \cdot$ cm^{-3} or (38.4 ± 0.2) s$^{-1} \cdot$ g^{-1} calculated per unit volume or weight of the crystal. Three gammas from the decay cascade could be

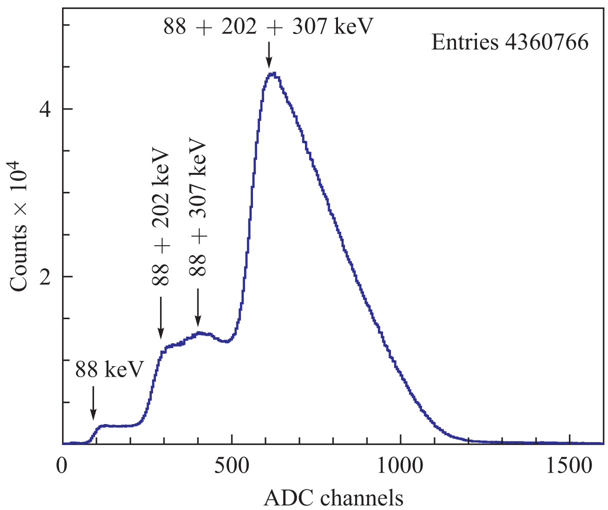

Fig. 4. The 30 × 30 × 130 mm LYSO crystal spectrum due to intrinsic radioactivity. Four sets of detected gammas are shown in the spectrum by arrows

absorbed in the crystal volume, or some of the gammas could escape giving four sets of gamma + beta energy distributions.

The LYSO spectrum due to intrinsic radioactivity is shown in Fig. 4. Sets of gamma energies corresponding to 88 keV ($\sim$ 90th ADC channel), 88 + 202 keV ($\sim$ 290th channel), 88+307 keV ($\sim$ 400th channel) and 88+202+307 keV ($\sim$ 600th channel) with superimposed beta-decay spectra are clearly seen in the same figure.

Gamma sources of ^{22}Na with energies 511 and 1275 keV, ^{137}Cs with energy 662 keV, and ^{60}Co with energies 1173 and 1333 keV were used for the crystal characterization. Data for ^{22}Na and ^{137}Cs irradiation were taken in crystal self-triggering mode (although the ^{22}Na back-to-back outgoing 511 keV gammas allow using a coincidence method for the triggering purposes, we did not employ that method for the measurements reported here). DAQ allows reading out only a small fraction of the LYSO signals due to high intrinsic counting rate. Gamma-source irradiation increases the total crystal counting rate, while the readout rate remains the same. That required to use the difference method in order to distinguish contribution of the external gamma source from the total spectrum when data were taken in the self-triggering mode.

The total spectrum due to intrinsic radioactivity and ^{22}Na irradiation is shown in Fig. 5 (solid line). The spectrum due to the LYSO intrinsic radioactivity is depicted in the same figure by the dashed line. Two spectra were normalized to the number of events due to the LYSO intrinsic radioactivity. The difference between these two spectra gives the spectrum solely due to ^{22}Na irradiation (dotted line). Two full absorption peaks corresponding to 511 and 1275 keV are clearly seen in the latter spectrum. Fitting these peaks with Gaussians gives the crystal energy resolutions $\sigma/E = 5.75\%$ and $\sigma/E = 3.7\%$ for energies of 511 and 1275 keV, respectively.

Similar spectra were obtained when the crystal was irradiated using the ^{137}Cs source (Fig. 6). The total spectrum due to intrinsic radioactivity and ^{137}Cs irradiation is

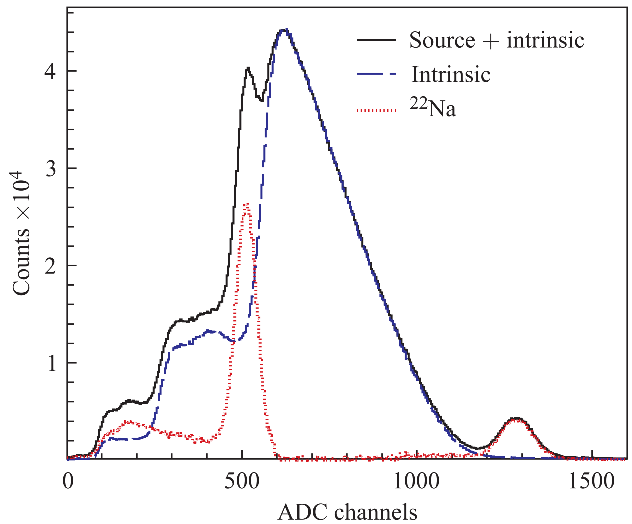

Fig. 5. The LYSO spectra due to intrinsic radioactivity and ^{22}Na irradiation: total spectrum (solid line), spectrum due to intrinsic radioactivity (dashed line), and spectrum due to ^{22}Na irradiation (dotted line)

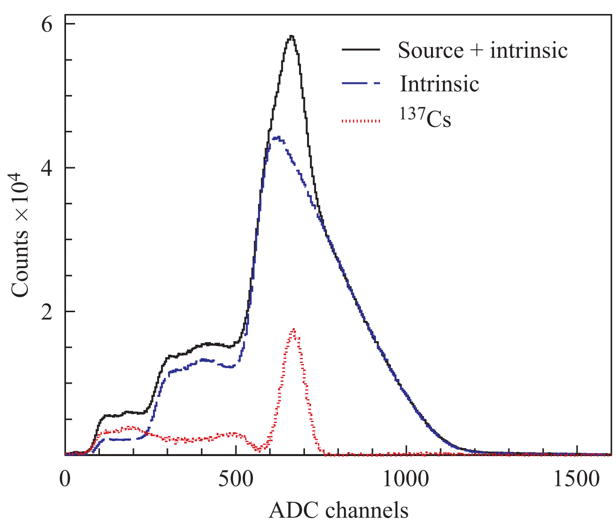

Fig. 6. The LYSO spectra due to intrinsic radioactivity and ^{137}Cs irradiation: total spectrum (solid line), spectrum due to intrinsic radioactivity (dashed line), and spectrum due to ^{137}Cs irradiation (dotted line)

shown by the solid line, while the spectrum due to intrinsic radioactivity is plotted by the dashed line. The difference spectrum corresponding to the ^{137}Cs contribution is shown by the dotted line. The full absorption peak and continuous Compton scattering distribution are clearly seen in Fig. 6. The energy resolution at $E = 662$ keV was estimated by fitting the full absorption peak by the Gaussian and found to be $\sigma/E = 4.8\%$.

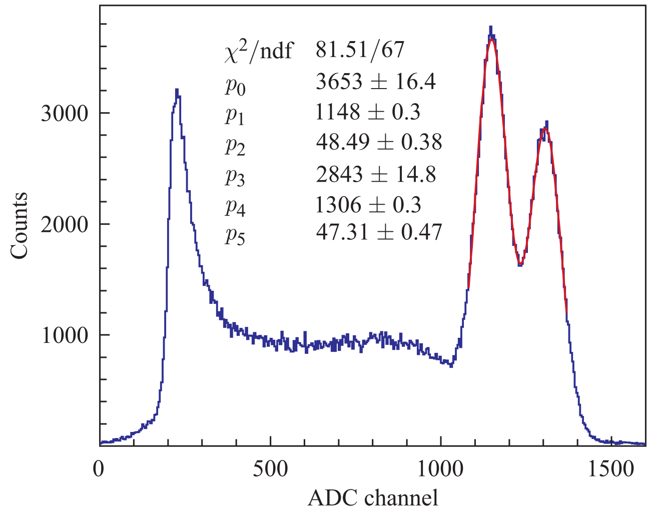

Fig. 7. The LYSO spectra due to ^{60}Co irradiation. Two full absorption peaks corresponding to 1173 and 1333 keV are fitted with the sum of two Gaussians

Two gammas from the ^{60}Co source are emitted simultaneously and almost isotropically. The data for ^{60}Co irradiation of the crystal were taken in coincidence with the H5783 counter. The resulting spectrum is shown in Fig. 7. Two full absorption peaks corresponding to 1173 and 1333 keV are well resolved. Fitting two peaks by the sum of two Gaussians gave the energy resolution estimations $\sigma/E = 3.9\%$ and $\sigma/E = 3.6\%$ for $E = 1173$ keV and $E = 1333$ keV, respectively. Maximum in the peak at $E = 1173$ keV is higher than that at $E = 1333$ keV, because the end of the continuous Compton spectrum from the latter peak overlaps the full absorption peak corresponding to $E = 1173$ keV. Subtraction of that continuous Compton spectrum should equalize both full absorption peaks and improve the crystal resolution.

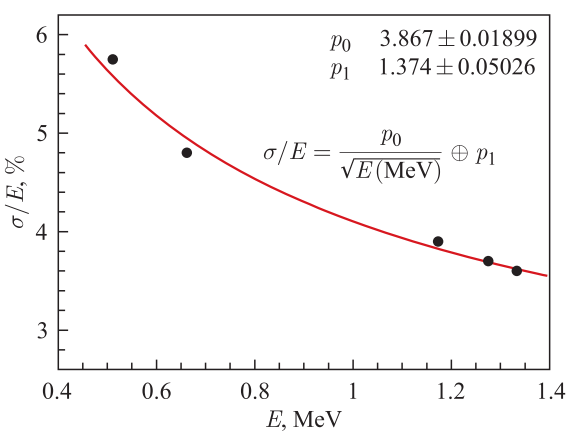

Fig. 8. The $30 \times 30 \times 130$ mm LYSO crystal energy resolution measured with the EMI 9813B PMT as a function of photon energy

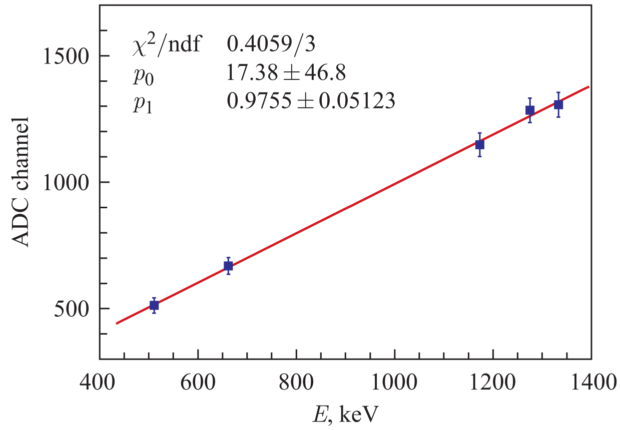

Fig. 9. The 30 × 30 × 130 mm LYSO crystal energy response linearity in the 511–1333 keV range

The LYSO energy resolution due to ^{22}Na, ^{137}Cs and ^{60}Co irradiation is depicted in Fig. 8. Error bars are smaller than the marker sizes. It is in agreement with other published data [5]. The experimental points are fitted with a function of $\sigma/E = p_0/\sqrt{E(\mathrm{MeV})} \oplus p_1$ with fit parameters $p_0 = (3.87 \pm 0.02)\%$ and $p_1 = (1.37 \pm 0.05)\%$. The $\oplus$ sign indicates the quadratic summing.

Linearity of the energy response in the energy range 511–1333 keV is shown in Fig. 9. The figure demonstrates that the crystal response is linear and all experimental points fit well a linear function.

2.1.2. Longitudinal Light Response Uniformity. Longitudinal light response uniformity was measured by comparing of light yields of the crystal, irradiated by the ^{22}Na source at different positions along the crystal axis. Pulse height spectra measured at room temperature are

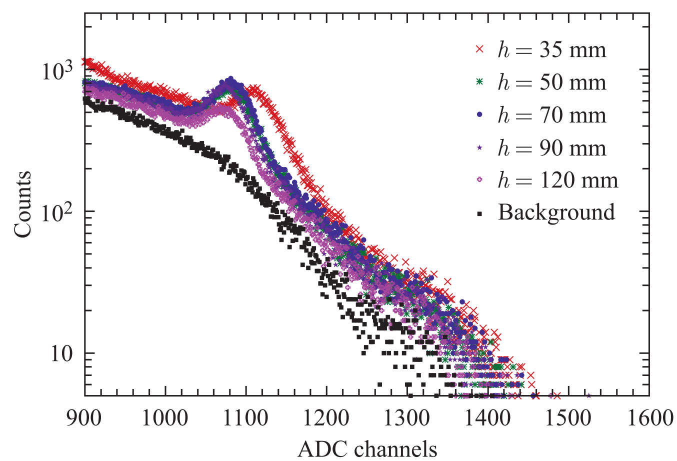

Fig. 10. Pulse height spectra of the 30 × 30 × 130 mm LYSO crystal irradiated by the ^{22}Na γ source placed at distances of 35, 50, 70, 90 and 120 mm from the PMT cathode (1786 keV peaks are around channel 1100)

presented in Fig. 10 and show peak positions of 1786 keV, which is a sum of two gammas with energies 511 and 1275 keV, for different distances of the ^{22}Na γ source from the PMT photocathode. The sum peak was chosen for the light response uniformity estimation, because it is less affected by the LYSO intrinsic radioactivity. The spectra were measured at distances of 35, 50, 70, 90 and 120 mm from the source to the PMT cathode. Radioactive background due to the intrinsic LYSO radioactivity is still presented in this energy range.

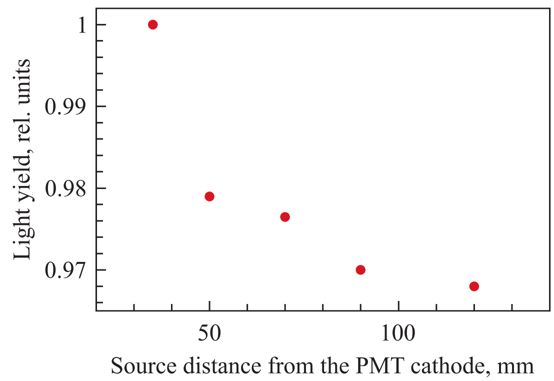

Fig. 11. Longitudinal light response uniformity of the $30 \times 30 \times 130$ mm LYSO crystal. Nonuniformity does not exceed 3.2% for the γ-source position ranging between 35 and 120 mm on the crystal axis

After subtraction of the background from the spectra, all peak positions were determined. Light yields for all points were normalized to the point nearest to the PMT (35 mm). The graph of longitudinal light response uniformity is presented in Fig. 11. One can see that light response nonuniformity does not exceed 3.2% for the γ-source position ranging between 35 and 120 mm on the crystal axis.

2.2. Tests of the $10 \times 10 \times 10$ **mm Crystal.** The smaller crystal has a much lower counting rate due to intrinsic radioactivity. In our case, the rate is about of 270 s^{-1}. The measured LYSO spectrum due to intrinsic radioactivity is shown in Fig. 12. The spectrum considerably differs from that for the $30 \times 30 \times 130$ mm crystal. The reason for that is the size of the

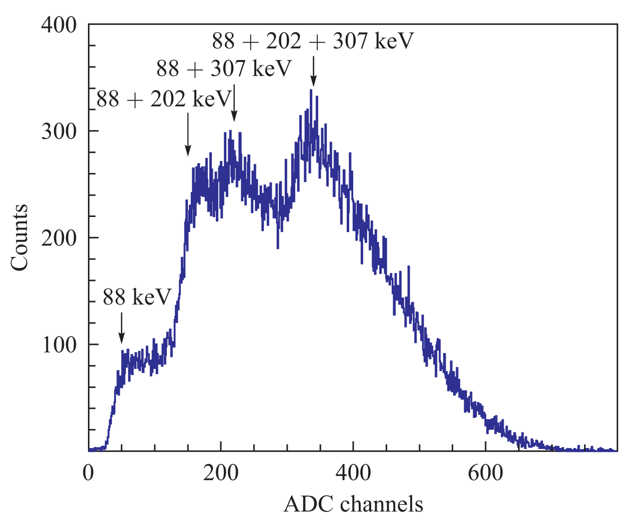

Fig. 12. The $10 \times 10 \times 10$ mm LYSO crystal spectrum due to intrinsic radioactivity measured with the S8664-1010 Hamamatsu APD. Four sets of detected gammas are shown in the spectrum by arrows

crystal. In fact, gammas with 202 and 307 keV could leave the smaller crystal with much higher probability, which results in suppression of the sum $88 + 202 + 307$ keV peak, as is seen in Fig. 12. Nevertheless, peaks of four sets of gammas could still be distinguished in the spectrum as marked by the arrows in Fig. 12.

A relatively small intrinsic counting rate of the $10 \times 10 \times 10$ mm crystal makes it possible to directly distinguish the full absorption peaks from the irradiation by the gamma sources, which is impossible with the $30 \times 30 \times 130$ mm crystal, where the difference method has to be employed. Moreover, when the crystal simultaneously is irradiated with the ^{22}Na and ^{137}Cs gamma sources, all three full absorption peaks (511, 662 and 1275 keV) are well resolved, as is seen in Fig. 13.

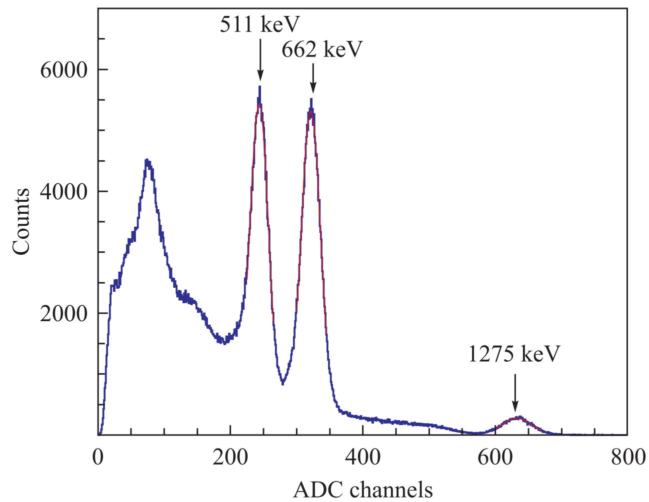

Fig. 13. The $10 \times 10 \times 10$ mm LYSO crystal spectrum due to intrinsic radioactivity and ^{22}Na and ^{137}Cs irradiation. Three full absorption peaks are fitted with Gaussians

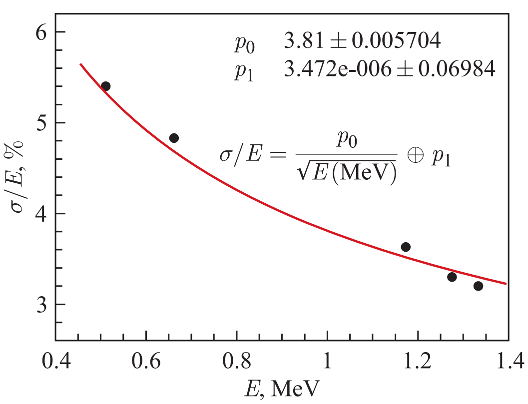

Fig. 14. The $10 \times 10 \times 10$ mm LYSO crystal energy resolution measured by the S8664-1010 Hamamatsu APD as a function of the photon energy

Energy resolutions were obtained for all full absorption peaks of three gamma sources. The energy resolution as a function of the gamma energy is shown in Fig. 14 for the whole measured energy range of 511–1333 keV. Error bars are smaller than the marker sizes. The experimental points are again fitted with a function of $\sigma/E = p_0/\sqrt{E(\mathrm{MeV})} \oplus p_1$ with fit parameters $p_0 = (3.81 \pm 0.01)\%$ and $p_1 = (0.00 \pm 0.07)\%$. One can see that the $10 \times 10 \times 10$ mm crystal with the S8664-1010 Hamamatsu APD readout has even better energy resolution than the $30 \times 30 \times 130$ mm crystal with the PMT readout. This is because the light collection conditions are better in the small crystal.

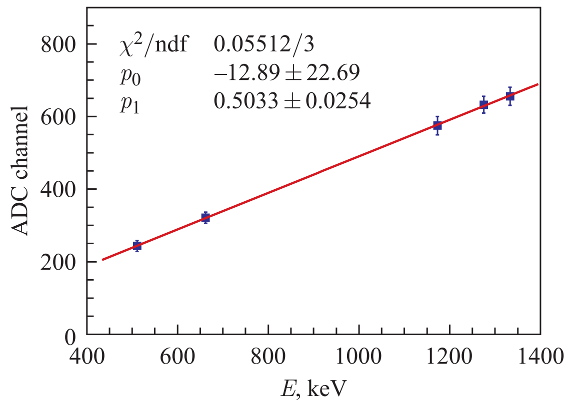

Fig. 15. The $10 \times 10 \times 10$ mm LYSO crystal energy response linearity in the 511–1333 keV range measured by the S8664-1010 Hamamatsu APD

The $10\times10\times10$ mm LYSO crystal energy response linearity for the range of 511–1333 keV is presented in Fig. 15. All points are well fitted with a linear function demonstrating good crystal energy response linearity.

CONCLUSION

The LYSO crystals of dimensions $30\times30\times130$ mm with PMT readout and $10\times10\times10$ mm with the S8664-1010 Hamamatsu APD readout were tested using the ^{22}Na, ^{137}Cs and ^{60}Co gamma sources. Energy resolutions and linearity of the crystal response in the energy range of 511–1333 keV were measured. It was found that the crystals had good linearity of the response in the full tested energy range. Light response nonuniformity of the $30\times30\times130$ mm crystal was measured with ^{22}Na moving along the crystal axis and found to be less than 3.2% in the 35–120 mm range from the crystal face.

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