Comparison of Photofraction for LuYAP:Ce, LYSO:Ce and BGO Crystals in Gamma Ray Detection

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Abstract
Photofractions of $Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce), $Lu_{1.95}Y_{0.05}SiO_5$:Ce (LYSO:Ce), and $Bi_4Ge_3O_{12}$ (BGO) scintillation crystals in gamma ray detection have been compared using photomultiplier tube readout for photon energies at 320, 511, and 662 keV. BGO showed much higher photofraction than LuYAP:Ce and LYSO:Ce in a same trend with the cross-section ratio obtained from WinXCOM program. The scintillation light yield and energy resolution of gamma ray energy were measured and the intrinsic resolution of all crystals was determined after correcting the measured energy resolution for PMT statistics. For 662 keV gamma rays (^{137}Cs source), LuYAP:Ce and LYSO:Ce showed the comparable energy resolution of about 8 %, while energy resolution of BGO is the worst.

Keyword: BGO, gamma ray detection, LuYAP:Ce, LYSO:Ce, photofraction

1. Introduction

The study of scintillation properties of inorganic crystal is important in many scientific, industrial and biological applications for their potential use in radiation physics, medical physics and dosimetry, industry, and radiation shielding. Scintillation materials play an important role in detection and spectroscopy of energetic photons. Important requirements for the scintillation crystals used in these applications include high light yield, fast response time, high stopping power, good energy resolution, good proportionality of the light yield, minimal afterglow, and low production costs. Good reviews on development of inorganic-scintillators and development of scintillation crystals for gamma ray spectrometry have been published by van Eijk[1], Moszynski[2], and recently by Lecoq et al.[3].

For gamma ray detection and medical imaging, important requirements for scintillation crystals are high stopping power and good energy resolution. During last years many efforts were devoted to the development of heavy scintillators based on cerium-doped crystals for these applications. Adding lutetium (Lu) in these crystals will help to detect high gamma rays better. The photofraction of spectrum of gamma ray energy can express high stopping power property of scintillation crystal.

The aims of this work are to perform a further study of photofraction of new heavy scintillator ($Lu_{0.7}Y_{0.3}AlO_3$:Ce and $Lu_{1.95}Y_{0.05}SiO_5$:Ce crystals) for photon energies at 320, 511, and 662 keV, and compare to those of $Bi_4Ge_3O_{12}$ crystal. The light yield versus the energy of gamma rays and corresponding energy resolution, and the intrinsic energy resolution of all tested crystals will also be discussed.

2. Methodology

$Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce) and $Lu_{1.95}Y_{0.05}SiO_5$:Ce (LYSO:Ce) crystals with the same size of 10x10x5 mm^3 were supplied by Proteus Inc. (USA) and $Bi_4Ge_3O_{12}$ (BGO) crystal with the size of 15x15x4 mm^3 was supplied by Shanghai Institute of Ceramics (P.R.China). Each crystal was optically coupled to a Photonis XP5200B photomultiplier tube (PMT) using silicone grease. All measurements were made using standard NIM level electronics. The gamma sources were positioned along the cylindrical axis of the scintillator and the PMT. The signal from the PMT anode was passed to a CANBERRA2005 preamplifier and was sent to a Tennelec TC243 spectroscopy amplifier. A shaping time constant of 4 µs was used in all measurements. The energy spectra were recorded using a Tukan PC-based multichannel analyzer (MCA) [4].

3. Results and Discussion

Energy Spectra and Photofraction.

The photofraction is defined here as the ratio of counts under the photopeak to the total counts of the spectrum as measured at a specific gamma ray energy. Fig. 1, 2, and 3 present a comparison of the energy spectra for 320, 511, and 662 keV gamma rays from a ^{51}Cr, ^{22}Na, and ^{137}Cs source, respectively, measured with all tested crystals.

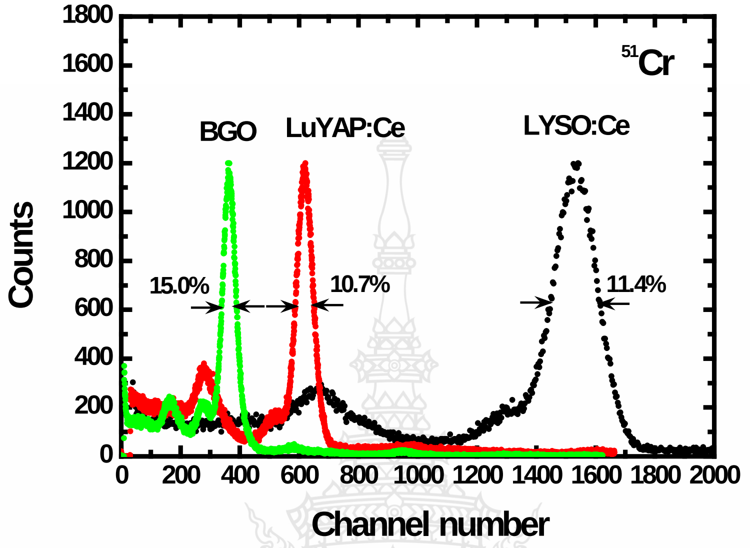

Fig. 1 Energy spectra of 320 keV gamma rays from a ^{51}Cr source measured with LuYAP:Ce, LYSO:Ce and BGO crystals.

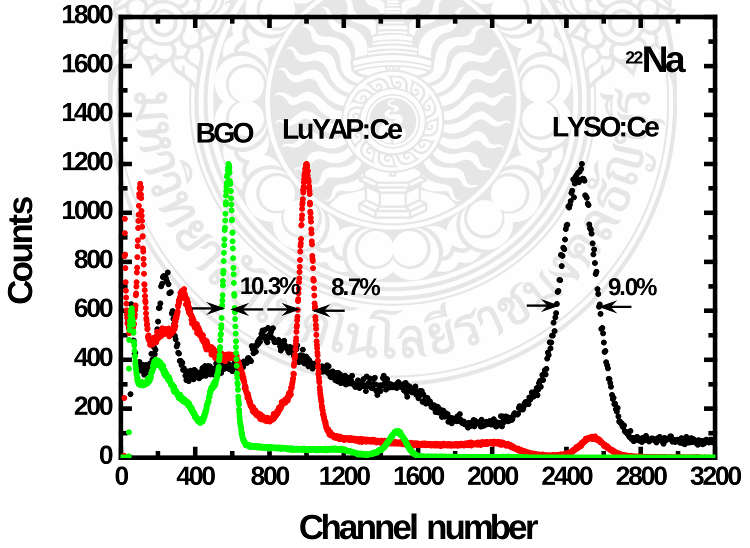

Fig. 2 Energy spectra of 511 keV gamma rays from a ^{22}Na source measured with LuYAP:Ce, LYSO:Ce and BGO crystals.

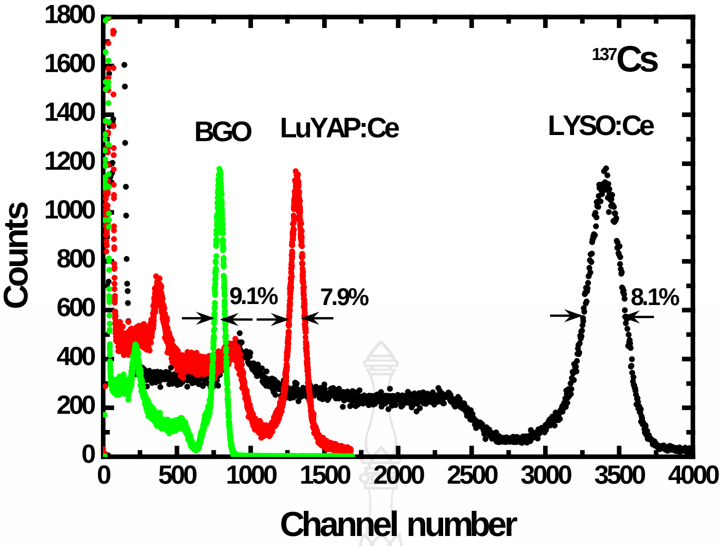

Fig. 3 Energy spectra of 662 keV gamma rays from a ^{137}Cs source measured with LuYAP:Ce, LYSO:Ce and BGO crystals.

The photofraction for LuYAP:Ce, LYSO:Ce, and BGO at 320, 511, and 662 keV gamma peak is collected in Table 1, 2,and 3, respectively. For a comparison, the ratio of the cross-sections for the photoelectric effect to the total one calculated using WinXCom program[5] are given too. The data indicate that BGO shows much higher photofraction than LuYAP:Ce and LYSO:Ce in a same trend with the cross-section ratio (σ-ratio) obtained from WinXCom program. The reason is due to much higher effective atomic number (Z_{eff}) and volume of the BGO crystal.

Table 1 Photofraction at 320 keV gamma peak for LuYAP:Ce, LYSO:Ce, and BGO crystals

Crystal	Z_{eff}	Volume (cm^3)	Photofraction (%)	σ-ratio (%)
LuYAP:Ce	60	0.5	45.62	47.3
LYSO:Ce	63.5	0.5	55.42	54.3
BGO	74	0.9	59.58	62.8

Table 2 Photofraction at 511 keV gamma peak for LuYAP:Ce, LYSO:Ce, and BGO crystals

Crystal	Z_{eff}	Volume (cm^3)	Photofraction (%)	σ-ratio (%)
LuYAP:Ce	60	0.5	26.60	25.9
LYSO:Ce	63.5	0.5	32.83	32.1
BGO	74	0.9	37.64	41.1

Table 3 Photofraction at 662 keV gamma peak for LuYAP:Ce, LYSO:Ce, and BGO crystals

Crystal	Z_{eff}	Volume (cm^3)	Photofraction (%)	σ-ratio (%)
LuYAP:Ce	60	0.5	21.98	17.8
LYSO:Ce	63.5	0.5	31.59	22.8
BGO	74	0.9	38.83	30.8

Table 4 summarizes comparative measurements of photoelectron yield and energy resolution at 662 keV gamma rays for the tested crystals. The photoelectron yield, expressed as a number of photoelectrons per MeV (phe/MeV) for each gamma peak, was measured by Bertolaccini method [6, 7]. In this method the numbers of photoelectrons are measured by comparing the position of a full energy peak of gamma rays detected in the crystals with that of the single photoelectron peak from the photocathode, which determines the gain of PMT. The LYSO:Ce showed the photoelectron yield of 7,620 phe/MeV. This value corresponds to about 28,600 photons/MeV (ph/MeV) at the PMT photocathode quantum efficiency (QE) of 26.5% for peak emission at 420 nm. The tested LuYAP:Ce showed the photoelectron yield of 2,930 phe/MeV. This value corresponds to about 9,800 ph/MeV at the QE of 29.8% for peak emission at 375 nm. The BGO showed the photoelectron yield of 1,780 phe/MeV. This value corresponds to about 8,600 ph/MeV at the QE of 20.5% for peak emission at 480 nm.

Table 4 Light yield and energy resolution at 662 keV gamma rays for tested crystals

Crystal	Photoelectron yield [phe/MeV]	Light yield [ph/MeV]	ΔE/E [%]
LuYAP:Ce	2,930 ± 150	9,800 ± 1000	7.9 ± 0.4
LYSO:Ce	7,620 ± 400	28,600 ± 2,800	8.1 ± 0.4
BGO	1,780 ± 100	8,600 ± 900	9.1 ± 0.5

Note the tested LuYAP:Ce showed the light yield of 9,800 ph/MeV. This value is higher than the value of 8,530 ph/MeV measured with small sample (2x2x10 mm^3) in Ref [8]. Superior energy resolution for tested LYSO:Ce than that of 8.7% reported for the 10x10x5 mm^3 LYSO:Ce crystal produced by Saint-Gobain [9] could be associated with its higher photoelectron yield, see above. These results show an improvement of light output for LuYAP:Ce and LYSO:Ce crystals. The light yield and energy resolution obtained for the tested BGO are comparable to the values recently measured for the small sample (7x7x1 mm^3) of BGO[10].

Energy Resolution.

The energy resolution (ΔE/E) of a full energy peak measured with a scintillator coupled to a PMT can be written as [11]

$$(\Delta E/E)^2 = (\delta_{sc})^2 + (\delta_p)^2 + (\delta_{st})^2, \qquad (1)$$

where δ_{sc} is the intrinsic resolution of the crystal, δ_p is the transfer resolution and δ_{st} is the statistical contribution of PMT to the resolution.

The statistical uncertainty of the signal from the PMT can be described as

$$\delta_{st} = 2.355 \times 1/N^{1/2} \times (1 + \varepsilon)^{1/2}, \qquad (2)$$

where N is the number of the photoelectrons and ε is the variance of the electron multiplier gain, equal to 0.1 for an XP5200B PMT.

The transfer component depends on the quality of optical coupling of the crystal and PMT, homogeneity of quantum efficiency of the photocathode and efficiency of photoelectron collection at the first dynode. The transfer component is negligible compared to the other components of the energy resolution, particularly in the dedicated experiments [11].

The intrinsic resolution of a crystal is mainly associated with the non-proportional response of the scintillator [11, 12] and many effects such as inhomogeneities in the scintillator which can cause local variations in the scintillation light output and non-uniform reflectivity of the reflecting cover of the crystal.

Overall energy resolution and PMT resolution can be determined experimentally. If δ_p is negligible, intrinsic resolution δ_{sc} of a crystal can be written as follows

$$(\delta_{sc})^2 = (\Delta E/E)^2 - (\delta_{st})^2. \qquad (3)$$

To better understand the energy resolution of tested crystals in gamma ray spectrometry, the contribution of various components to the overall energy resolution was analyzed for 662 keV photopeak, and the results are presented in Table 5. The second column gives N, the number of photoelectrons produced in the PMT. The third column gives ΔE/E, the overall energy resolution at 662 keV photopeak. The PMT contribution (δ_{st}) was calculated using Eq.(2). From the values of ΔE/E and δ_{st} , the intrinsic resolution (δ_{sc}) was calculated using Eq.(3).

Table 5 Analysis of the 662 keV energy resolution for LuYAP:Ce, LYSO:Ce, and BGO detectors

Detector	N[electrons]	ΔE/E [%]	δ_{st} [%]	δ_{sc} [%]
LuYAP:Ce+XP5200B	1,940 ± 190	7.9 ± 0.4	4.8 ± 0.2	6.3 ± 0.3
LYSO:Ce+XP5200B	5,040 ± 500	8.1 ± 0.4	3.0 ± 0.2	7.5 ± 0.4
BGO+XP5200B	1,180 ± 120	9.1 ± 0.5	7.2 ± 0.4	5.5 ± 0.3

The photoelectron yield (and δ_{st}) of LYSO:Ce is clearly superior to LuYAP:Ce and BGO. However, there is a little progress in energy resolution for LYSO:Ce which due to a large contribution of its intrinsic resolution to the overall energy resolution.

4. Summary

In this work, the photofraction of LuYAP:Ce, LYSO:Ce, and BGO crystals were studied and compared in gamma ray spectrometry. Although BGO showed much higher photofraction than LuYAP:Ce and LYSO:Ce in all tested energies but its energy resolution is the worst. While LYSO:Ce showed highest photoelectron yield but there is a little progress in energy resolution for LYSO:Ce which due to a large contribution of its intrinsic resolution to the overall energy resolution. However, inhomogeneities of Ce-doped and some defects in the LYSO:Ce crystal could affect the energy resolution, and the crystalline quality of this sample could be further improved. In conclusion, the main advantages of LYSO:Ce are high density and photofraction which make it very promising scintillator for medical imaging and high energy gamma ray detection.

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