Scintillation Properties of YAP:Ce and LuYAP:Ce Crystals for Gamma Ray Detection

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Abstract

The scintillation properties of YAP:Ce and LuYAP:Ce crystals with the same size of 10 x 10 x 5 mm^3 were studied for gamma ray energies ranging from 22.1 keV to 1,274.5 keV. The light yield, its non-proportionality and the energy resolution were measured with a Photonis XP5200B PMT. For 661.6 keV gamma rays (^{137}Cs source), an energy resolution of 4.7 % obtained for YAP:Ce is much better than that of 8.6% obtained for LuYAP:Ce. The YAP:Ce showed a light yield non-proportionality of about 18 % upon lowering energy from 1,274.5 keV to 22.1 keV, which is better than that of about 22 % obtained for LuYAP:Ce. The estimated photofraction of 29.5% at 661.6 keV for LuYAP:Ce is much higher than that of 5.3% for YAP:Ce. The intrinsic resolution of the crystals versus energy of gamma rays has been determined after correcting the measured energy resolution for photomultiplier tube statistics. The overall and intrinsic energy resolutions are discussed.

Keywords: energy resolution, LuYAP:Ce, non-proportionality of the light yield, scintillation, YAP:Ce

1. INTRODUCTION

Inorganic scintillators play an important role in detection and spectroscopy of energetic photons and nuclear particles. 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 light yield, minimal afterglow and low production costs. Good reviews on development of inorganic-scintillators and inorganic scintillation detectors/systems have been published by Moszynski [1], van Eijk [2], and recently by Lecoq et al. [3].

The phenomenon of non-proportionality response and its relation with energy resolution have been studied for many alkali halide scintillators [4-10] and oxide based scintillators [11-16]. The scintillation response of alkali halides decreases as the photon energy increases, whereas oxide based scintillators in general show an increasing scintillation response with increasing photon energy, which levels at higher energies.

The aims of this work are to perform a further study of energy resolution and light output proportionality of $YAlO_3$:Ce (YAP:Ce) and $Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce) crystals covering energies from 22.1 keV to 1,274.5 keV. From the obtained data on photoelectron yield versus the energy of gamma rays and corresponding energy resolution, the light yield non-proportionality and the intrinsic energy resolution of both crystals were calculated. The estimated photofraction for both crystals at 661.6 keV gamma peak will also be discussed.

2. METHODOLOGY

Two cerium-doped crystals, YAP:Ce and LuYAP:Ce, with the same dimensions of 10 x10 x5 mm^3,supplied by Crytur Ltd.(Czech republic) and Opto Materials S.r.l. (Italy), respectively, were studied.

The crystals were optically coupled to a Photonis XP5200B photomultiplier tube using silicone grease. All measurements were made using standard NIM level electronics. The 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 TC244 spectroscopy amplifier. A shaping time constant of 4 μs was used with both crystals. The energy spectra were recorded using a Tukan PC-based multichannel analyzer (MCA) [17].

The photoelectron yield, expressed as a number of photoelectrons per MeV (phe/MeV) for each γ-peak, was measured by Bertolaccini method [18, 19]. 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 measurements of photoelectron yield and energy resolution were carried out for a series of gamma rays emitted by different radioactive sources in the energy range between 22.1 keV and 1,274.5 keV. For each gamma peak, the full width at half maximum (FWHM) and centroid of the full energy peak were obtained from Gaussian fitting software of Tukan MCA.

3. RESULTS AND DISCUSSION

3.1 Photoelectron yield and energy resolution

Fig 1. presents the energy spectra of 661.6 keV gamma rays from a ^{137}Cs source measured with YAP:Ce and LuYAP:Ce detectors. It is seen that YAP:Ce gives better energy resolution than LuYAP:Ce. The energy resolution of 4.7% obtained with YAP:Ce is much better than the value of 8.6% obtained with LuYAP:Ce. The energy resolution of 4.7% for the tested YAP:Ce crystal in this study is much better than the value of 5.7% observed by Moszynski et al.[20] for an equal sized YAP:Ce crystal supplied by Preciosa Co.(Turnov, Czech Republic). Note a higher photofraction in the spectrum measured with LuYAP:Ce, as would be expected due to a higher effective atomic number and density of the LuYAP:Ce crystal.

Table 1 summarizes comparative measurements of photoelectron yield, light yield and energy resolution at 661.6 keV gamma rays for the studied crystals coupled to the Photonis XP5200B PMT, as measured at 4 μs shaping time constant in the spectroscopy amplifier. The YAP:Ce showed a photoelectron yield of 10,790 phe/MeV. This value corresponds to about 40,700 Photon/MeV (ph/MeV) at the PMT photocathode quantum efficiency (QE) of 26.5% for peak emission of 347 nm. The tested LuYAP:Ce showed a photoelectron yield of 3,570 phe/MeV. This value corresponds to about 13,700 ph/MeV at a QE of 26% for peak emission of 375 nm.

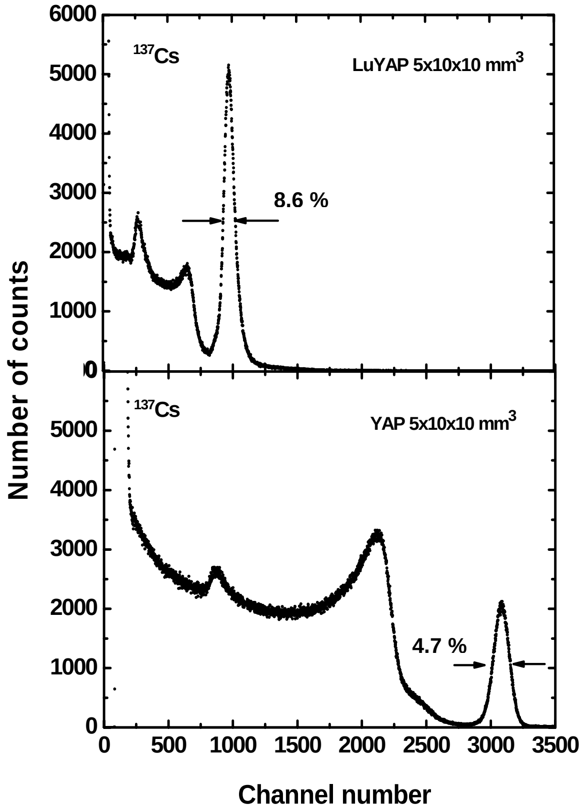

Fig.1 Energy spectra of 661.6 keV gamma rays from a ^{137}Cs source measured with YAP:Ce, and LuYAP:Ce crystals.

Table 1 Photoelectron yield, light yield and energy resolution at 661.6 keV gamma rays for the test crystals as measured with the Photonis XP5200B PMT.

Crystal	Photoelectron yield [phe/MeV]	Light yield [ph/MeV]	Energy resolution [%]
YAP:Ce	10,790	40,700	4.7
LuYAP:Ce	3,570	13,700	8.6

Note a significantly higher light yield of 40,700 ph/MeV for the tested YAP:Ce crystal, by about 240% compared with a same sized sample in Ref [20]. The tested LuYAP:Ce showed the light yield of 13,700 ph/MeV. This value is higher than the value of 8,530 ph/MeV measured with small sample ($2x2x10\ mm^3$) in Ref [21].

3.2 Non-proportionality of light yield

Light yield non-proportionality as a function of energy can be one of the important reasons for degradation in energy resolution of scintillators [22]. The non-proportionality is defined here as the ratio of photoelectron yield measured for photopeaks at specific gamma ray energy relative to the yield at 661.6 keV gamma peak.

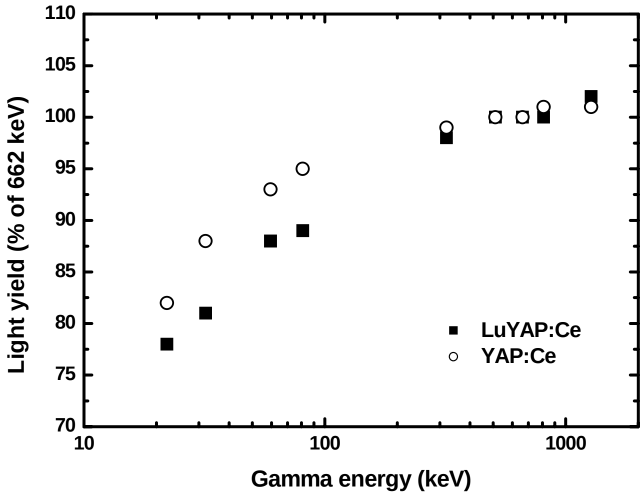

Fig.2 Non-proportionality in the light yield of YAP:Ce and LuYAP:Ce crystals. Error bars are within the size of the points.

Fig2. presents the non-proportionality characteristics of YAP:Ce and LuYAP:Ce crystals. Both crystals exhibit different non-proportionality curves. YAP:Ce is clearly superior to LuYAP:Ce in terms of light yield proportionality. Over the energy range from 22.1 keV to 1,274.5 keV, the non-proportionality is about 18% for YAP:Ce, which is better than that of about 22% for LuYAP:Ce. The higher proportionality of YAP:Ce should be reflected in its better intrinsic resolution.

3.3 Energy resolution

The energy resolution ($\Delta E/E$) of a full energy peak measured with a scintillator coupled to a photomultiplier can be written as [8]

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

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

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

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 [8].

The intrinsic resolution of a crystal is mainly associated with the non-proportional response of the scintillator [8,22] 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

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

Figs.3 and 4 present the measured energy resolution versus energy of gamma rays for YAP:Ce and LuYAP:Ce crystals, respectively. Other curves shown in Figs.3 and 4 represent the PMT resolution calculated from the number of photoelectrons and the intrinsic resolution of the crystals calculated from Eq. (3). Apparently, the energy resolution for the both crystals is mainly contributed by the intrinsic resolution over the whole energy range from 22.1 keV to 1,274.5 keV.

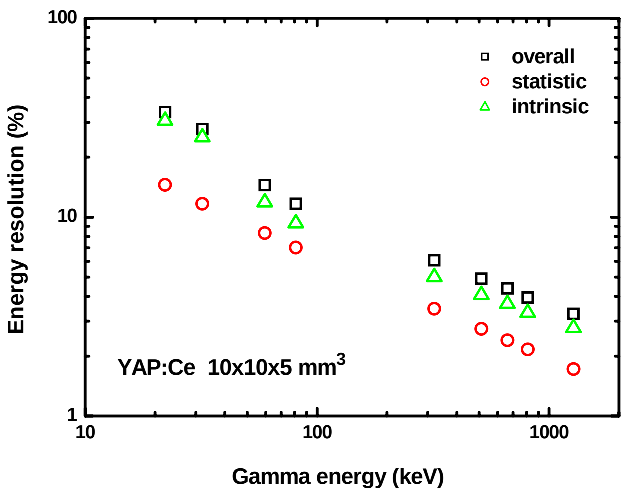

Fig. 3 Energy resolution and contributed factors versus energy of YAP:Ce crystal. Error bars are within the size of the points.

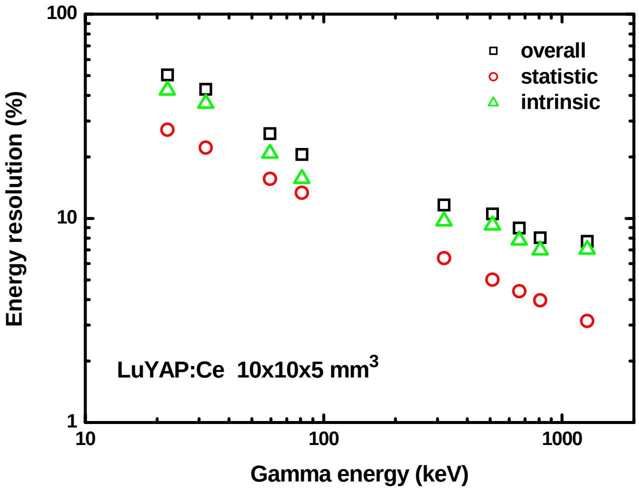

Fig. 4 Energy resolution and contributed factors versus energy of LuYAP:Ce crystal. Error bars are within the size of the points.

Overall energy resolution of YAP:Ce and LuYAP:Ce detectors versus energy is shown in Fig.5. The energy resolution for both crystals is approximately inversely proportional to the square root of the energy. The energy resolution of YAP:Ce is superior than that of LuYAP:Ce over the whole energy range from 22.1 keV to 1,274.5 keV.

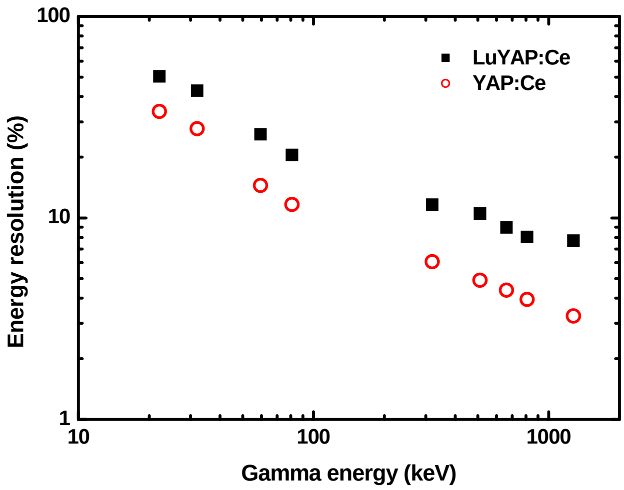

Fig. 5 Overall energy resolution of YAP:Ce and LuYAP:Ce crystals versus energy of gamma rays. Error bars are within the size of the points.

Fig. 6 presents a direct comparison of the intrinsic resolution for the studied crystals. The intrinsic resolution of YAP:Ce crystal is better (almost a factor of two at high energies) than that of LuYAP:Ce crystal, reflected by a better proportionality of the light yield (see Fig. 2).

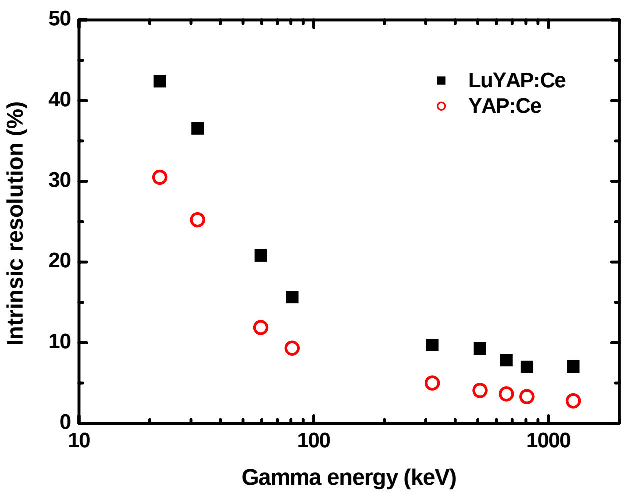

Fig. 6 Intrinsic resolution of YAP:Ce and LuYAP:Ce crystals versus energy of gamma rays. Error bars are within the size of the points.

To better understand the energy resolution of the studied crystals in gamma ray spectrometry, the contribution of various components to the overall energy resolution was analyzed for 661.6 keV photopeak, and the results are presented in Table 2. The second column gives N, the number of photoelectrons produced in the PMT. The third column gives ΔE/E, the overall energy resolution at 661.6 keV photopeak. The PMT contribution (δ_{st}) was calculated using (2). From the values of ΔE/E and δ_{st} , the intrinsic resolution (δ_{sc}) was calculated using (3).

Table 2 Analysis of the 661.6 keV energy resolution for YAP:Ce and LuYAP:Ce crystals.

Detector	N [electrons]	ΔE/E [%]	δ_{st} [%]	δ_{sc} [%]
YAP:Ce	7,140	4.7	2.9	3.7
LuYAP:Ce	2,360	8.6	5.1	7.0

The superior energy resolution of YAP:Ce as compared to LuYAP:Ce is mainly due to a small contribution of both δ_{st} and δ_{sc} , which seems to follow a high light output (almost a factor of three) and good proportionality of the light yield, respectively, for YAP:Ce crystal.

3.4 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. The photofraction for YAP:Ce and LuYAP:Ce at 661.6 keV gamma peak is collected in Table 3. For a comparison, the ratio of the cross-sections for the photoelectric effect to the total one calculated using WinXCom program [23] are given too. The data indicate that LuYAP:Ce shows much higher photofraction than YAP: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 and density of the LuYAP:Ce crystal.

Table 3 Photofraction at 661.6 keV gamma peak for YAP:Ce and LuYAP:Ce crystals.

Crystal	Photofraction (%)	σ- ratio (%)
YAP:Ce	5.3	2.6
LuYAP:Ce	29.5	17.8

4. CONCLUSION

In this work, the scintillation properties of YAP:Ce and LuYAP:Ce crystals were studied and compared in gamma ray spectrometry. The energy resolution of YAP:Ce is superior than that of LuYAP:Ce due to a high light output and small contribution from its intrinsic resolution, reflecting a better proportionality of light yield between 22.1 keV and 1,274.5 keV. This study demonstrates that the contribution from the non-proportional response of the scintillator is correlated with the intrinsic resolution of the scintillators. Moreover, inhomogeneities of Ce-doped and some defects in the LuYAP:Ce crystal could affect the energy resolution, and the crystalline quality of this sample could be further improved. In conclusion, the main advantages of LuYAP:Ce are high density and photofraction which make it very promising scintillator for high energy gamma ray detection. The main advantage of YAP:Ce is a good energy resolution. However, it is not suitable for gamma rays above 300 keV due to its low effective atomic number and density which limit the photopeak detection efficiency.

5. ACKNOWLEDGMENTS

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