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# Light output and energy resolution of $Lu_{0.7}Y_{0.3}AlO_3$:Ce and $Lu_{1.95}Y_{0.05}SiO_5$:Ce scintillators

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**Abstract**

Light output and energy resolution of $Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce) and $Lu_{1.95}Y_{0.05}SiO_5$:Ce (LYSO:Ce) single crystals with the same size were investigated for gamma ray energies ranging from 22.1 to 1,274.5 keV. The light yield and energy resolution were measured with a Photonis XP5200B PMT. For 662 keV gamma rays ($^{137}$Cs source), the LYSO:Ce showed the light yield of 28,600 ph/MeV,which is much higher than that of 9,800 ph/MeV obtained for LuYAP:Ce. Both crystals showed comparable energy resolution of about 8%. The light yield non-proportionality and energy resolution versus energy of gamma rays were measured and the intrinsic resolution of the crystals was determined after correcting the measured energy resolution for PMT statistics. The LuYAP:Ce showed a light yield non-proportionality of about 20% upon lowering energy from 1,274.5 to 22.1 keV, which is better than that of about 29% obtained for LYSO:Ce. The experimental results of photofraction are in good agreement with the theoretical values, calculated by WinXCom program.



*Keywords*: gamma-ray detectors ; LuYAP:Ce ; LYSO:Ce ; scintillators

## 1. Introduction

Inorganic scintillators play an important role in detection and spectroscopy of energetic photons and nuclear particles. Important requirements for the scintillators used in these applications include high light yield, fast response time, high stopping power and good energy resolution. Good reviews on development of inorganic-scintillators and inorganic scintillation detectors/systems have been published by van Eijk [1], Moszynski [2], and recently by Lecoq et al. [3].

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The phenomenon of non-proportionality response and its relation with energy resolution have been studied for many alkali halide scintillators [4-6] and oxide based scintillators [7-9]. 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 light output, energy resolution and non-proportionality of the light yield of $Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce) and $Lu_{1.95}Y_{0.05}SiO_5$:Ce (LYSO: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 662 keV gamma peak will also be discussed.

## 2. Methodology

LuYAP:Ce and LYSO:Ce crystals with the same size of 10x10x5 $mm^3$ were supplied by Proteus Inc. (USA). Each crystal was optically coupled to a Photonis XP5200B photomultiplier tube (PMT) using silicone grease and covered with several layers of Teflon tape. 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 Canberra 2005 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) [10].

The photoelectron yield, expressed as a number of photoelectrons per MeV (phe/MeV) for each gamma peak, was measured by Bertolaccini method [11,12]. In this method the number of photoelectrons is 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 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. Energy Spectra and Light Yield*

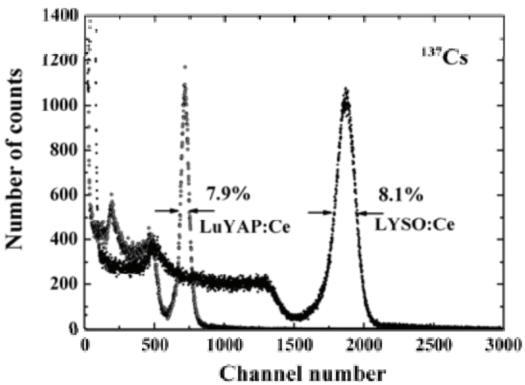



Fig. 1. Energy spectra of 662 keV gamma rays from a $^{137}$Cs source measured with LuYAP:Ce and LYSO:Ce crystals

Fig. 1 presents a comparison of the energy spectra for 662 keV gamma rays from a $^{137}Cs$ source measured with LuYAP:Ce and LYSO:Ce crystals. It is seen that both crystals give a comparable energy resolution of about 8 %. Note a higher photofraction in the spectrum measured with LYSO:Ce, as would be expected due to a higher effective atomic number of the LYSO:Ce crystal.

Table 1 summarizes comparative measurements of photoelectron yield and energy resolution at 662 keV gamma rays for the tested crystals. The LuYAP:Ce showed a photoelectron yield of 2,930 phe/MeV. This value corresponds to about 9,800 photons/MeV (ph/MeV) at the PMT photocathode quantum efficiency (QE) of 29.8% for peak emission at 375 nm. The LYSO:Ce showed a photoelectron yield of 7,620 phe/MeV. This value corresponds to about 28,600 ph/MeV at a QE of 26.6% for peak emission at 420 nm. Note the light yield of 9,800 ph/MeV for LuYAP:Ce is higher than the value of 8,530 ph/MeV measured with small sample ($2\times2\times10$ mm$^3$) in Ref. [13].

Table 1. Photoelectron yield, light yield and energy resolution at 662 keV γ-rays for the studied crystals as measured with the XP5200B PMT

| Crystal | Photoelectron yield [phe/MeV] | Light yield [ph/MeV] | ΔE/E [%] |
|---|---|---|---|
| LuYAP:Ce | 2,930 ± 300 | 9,800 ± 1,000 | 7.9 ± 0.4 |
| LYSO:Ce | 7,620 ± 800 | 28,600 ± 2,800 | 8.1 ± 0.4 |

### 3.2. Non-proportionality of the Light Yield

Non-proportionality of the light yield as a function of energy can be one of the important reasons for degradation in energy resolution of scintillators [4]. The non-proportionality is defined here as the ratio of photoelectron yield measured for photopeaks at specific gamma ray energies relative to the yield at 662 keV gamma peak.

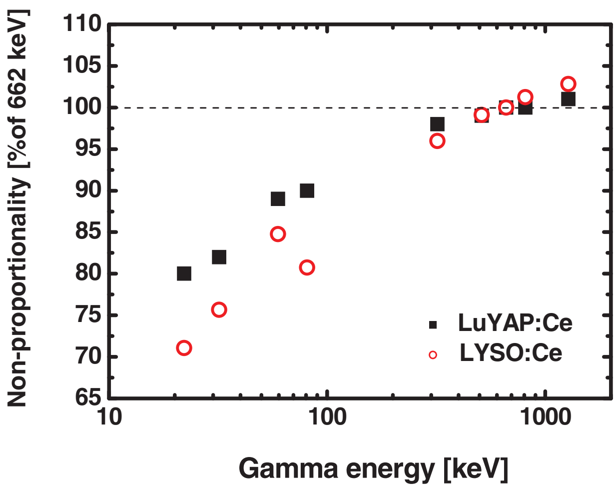



Fig. 2. Non-proportionality of the light yield as a function of γ-ray energy, measured with LYSO:Ce and LSO:Ce crystals

Fig. 2 presents the non-proportionality characteristics of LuYAP:Ce and LYSO:Ce crystals. both crystals exhibit different non-proportionality curves. LuYAP:Ce is clearly superior to LYSO:Ce in terms of light yield proportionality. Over the energy range from 22.1 to 1,274.5 keV, the non-proportionality is about 20 % for LuYAP:Ce, which is better than that of about 29 % for LYSO:Ce. The higher proportionality of LuYAP: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 PMT can be written as [5]

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

where $\delta_{sc}$ is the intrinsic resolution of the crystal, $\delta_p$ is the transfer resolution and $\delta_{st}$ is the statistical contribution of PMT to the resolution.

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

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

where N is the number of the photoelectrons and $\varepsilon$ 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 [5].

The intrinsic resolution of a crystal is mainly associated with the non-proportional response of the scintillator [5] 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 $\delta_p$ is negligible, intrinsic resolution $\delta_{sc}$ of a crystal can be written as follows

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

Fig. 3 presents the measured energy resolution versus energy of gamma rays for LuYAP:Ce and LYSO:Ce crystals. Other curves shown in Fig. 3 represent the PMT resolution calculated from the number of photoelectrons and the intrinsic resolution of the crystals calculated from Eq. (3).

Overall energy resolution and the intrinsic resolution of both crystals versus energy are shown in Fig.4 (a) and (b), respectively. The energy resolution for both crystals is approximately inversely proportional to the square root of the energy. The energy resolution of both crystals is comparable. The intrinsic resolution of LuYAP:Ce is better than that of LYSO:Ce, which is reflected by a better proportionality of its light yield (see Fig. 2).

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 2. The second column gives N, the number of photoelectrons produced in the PMT. The third column gives $\Delta E/E$, the overall energy resolution at 662 keV photopeak. The PMT contribution ($\delta_{st}$) was calculated using Eq. (2). From the values of $\Delta E/E$ and $\delta_{st}$, the intrinsic resolution ($\delta_{sc}$) was calculated using Eq. (3).

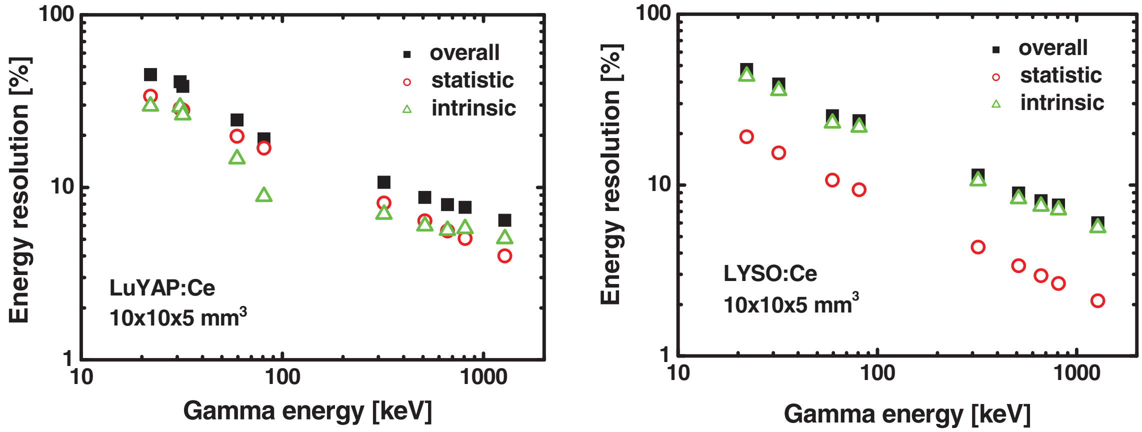
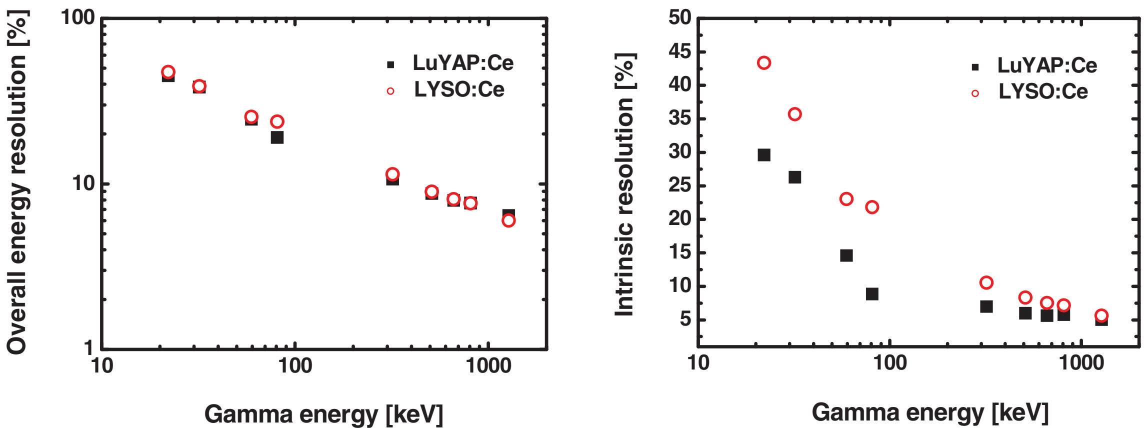



Fig. 3. Energy resolutions and its contributed factors versus gamma energy for LuYAP:Ce and LYSO:Ce crystals




(a) (b)

Fig. 4. (a) Overall energy resolution and (b) intrinsic resolution of LuYAP:Ce and LYSO:Ce crystals

The photoelectron yield (and $\delta_{st}$) of LYSO:Ce is clearly superior to LuYAP:Ce. 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.

Table 2. Analysis of the 662 keV energy resolution for LuYAP:Ce and LYSO:Ce crystals

| Detector | N [electrons] | $\Delta E/E$ [%] | $\delta_{st}$ [%] | $\delta_{sc}$ [%] |
|---|---|---|---|---|
| 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 |

### *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 LuYAP:Ce and LYSO:Ce at 662 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 [14] are given too. The data indicate that LYSO:Ce shows higher photofraction than LuYAP:Ce in a same trend with the cross-section ratio ($\sigma$-ratio) obtained from WinXCom program. The reason is due to higher effective atomic number ($Z_{eff}$) of the LYSO:Ce crystal.

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

| Crystal | $Z_{eff}$ | Density (g/cm$^3$) | Photofraction (%) | $\sigma$- ratio (%) |
|---|---|---|---|---|
| LuYAP:Ce | 60 | 7.1 | 27.9 ± 2.8 | 20.5 |
| LYSO:Ce | 63.5 | 7.1 | 34.9 ± 3.5 | 22.6 |

## 4. Summary

In this work, the light output and the energy resolution of LuYAP:Ce and LYSO:Ce crystals were studied and compared in gamma ray spectrometry. Both crystals showed comparable energy resolution of about 8% for 662 keV gamma rays from a $^{137}$Cs source. Although the light yield (and $\delta_{st}$) of LYSO:Ce is clearly superior to LuYAP:Ce 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. The photofraction of LYSO:Ce is superior to that of LuYAP:Ce due to higher effective atomic number of the LYSO:Ce crystal.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