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Comparative study of light yield non-proportionality and energy resolution properties of Ce-doped $LaBr_3$ and LuYAP scintillator crystals

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Abstract

The purpose of this work is to compare the light yield non-proportionality and energy resolution of Ce-doped $LaBr_3$ ($LaBr_3$:Ce) and $Lu_{0.7}Y_{0.3}AlO_3$ (LuYAP:Ce) scintillator crystals at the energy range from 356 keV to 1,332 keV. The result showed that the $LaBr_3$:Ce detector has an energy resolution of 4.0% that is better than that of 8.3% for LuYAP:Ce at the gamma ray energy 662 keV (137Cs source). Moreover, the $LaBr_3$:Ce and LuYAP:Ce scintillators have intrinsic resolution of 2.2% and 5.4%, respectively at the gamma ray energy 662 keV. However, the energy resolution of $LaBr_3$:Ce depends on the characteristic of $LaBr_3$:Ce and the type of PMT. From LuYAP:Ce it was found that the energy resolution depended on the characteristic of LuYAP:Ce and the type of PMT at high energy. But in low energy, the energy resolution depends on the characteristic of LuYAP:Ce only. Both crystals showed the trend of energy resolution, intrinsic resolution and statistical resolution are linear function with $1/\sqrt{E}$. At the gamma – ray energy 662 keV (^{137}Cs source) the $LaBr_3$:Ce showed the light yield of 46,381 ph/MeV, which is higher than that of 12,934 ph/MeV obtained from LuYAP:Ce. The light yield non-proportionality of the LaBr3:Ce and LuYAP:Ce scintillator was measured at the energy range from 356 keV to 1,332 keV. The results showed the non-proportionality within 1% of both crystals. It can be concluded that the $LaBr_3$:Ce and LuYAP:Ce have good proportionality at this energy range.

Keywords: Energy resolution; Light yield; $LaBr_3$:Ce; $Lu_{0.7}Y_{0.3}AlO_3$:Ce

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1. Introduction

A scintillator is the transparent material which can be solid, liquid or gas. They can emit a flash of light in a short duration when it absorbs gamma – rays photon, the process is called scintillation. Scintillation crystals are widely used as spectroscopic detectors of ionizing radiation in nuclear science [1]. Scintillation detectors are divided into two categories: organic and inorganic, and the type of materials used depends on their application. In particular, the inorganic scintillator detector is widely used [2]. The important parameters indicate that the properties of scintillation crystals are the total light output expressed in the emitted number of photons per MeV of absorbed gamma rays photon and energy resolution of scintillation detectors. Experimental and theoretical studies have been showed that the energy resolution of scintillators does not depend only on the light output of a crystal, but also limited by the non-proportional response of scintillators [3]. The light yield non-proportionality is the nonlinear dependence of the total light output of the scintillator on the detected amount of gamma rays energy. The properties of scintillator crystals through the energy resolution and the light yield non-proportionality have been studied from last decade. Discovery of Ce-doped scintillators is particularly interesting because it has good energy resolution and show an effective proportionality of the light output in the large range of gamma ray energies [4].

$LaBr_3$:Ce scintillator, is one of the best inorganic scintillators commercially available due to high light output, fast decay time with an excellent energy resolution and wide usage [5]. It has potential to replace NaI:Tl scintillator as the best choice for SPECT camera and gamma ray spectrometry [3]. $LaBr_3$:Ce could become an interesting alternative material to HPGe detector in gamma spectroscopy in situations in which the measured spectra are not very complex because the velocity of the emitting source is larger than the intrinsic resolution of the HPGe and comparable to that of $LaBr_3$:Ce [6]. The general properties of $LaBr_3$:Ce are described in [7,8].

$Lu_{0.7}Y_{0.3}AlO_3$:Ce (LuYAP:Ce) scintillator, was proposed some years ago as attractive candidates for application in nuclear physics and medical imaging mainly due to their fast decay time and high stopping power for 511 keV photons [9]. LuYAP:Ce shows better properties with respect to its precursor: an increased light yield and energy resolution and shorter decay time. LuYAP:Ce is not hygroscopic that makes crystal easy to be cut and polished and consequently particularly attractive for array configuration with a wide possibility of optical treatment surfaces [9]. These features made LuYAP:Ce crystal interesting for Positron emission tomography (PET) applications and in particular, its short decay time, it was chosen to be used together with LYSO in a phoswich configuration of a time of flight PET scanner with depth of interaction capability [9]. The general properties of LuYAP:Ce are described in the previous literature [10–12].

The purposes of this work is to compare the light yield non-proportionality at the energy range 356 keV to 1,332 keV and energy resolution at gamma–ray energy 662 keV (^{137}Cs source) of $LaBr_3$:Ce and LuYAP:Ce scintillators.

2. Theory of Energy Resolution and Light Yield Non-Proportionality of Scintillation Detectors

2.1 Energy Resolution and Intrinsic Resolution

The energy resolution is a factor that indicates the ability of the detector to resolve small difference in the energy of incident gamma rays. When a pulse spectrum (energy spectrum) is obtained, the energy resolution R , is defined as the full width at half maximum ΔE_{FWHM} , of the energy peak. It is often expressed as a percentage of the energy corresponding to the position of the peak along the x – axis E_0 . which is defined as [13]:

$$R = \frac{\Delta E_{\mathrm{FWHM}}}{E_0} \times 100\% \tag{1}$$

The three basic parameters that affect the energy resolution of the whole systems R , are the intrinsic resolution of scintillation R_{i} , transport resolution R_{p} and resolution of the photomultiplier tube (PMT) R_{M} (statistic resolution). Therefore, the total energy resolution of the detector can be written as [14]

$$R^2 = R_{\mathrm{i}}^{\,2} + R_{\mathrm{p}}^{\,2} + R_{\mathrm{M}}^{\,2} \tag{2}$$

The contribution of the PMT, R_{M} to the total energy resolution of the scintillation detector depends on the light output that can be accordingly described as [15]

$$R_{\mathrm{M}} = 2.355 \times \left(\frac{1}{\sqrt{N}} \right) \times \left(1+\varepsilon\right)^{1/2}, \tag{3}$$

Where N is the number of photoelectron, and ε is the variance of the gain during multiplication of photoelectron in the PMT that equals to 0.1 for an R4607A – 27 PMT.

The transferred component depends on the quality of the optical coupling of the crystal and PMT, homogeneity of the 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 [15].

The intrinsic resolution is particularly important for the non-proportional light output [14–15], and connected with many effects such as inhomogeneities in the scintillator causing local variations of the light output and non – uniform reflectivity of the reflecting covering of the crystal.

The transfer resolution R_{p}, is often assumed to be negligible compared to the two other factors [16]. Therefore from the Eq. (2) the value of intrinsic resolution R_{i} can be found as follows [15]:

$$R_{\mathrm{i}}^2 = R^2 - R_{\mathrm{M}}^2 \tag{4}$$

2.2 Light Yield and Light Yield Non-Proportionality

Light yield of crystal derived from pulse height spectra under gamma ray energy excitation can be expressed in number of photoelectrons $\left(N_{\mathrm{phe}}\right)$ per MeV of absorbed gamma ray energy, following this expression [17]:

$$Y = \frac{N_{\mathrm{phe}}}{E_{\gamma}\left(\mathrm{MeV}\right)} \tag{5}$$

Light yield of each gamma energy derived normalization compared to light yield measured by ^{137}Cs, 662 keV gamma energy can be defined as the following expression [17]:

$$\text{Light yield non-proportionality} = \frac{\text{light yield of each } E_{\gamma}}{\text{light yield of 662 keV } E_{\gamma}} \tag{6}$$

3. Experimental

The $LaBr_3$:Ce scintillator was encapsulated in an aluminum in cylindrical shape with dimension $\phi\, 25.40\,\mathrm{mm} \times 10\,\mathrm{mm}$ and LuYAP:Ce scintillator is in the rectangular shape with dimension $10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 3\,\mathrm{mm}$. Both scintillators are coupled to a photomultiplier tube (PMT) model R4607A – 27 PMT using silicone grease and covered with several layers of Teflon tape to prevent light from outside and connected to a Canberra HV supply and a Canberra preamplifier (Model 2007B). The electronic signal is amplified by a Canberra amplifier (Model 2022) and convert to the digital signal by analog to digital converter (ADC). The digital signal was analyzed and the spectrum was showed using Multichannel Analyzer Gamma Acquisition & Analysis (MCA). The experimental setup is shown in Fig. 1. Gamma-rays sources ^{133}Ba (356 keV), ^{22}Na (511 keV and 1274keV), ^{137}Cs (662 keV) and ^{60}Co (1173 keV and 1332 keV) were used in this work. A shaping time constant of 4 μs was used in this measurement.

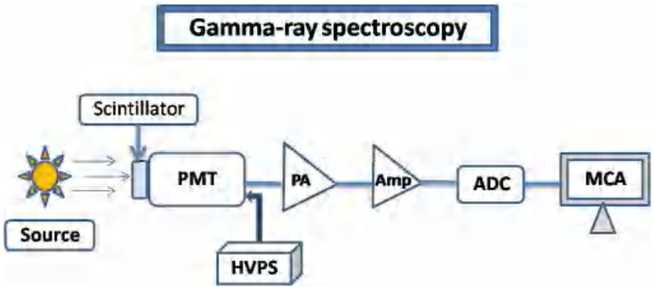

Fig. 1. Experimental setup for the light yield measurement of $LaBr_3$:Ce and LuYAP:Ce detectors.

4. Result and discussion

The gamma ray spectra have been measured for $LaBr_3$:Ce and LuYAP:Ce scintillations. From fig. 2. presents a comparison of the energy spectra at the gamma–ray energy of 662 keV (^{137}Cs source) measured with $LaBr_3$:Ce and LuYAP:Ce scintillators. The result shows that $LaBr_3$:Ce detector has an energy resolution of 4.0% that is better than that of 8.3% for LuYAP:Ce at the gamma–ray energy of 662 keV (^{137}Cs source). However, the energy resolution of $LaBr_3$:Ce detector makes the resolution of this detector better than NaI:Tl ~6% [18].

Fig. 3, presents a comparison of the energy resolution calculated using Eq. (1) for $LaBr_3$:Ce and LuYAP:Ce scintillators at the energy range from 356 keV to 1,332 keV. The energy resolution of $LaBr_3$:Ce is found to be decreased from 5.3% at 356 keV to 3.3% at 1,332 keV and LuYAP:Ce decreases from 18.7% at 356 keV to 5.4% at 1,332 keV. The results show that $LaBr_3$:Ce has better energy resolution than LuYAP:Ce in this energy range. The energy resolution is found to be a linear function with $1/\sqrt{E}$.

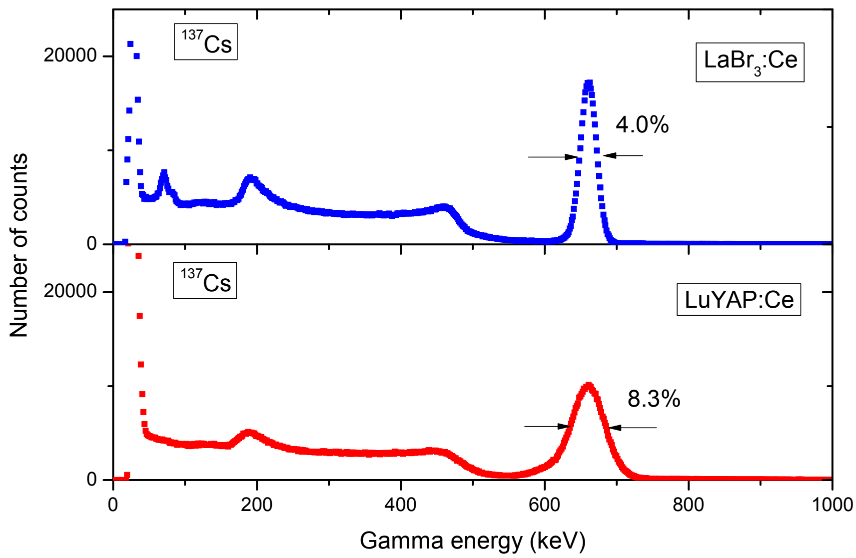

Fig. 2. Typical spectrum of 662 keV gamma – rays energy (^{137}Cs source) measured with $LaBr_3$:Ce and LuYAP:Ce scintillators.

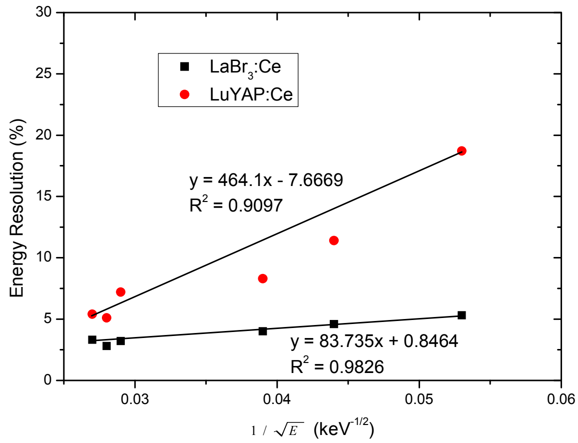

Fig. 3. Energy resolution of $LaBr_3$:Ce and LuYAP:Ce scintillators.

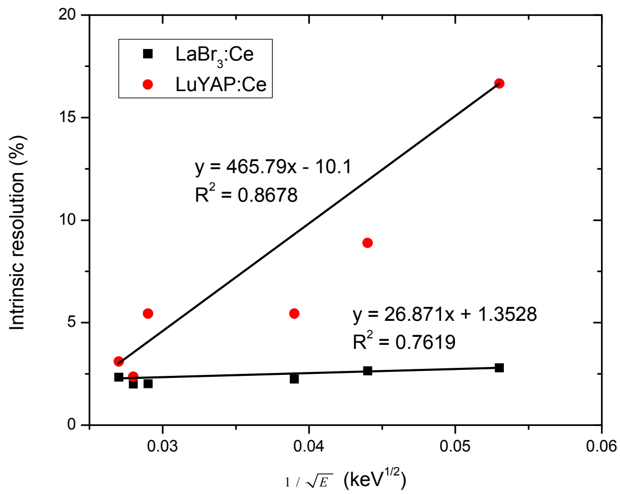

Fig. 4. Intrinsic resolution of $LaBr_3$:Ce and LuYAP:Ce scintillators.

Fig. 4, presents a comparison of the intrinsic resolution calculated using Eq. (4) for $LaBr_3$:Ce and LuYAP:Ce scintillators at the energy range from 356 keV to 1,332 keV. The intrinsic resolution of $LaBr_3$:Ce is found to be decreased from 2.8% at 356 keV to 2.3% at 1,332 keV and LuYAP:Ce decreases from 16.7% at 356 keV to 3.1% at 1,332 keV. The results show that $LaBr_3$:Ce has better intrinsic resolution than LuYAP:Ce in this energy range. The intrinsic resolution is found to be a linear function with $1/\sqrt{E}$.

Fig. 5, presents a comparison of the statistical resolution calculated by using Eq. (3) for $LaBr_3$:Ce and LuYAP:Ce scintillators at the energy range from 356 keV to 1,332 keV. The statistical resolution of $LaBr_3$:Ce is found to be decreased from 4.5% at 356 keV to 2.3% at 1,332 keV and LuYAP:Ce decreases from 8.5% at 356 keV to 4.4% at 1,332 keV. The results showed that $LaBr_3$:Ce has batter statistical resolution than LuYAP:Ce atthis energy range. The statistical resolution is found to be a linear function with $1/\sqrt{E}$.

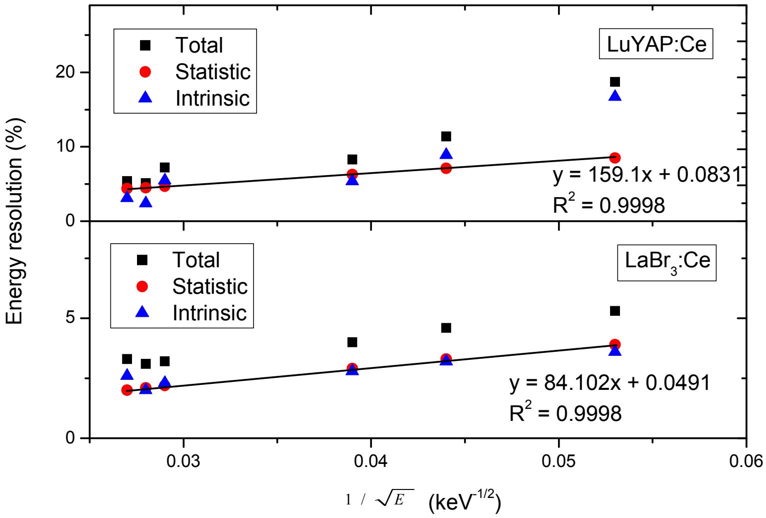

Fig. 5. Energy resolution and its contributed factors versus gamma energy for $LaBr_3$:Ce and LuYAP:Ce scintillators.

In $LaBr_3$:Ce was found to be the intrinsic resolutions similar with statistical resolutions. This result reflected to the energy resolution of $LaBr_3$:Ce, which is depend on the characteristic of $LaBr_3$:Ce and the type of PMT. In LuYAP:Ce it was found that the energy resolution is depend on the characteristic of LuYAP:Ce and the type of PMT at high energy. But at low energy, the energy resolution is depend on the characteristic of LuYAP:Ce only.

Fig. 6, presents a comparison of the light yield calculated using Eq. (5) for $LaBr_3$:Ce and LuYAP:Ce scintillators at energy range from 356 keV to 1,332 keV.

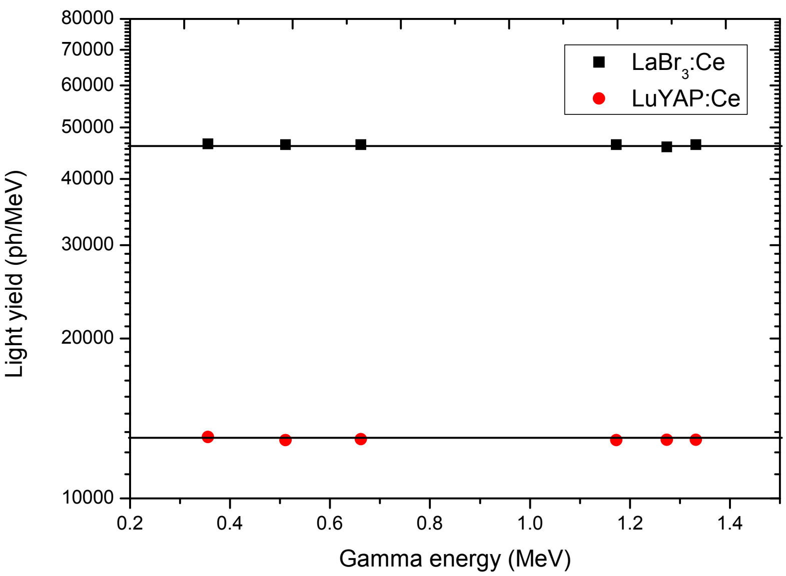

Fig. 6. The light yield of $LaBr_3$:Ce and LuYAP:Ce scintillators

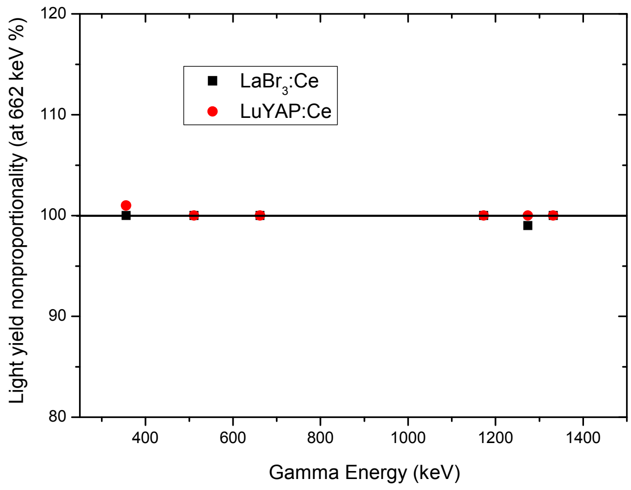

Fig. 7. The light yield non-proportionality as a function of gamma – ray energy, measured with $LaBr_3$:Ce and LuYAP:Ce scintillators.

The $LaBr_3$:Ce showed the light yield of 46,381 ph/MeV at the gamma – ray energy 662 keV (^{137}Cs source). The LuYAP:Ce showed the light yield of 12,934 ph/MeV at the gamma – ray energy 662 keV (^{137}Cs source). The results showed that $LaBr_3$:Ce has higher light yield than LuYAP:Ce at this energy range.

The light yield non-proportionality is defined as the ratio of light yield measured at specific gamma ray energy relative to the light at 662 keV (^{137}Cs source) gamma peak. Fig. 7, presents the comparison of the light yield non-proportionality characteristics measured for $LaBr_3$:Ce and LuYAP:Ce scintillators.

The results showed the non – proportionality within 1% of both crystal. It can be concluded that the $LaBr_3$:Ce and LuYAP:Ce have good proportionality at this energy range.

5. Conclusion (Please revise all conclusion part specifically in grammar and English)

In the present work, the comparative study of light yield non-proportionality and the energy resolution of $LaBr_3$:Ce and LuYAP:Ce scintillators were studied and compared in gamma ray spectrometry. The obtained results showed that the $LaBr_3$:Ce detector was excellent and better energy resolution at the gamma – ray energy 662 keV (^{137}Cs source) as compared with LuYAP:Ce. The intrinsic resolution of $LaBr_3$:Ce at energy range from 356 keV to 1,332 keV is also better than LuYAP:Ce. However, the energy resolution of both crystals were depended on the characteristic of $LaBr_3$:Ce, LuYAP:Ce and the type of PMT, but at low energy the energy resolution is depended on the characteristic of LuYAP:Ce only. Both crystals were showed a trend of energy resolution, intrinsic resolution and statistical resolutions are linear function with $1/\sqrt{E}$. Moreover, the light yield of $LaBr_3$:Ce is higher than LuYAP:Ce at energy range from 356 keV to 1,332 keV. The non–proportionality within 1% of both crystal. It can be conclude that the $LaBr_3$:Ce and LuYAP:Ce have good proportional in this energy range.

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