The 15th International Conference of International Academy Physical Sciences (CONIAPS XV)
Dec 9 - 13, 2012, Rajamangala University of Technology Thanyaburi, Thailand

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<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of Photofraction for LuYAP:Ce, LYSO:Ce and BGO Crystals in Gamma Ray Detection</td>
<td>1</td>
</tr>
<tr>
<td>Akapong Phunpuek, Weerapong Cheowpraditkul, Voranuch Thongpool</td>
<td></td>
</tr>
<tr>
<td>Similarity Solution for MHD Plane Free Jet as Boundary Layer Flow Induced by Impermeable Stretching Plane</td>
<td>7</td>
</tr>
<tr>
<td>Anuj Kumar Jhankal and Manoj Kumar</td>
<td></td>
</tr>
<tr>
<td>Automatic Adaptive Retrieval of Learning Objects Based on Learner Characteristics</td>
<td>11</td>
</tr>
<tr>
<td>Burasakorn Yoosooka</td>
<td></td>
</tr>
<tr>
<td>On the Diophantine Equation $p^x + p^y = z^2$</td>
<td>17</td>
</tr>
<tr>
<td>Mongkol Tatong and Alongkol Suvarnamani</td>
<td></td>
</tr>
<tr>
<td>Hybrid Dhage's Fixed Point Theorem for Abstract Measure Integro-Differential Equations</td>
<td>21</td>
</tr>
<tr>
<td>Sidheshwar S. Bellale</td>
<td></td>
</tr>
<tr>
<td>Information System of Personalization Thai Health Food Menu for Elderly Persons</td>
<td>27</td>
</tr>
<tr>
<td>Suvarin Pattamavorakun, Jaturapith Krohkaew</td>
<td></td>
</tr>
<tr>
<td>Experimental Set for Measuring the Planck's Constant using LED</td>
<td>33</td>
</tr>
<tr>
<td>Jitlada Sunu, Siriya Satsanapitak, Kheamrutai Thamaphat, Chutima Oopathump, Pyarat Bharmar and Pichet Limsuwan</td>
<td></td>
</tr>
<tr>
<td>Tasks Management Algorithm for Distributed System</td>
<td>37</td>
</tr>
<tr>
<td>Avnish Kumar</td>
<td></td>
</tr>
<tr>
<td>Effects of Variable Viscosity and Thermal Conductivity of Unsteady Mixed Convection Flow at the Stagnation Point and an Applied Magnetic Field</td>
<td>45</td>
</tr>
<tr>
<td>Jatindra Lakkar</td>
<td></td>
</tr>
<tr>
<td>Differential Inequalities for a Finite System of Hybrid Fractional Differential Equations</td>
<td>55</td>
</tr>
<tr>
<td>Bapurao C. Dhage and Pradeep V. Mugale</td>
<td></td>
</tr>
<tr>
<td>Jump-Diffusion with Stochastic Volatility and Intensity</td>
<td>61</td>
</tr>
<tr>
<td>Montakan Thongpan, Sarun Wongwai and Nonthiya Makate</td>
<td></td>
</tr>
<tr>
<td>Growth of Hydroxyapatite on Sericin Coated Silk Fibers Using Simulated Body Fluid at Various Time</td>
<td>69</td>
</tr>
<tr>
<td>Onanong Subjai, Piyapong Asanithi, Pichet Limsuwan and Supane Limsuwan</td>
<td></td>
</tr>
<tr>
<td>A Novel Method for Measurement of Equivalent Circuit Component of Piezoelectric Material by using Impedance Spectroscopy</td>
<td>73</td>
</tr>
<tr>
<td>Pramod Chaitanya and Lakshman Pandey</td>
<td></td>
</tr>
<tr>
<td>Quantum Mechanical Study of Some Atomic Properties</td>
<td>81</td>
</tr>
<tr>
<td>Prabhat Ranjan and Tanmoy Chakraborty</td>
<td></td>
</tr>
</tbody>
</table>
Contents

Preparation of Mesa Structural Near-Infrared n-Type Nanocrystalline-FeSi/p-Type Si Heterojunction Photodiodes
Nathaporn Promros, Ryūhei Iwasaki, Suguru Funasaki, Kyohei Yamashita, and Tsuyoshi Yoshitake 95

A Job Recruitment System using Semantic Web Technology
Pongpon Nilaphruek 101

A Novel Method for Measurement of Equivalent Circuit Component of Piezoelectric Material by using Impedance Spectroscopy
Pramod Chaitanya and Lakshman Pandey 107

On Generalised B-Manifolds
S.K. Srivastava, Virendra Nath Pathak 115

The Propagation of Flare Generated Shockwaves in Self-Gravitating Solar Atmosphere
S. N. Ojha 119

New Circuit Model of Small-Signal Amplifier Developed by Using MOSFETs in Triple Darlington Configuration
Sachchita Nand Shukla, Susmita Srivastava and Beena Pandey 125

Effect of Ca$^{2+}$ ions on Swelling Behavior of Silk Fibroin Hydrogel
T. Lee teera, P. Asaniti, P. Lim suwan, S. Lim suwan 133

Preparation of Alumina – Graphene Composites by Long Pulsed Laser Ablation
Voranuch Thongpool, Akapong Phupueok, Veeradate Piriyawong, Supanee Lim suwan, Veeradate Piriyawong and Pichet Lim suwan 139

Y-Combinator based Continuation-Passing Style Technique in Python Programming
Songphon Klubwong 145
Comparison of Photofraction for LuYAP:Ce, LYSO:Ce and BGO Crystals in Gamma Ray Detection

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Abstract

Photofractions of Lu0.7Y0.3Al2O3:Ce (LuYAP:Ce), Lu0.95Y0.05SiO2:Ce (LYSO:Ce), and Bi4Ge3O12 (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 (137Cs 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 Leeq 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 (Lu0.7Y0.3Al2O3:Ce and Lu0.95Y0.05SiO2:Ce crystals) for photon energies at 320, 511, and 662 keV, and compare to those of Bi4Ge3O12 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

Lu0.7Y0.3Al2O3:Ce (LuYAP:Ce) and Lu0.95Y0.05SiO2:Ce (LYSO:Ce) crystals with the same size of 10x10x5 mm³ were supplied by Proticus Inc. (USA) and Bi4Ge3O12 (BGO) crystal with the size of 15x15x4 mm³ 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].

- 1 -
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 ($\sigma$-ratio) obtained from WinXCom program. The reason is due to much higher effective atomic number ($Z_{\text{eff}}$) and volume of the BGO crystal.

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

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$Z_{\text{eff}}$</th>
<th>Volume (cm$^3$)</th>
<th>Photofraction (%)</th>
<th>$\sigma$-ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LuYAP:Ce</td>
<td>60</td>
<td>0.5</td>
<td>45.62</td>
<td>47.3</td>
</tr>
<tr>
<td>LYSO:Ce</td>
<td>63.5</td>
<td>0.5</td>
<td>55.42</td>
<td>54.3</td>
</tr>
<tr>
<td>BGO</td>
<td>74</td>
<td>0.9</td>
<td>59.58</td>
<td>62.8</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$Z_{\text{eff}}$</th>
<th>Volume (cm$^3$)</th>
<th>Photofraction (%)</th>
<th>$\sigma$-ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LuYAP:Ce</td>
<td>60</td>
<td>0.5</td>
<td>26.60</td>
<td>25.9</td>
</tr>
<tr>
<td>LYSO:Ce</td>
<td>63.5</td>
<td>0.5</td>
<td>32.83</td>
<td>32.1</td>
</tr>
<tr>
<td>BGO</td>
<td>74</td>
<td>0.9</td>
<td>37.64</td>
<td>41.1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$Z_{\text{eff}}$</th>
<th>Volume (cm$^3$)</th>
<th>Photofraction (%)</th>
<th>$\sigma$-ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LuYAP:Ce</td>
<td>60</td>
<td>0.5</td>
<td>21.98</td>
<td>17.8</td>
</tr>
<tr>
<td>LYSO:Ce</td>
<td>63.5</td>
<td>0.5</td>
<td>31.59</td>
<td>22.8</td>
</tr>
<tr>
<td>BGO</td>
<td>74</td>
<td>0.9</td>
<td>38.83</td>
<td>30.8</td>
</tr>
</tbody>
</table>
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

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

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 mm³) in Ref [8]. Superior energy resolution for tested LYSO:Ce than that of 8.7% reported for the 10x10x5 mm³ 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 mm³) 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]

\[(ΔE/E)^2 = (δ_e)^2 + (δ_t)^2 + (δ_a)^2,\]  
(1)

where \(δ_e\) is the intrinsic resolution of the crystal, \(δ_t\) is the transfer resolution and \(δ_a\) is the statistical contribution of PMT to the resolution.

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

\[δ_a = 2.355 \times \sqrt{1/N} \times (1 + ε)^{1/2},\]  
(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 \(δ_e\) is negligible, intrinsic resolution \(δ_a\) of a crystal can be written as follows

\[(δ_a)^2 = (ΔE/E)^2 - (δ_t)^2.\]  
(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 photpeak, 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 photpeak. The PMT contribution \((δ_t)^2\) was calculated using Eq.(2). From the values of \(ΔE/E\) and \(δ_a\), the intrinsic resolution \((δ_a)^2\) was calculated using Eq.(3).
Table 5 Analysis of the 662 keV energy resolution for LuYAP:Ce, LYSO:Ce, and BGO detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>N[electrons]</th>
<th>ΔE/E [%]</th>
<th>δ₁ [%]</th>
<th>δₑ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LuYAP:Ce+XP5200B</td>
<td>1,940 ± 190</td>
<td>7.9 ± 0.4</td>
<td>4.8 ± 0.2</td>
<td>6.3 ± 0.3</td>
</tr>
<tr>
<td>LYSO:Ce+XP5200B</td>
<td>5,040 ± 500</td>
<td>8.1 ± 0.4</td>
<td>3.0 ± 0.2</td>
<td>7.5 ± 0.4</td>
</tr>
<tr>
<td>BGO+XP5200B</td>
<td>1,180 ± 120</td>
<td>9.1 ± 0.5</td>
<td>7.2 ± 0.4</td>
<td>5.5 ± 0.3</td>
</tr>
</tbody>
</table>

The photoelectron yield (and δₑ) 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.

5. Acknowledgement
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References