

COMPARATIVE STUDY OF MASS ATTENUATION COEFFICIENTS, EFFECTIVE ATOMIC NUMBERS, AND EFFECTIVE ELECTRON DENSITIES OF EU-DOPED CsCaBrI₂, CsSrBrI, AND CsSrClBr₂ SCINTILLATORS

Kittisak Sriwongsa^{1,2*}, Noppasit Laopoonphol², Sirimongkol Ariyalerdchai², Punsak Glumglomchit³, Nitcha Pungpang³, Sunantasak Ravangvong⁴, and Chumphon Khobkham⁵

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Abstract

This work presents comparative studies of mass attenuation coefficients, effective atomic numbers, and effective electron densities of Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at the photon energy range from 100 keV to 1,500 keV using the WinXCom program. The results show that the photoelectric interaction occurs at low energy and at high energy, resulting in a lower rate of interaction. However, at the photon energy range from 251 to 1,500 keV the photoelectric effect cross-section values of all 3 scintillators are very similar. The Compton interaction occurs at the photon energy range from 100 to 250 keV. At 100 keV, the Eu-doped CsCaBrI₂ scintillator has higher mass attenuation coefficients than the Eu-doped CsSrBrI₂ and CsSrClBr₂ scintillators. The Eu-doped CsCaBrI₂ scintillator has a higher effective atomic number than the Eu-doped CsSrBrI₂ and CsSrClBr₂ scintillators at 100 keV. But at the photon energy range from 101 to 1,500 keV, the results showed that the Eu-doped CsSrBrI₂ scintillator has a higher effective atomic number than the Eu-doped CsCaBrI₂ and CsSrClBr₂ scintillators. The Eu-doped CsSrClBr₂ scintillator has a higher effective electron density than the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators at this photon energy range.

¹ Lecturer responsible for Bachelor of Education Program in Physics, Faculty of Education, Silpakorn University, Nakhon Pathom, 73000, Thailand. Tel:(034)255095; Fax:(034)255796; E-mail: Sriwongsa_k@silpakorn.edu

² The Demonstration School of Silpakorn University, Nakhon Pathom, 73000, Thailand.

³ Huahin Vitthayalai School, Hua Hin, Prachuap Khiri Khan, 77110, Thailand.

⁴ Division of Science and Technology, Faculty of Science and Technology, Phetchaburi Rajabhat University, Phetchaburi, 76000, Thailand.

⁵ Faculty of Engineering, Thonburi University, Bangkok, 10160, Thailand.

* Corresponding author

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Introduction

Scintillator crystals are divided into 2 types, organic and inorganic. These types of scintillator crystal can emit flashes for a short period of time when the photon energy passes into the scintillator crystal. This process is called scintillation. Scintillation crystals have many key uses in the fields of medical imaging, high-energy physics, oil well logging, and national security. The ideal scintillator must have a high light yield, good energy resolution, fast decay time, and high effective atomic number (Derenzo *et al.*, 2003). Radiation detection using scintillation crystals is based on the principle that when photon energy passes into a crystal, there is an interaction within the scintillation crystal. The main interactions are the photoelectric absorption, Compton scattering, and pair production. The fundamental parameters to the probability of these interactions are the mass attenuation coefficient (μ_m), effective atomic number (Z_{eff}), and electron density (N_{el}).

Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators were grown in evacuated quartz ampoules via the vertical Bridgman technique. They have a high light yield, fast decay times, and excellent energy resolution. These 3 new scintillators are expected to be used in the field of radiation measurement. The other properties of the 3 scintillator crystals are described in Bourret-Courchesne *et al.* (2010), Bizarri *et al.* (2011), Swiderski *et al.* (2008), Gundiah *et al.* (2011), and Stand *et al.* (2019).

The purposes of this work were to undertake a comparative study of the mass attenuation coefficients, effective atomic numbers, and effective electron densities of Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators in the energy range from 100 to 1,500 keV using the WinXCom program.

Methods

When photon energy passes into a material, there is a certain probability that there is an interaction and the energy is absorbed or scattered. The interactions of photon energy with matter are photoelectric absorption, Compton scattering, and pair production. The mass attenuation coefficient (μ_m) in (cm²/g) shows the probability of interaction of the photon energy with the material. For an event of the mixture or compound of elements, μ_m can be calculated by using the equation of Chanthima and Kaewkhao (2013):

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (1)$$

where w_i represents the weight fraction and $(\mu_m)_i$ represents the mass attenuation coefficient of element i . In this work, μ_m has been determined using WinXCom software in the energy range from 100 keV to 1,000 keV.

The effective atomic number (Z_{eff}) is the basic quantity required in determining the penetration of photon energy when it interacts with matter and can be defined by following Chanthima and Kaewkhao (2013):

$$Z_{\text{eff}} = \frac{\sigma_{\text{t,a}}}{\sigma_{\text{t,el}}} \quad (2)$$

The total atomic cross-section ($\sigma_{\text{t,a}}$) was evaluated by using the following equation from Chanthima and Kaewkhao (2013):

$$\sigma_{\text{t,a}} = \frac{\mu/\rho}{N_A \sum_i (w_i/A_i)} \quad (3)$$

where μ represents the linear attenuation coefficient (cm^2/g), ρ represents the density of the medium (g/cm^3), and N_A represents Avogadro's number (6.0221415×10^{23} atom/mol).

The total electron cross-section ($\sigma_{t,el}$) of the element can be expressed by following Dong *et al.* (2017):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} (\mu/\rho)_i \quad (4)$$

where Z_i represents the atomic number and f_i represents the fractional abundance of the mixture element i .

The effective electron density (N_{el}) is the number of electrons per unit mass and is calculated by the following equation from Chanthima *et al.* (2017):

$$N_{el} = (\mu/\rho) / (\sigma_{t,el}) \quad (5)$$

Results and Discussion

Figure 1 presents the photoelectric effect cross-section at the photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators. The results show the trend when the photoelectric effect cross-section decreases with the increasing photon energy. The photoelectric effect cross-section for the Eu-doped CsCaBrI₂ scintillator is found to be decreased from $1.45 \text{ cm}^2/\text{g}$ at 100 keV to $0.001588 \text{ cm}^2/\text{g}$ at 1,500 keV, the CsSrBrI₂ scintillator decreases from $1.423 \text{ cm}^2/\text{g}$ at 100 keV to $0.001542 \text{ cm}^2/\text{g}$ at 1,500 keV, and the CsSrClBr₂ scintillator decreases from $0.9457 \text{ cm}^2/\text{g}$ at 100 keV to $0.0009905 \text{ cm}^2/\text{g}$ at 1,500 keV. At the photon energy range from 100 to 250 keV, the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators have a greater photoelectric cross-section than the CsSrClBr₂ scintillator. This result shows that the photoelectric interaction occurs at low energy and at high energy, resulting in a lower rate of interaction. The result reflects that at this photon energy range,

both scintillators are best suited for applications in radiation measurement. In other words, this value results in this value results in the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators having an excellent energy resolution value at this photon energy range. However, at the photon energy range from 251 to 1,500 keV, the photoelectric effect cross-section values of all 3 scintillators are very similar.

Figure 2 presents the Compton scattering cross-section at the photon energy range from 100 to 1,500 keV measured with the Eu-doped

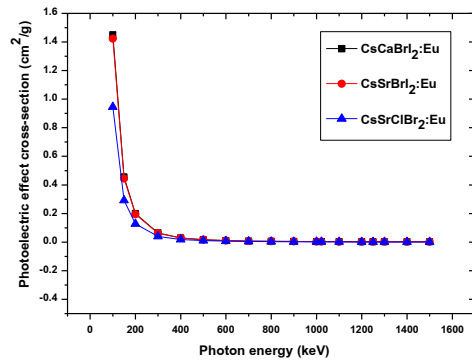


Figure 1. Photoelectric effect cross-section at photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators

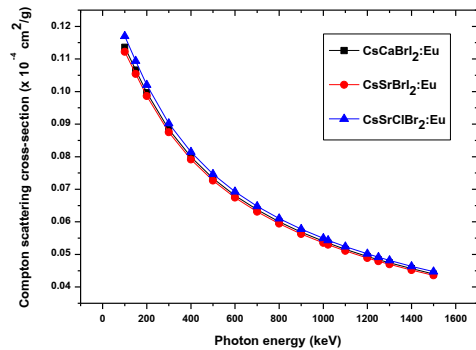


Figure 2. Compton scattering cross-section at photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators

CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators. The results show the trend when the Compton scattering cross-section decreases with the increasing photon energy at this photon energy range. The Compton scattering cross-section for the Eu-doped CsCaBrI₂ scintillator is found to be decreased from 0.1136 cm²/g at 100 keV to 0.044 cm²/g at 1,500 keV, the CsSrBrI₂ scintillator decreases from 0.1122 cm²/g at 100 keV to 0.04358 cm²/g at 1,500 keV, and the CsSrClBr₂ scintillator decreases from 0.117 cm²/g at 100 keV to 0.0447 cm²/g at 1,500 keV. At this photon energy range, the Eu-doped CsSrClBr₂ scintillator has greater a Compton scattering cross-section than the CsSrBrI₂ and CsCaBrI₂ scintillators. This resulted in the Eu-doped CsSrClBr₂ scintillator having a low photoelectric effect cross-section, in accordance with the results obtained in Figure 1. This result shows that the Compton interaction occurs at the photon energy range from 100 to 250 keV but at high energy, resulting in a lower rate of interaction. However, at the high energy range the Compton scattering cross-section values of all 3 scintillators are very similar.

Figure 3 presents the total cross-section or mass attenuation coefficients at the photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators. The mass attenuation

coefficients for the Eu-doped CsCaBrI₂ scintillator is found to be decreased from 1.659 cm²/g at 100 keV to 0.0469 cm²/g at 1,500 keV, the CsSrBrI₂ scintillator decreases from 1.63 cm²/g at 100 keV to 0.04644 cm²/g at 1,500 keV, and the CsSrClBr₂ scintillator decreases from 1.137 cm²/g at 100 keV to 0.04672 cm²/g at 1,500 keV. This result is consistent with the results of the photoelectric effect cross-section. At the photon energy range from 100 to 250, the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators have greater mass attenuation coefficients than the Eu-doped CsSrClBr₂ scintillator. This result implies that at the photon energy range from 100 to 250 keV, both scintillators will have good energy resolution and a higher light yield than the Eu-doped CsSrClBr₂ scintillator, corresponding to the research of Swiderski *et al.* (2008); Bourret-Courchesne *et al.* (2010); Bizarri *et al.* (2011); and Gundiah *et al.* (2011). At high photon energy, all 3 scintillators have similar energy resolution values (Stand *et al.*, 2019). The energy resolution is a factor that indicates the ability of the detector to resolve a small difference in the energy of incident photon energy. The light yield is the ratio of the number of photons emitted per incident photon energy (MeV). It can be expressed in terms of the number of photoelectrons per MeV of absorbed photon energy by the average quantum efficiency of the photomultiplier tube.

The typical mass attenuation coefficients of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some photon energy ranges are exhibited in Table 1.

Figure 4 presents the effective atomic numbers (Z_{eff}) at the photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators. The results show the trend when the effective atomic number decreases with the increasing photon energy at this photon energy range. The Eu-doped CsCaBrI₂ scintillator has a higher effective atomic number than the Eu-doped CsSrBrI₂ and CsSrClBr₂ scintillators at 100 keV. But at the energy range from 101 to 1,500 keV the results showed that the Eu-doped CsSrBrI₂ scintillator has a higher effective

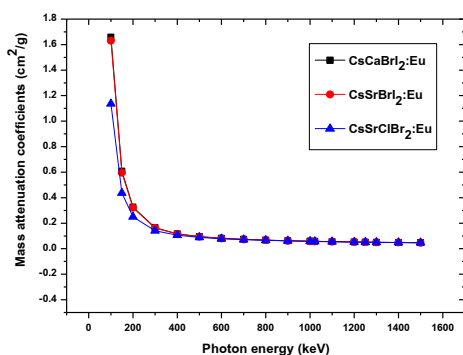


Figure 3. Mass attenuation coefficients at photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators

atomic number than the Eu-doped CsCaBrI₂ and CsSrClBr₂ scintillators. The effective atomic number for the Eu-doped CsCaBrI₂ scintillator is found to be decreased from 50.90267641 electron/atom at 100 keV to 43.58880155 electron/atom at 1,500 keV, the CsSrBrI₂ scintillator decreases from 50.39191485 electron/atom at 100 keV to 47.00280516 electron/atom at 1,500 keV, and the CsSrClBr₂ scintillator decreases from 44.50833768 electron/atom at 100 keV to 36.28427954 electron/atom at 1,500 keV. The

results reflect that the Eu-doped CsCaBrI₂ scintillator has a good interaction probability that is stronger than the Eu-doped CsSrBrI₂ and CsSrClBr₂ scintillators at 100 keV. But at the photon energy range from 101 to 1,500 keV the Eu-doped CsSrBrI₂ scintillator has a good interaction probability that is stronger than the Eu-doped CsCaBrI₂ and CsSrClBr₂ scintillators. This result shows that at low energy, the Eu-doped CsCaBrI₂ scintillator is suitable for use in measuring radiation well, but at the photon energy range from 101 to 1,500 keV the Eu-doped CsSrBrI₂ scintillator is a good option to be used in radiation measurement corresponding to the research (Stand *et al.*, 2019). At 662 keV (¹³⁷Cs source), the Eu-doped CsSrBrI₂ has energy resolution about 4.4% to 3.4%, the Eu-doped CsCaBrI₂ has energy resolution about 5.0% to 3.8%, and the Eu-doped CsSrClBr₂ has energy resolution about 5.0% to 3.9% (Stand *et al.*, 2019).

The typical effective atomic numbers of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some photon energy ranges are exhibited in Table 2.

Figure 5 presents the effective electron density at the photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators. The effective electron density for the Eu-doped CsCaBrI₂ scintillator is found to be decreased

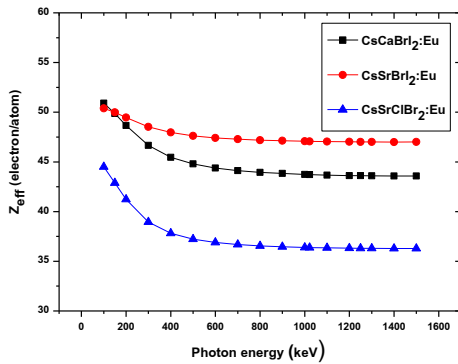


Figure 4. Effective atomic number at photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators

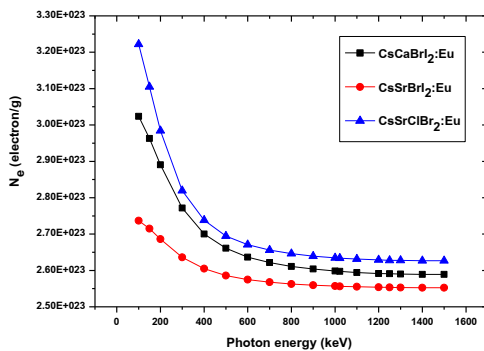


Figure 5. Effective electron density at photon energy range from 100 to 1,500 keV measured with the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators

Table 1. Typical mass attenuation coefficients of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some gamma ray energies

E (keV)	CsCaBrI ₂	CsSrBrI ₂	CsSrClBr ₂
	μ_m (cm ² /g)	μ_m (cm ² /g)	μ_m (cm ² /g)
100	1.659	1.63	1.137
200	0.3267	0.321	0.2505
300	0.1651	0.1626	0.1404
400	0.1167	0.1152	0.1056
500	0.09473	0.09355	0.08869
600	0.08205	0.08109	0.07844
700	0.07358	0.07275	0.07128
800	0.06741	0.06667	0.06587
900	0.06263	0.06196	0.06157
1,000	0.0587	0.05808	0.05799
1,100	0.05541	0.05483	0.05496
1,200	0.05271	0.05217	0.0524
1,300	0.05046	0.04994	0.05022
1,400	0.04854	0.04805	0.04834
1,500	0.0469	0.04644	0.04672

Table 2. Typical effective atomic numbers of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some gamma ray energies

E (keV)	CsCaBrI ₂	CsSrBrI ₂	CsSrClBr ₂
	Z _{eff} (electron/atom)	Z _{eff} (electron/atom)	Z _{eff} (electron/atom)
100	50.90267641	50.39191485	44.50833768
200	48.6613868	49.46169646	41.22624266
300	46.65871588	48.53409931	38.94858338
400	45.45377003	47.96676749	37.82515022
500	44.79317524	47.61639969	37.22098289
600	44.3841731	47.41016542	36.89320226
700	44.12883744	47.28180847	36.68885241
800	43.95440886	47.18887369	36.55159386
900	43.83399123	47.12809807	36.46078305
1,000	43.74275611	47.08245145	36.39205116
1,100	43.67114232	47.04831204	36.34693362
1,200	43.62180348	47.02373111	36.31439524
1,300	43.60383072	47.00641353	36.29450485
1,400	43.58876773	46.99815352	36.28193289
1,500	43.58880155	47.00280516	36.28427954

Table 3. Typical effective electron densities of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some gamma ray energies

E (keV)	CsCaBrI ₂	CsSrBrI ₂	CsSrClBr ₂
	N _e × 10 ³ (electron/g)	N _e × 10 ³ (electron/g)	N _e × 10 ³ (electron/g)
100	3.02385	2.73673	3.22209
200	2.89071	2.68621	2.98449
300	2.77174	2.63583	2.8196
400	2.70016	2.60502	2.73827
500	2.66092	2.58599	2.69454
600	2.63662	2.57479	2.67081
700	2.62145	2.56782	2.65601
800	2.61109	2.56277	2.64608
900	2.60394	2.55947	2.63950
1,000	2.59852	2.55700	2.63453
1,100	2.59427	2.55514	2.63126
1,200	2.59133	2.55381	2.62891
1,250	2.59081	2.55331	2.62754
1,300	2.59027	2.55287	2.62747
1,400	2.58937	2.55242	2.62656
1,500	2.58937	2.55267	2.62673

from 3.02385×10^{23} electron/g at 100 keV to 2.58937×10^{23} electron/g at 1,500 keV, the CsSrBrI₂ scintillator decreases from 2.73673×10^{23} electron/g at 100 keV to 2.55267×10^{23} electron/g at 1,500 keV, and the CsSrClBr₂ scintillator decreases from 3.22209×10^{23} electron/g at 100 keV to 2.62673×10^{23} electron/g at 1,500 keV. The results showed that the Eu-doped CsSrClBr₂ scintillator has a higher effective electron density than the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators at this photon energy range. The results reflected that at this photon energy range the Eu-doped CsSrClBr₂ scintillator has a good proportionality of light yield corresponding to the research (Stand *et al.*, 2019). The non-proportionality of the light yield is a non-linear relationship between the deposited particle energy and the light yield depending on the density of the charge carriers. The properties of the scintillator crystals through the energy resolution and the light yield non-proportionality have been studied during the last decade.

All the results show that the 3 scintillators have different characteristics. All 3 scintillators can be applied, depending on the work being used and how much energy is in the range.

The typical effective electron densities of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators at some photon energy ranges are exhibited in Table 3.

Conclusions

Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators were grown in evacuated quartz ampoules via the vertical Bridgman technique. This work undertook a comparative study of the mass attenuation coefficients, effective atomic numbers, and effective electron densities of the Eu-doped CsCaBrI₂, CsSrBrI₂, and CsSrClBr₂ scintillators in the photon energy range from 100 keV to 1,500 keV using the WinXCom program. The results show that at low energy the Eu-doped CsCaBrI₂ scintillator has better basic properties than the Eu-doped CsSrBrI₂ and CsSrClBr₂ scintillators. But at high energy, the Eu-doped CsSrBrI₂ scintillator has better basic properties than the Eu-doped CsCaBrI₂ and CsSrClBr₂ scintillators. However, the Eu-doped CsSrClBr₂ scintillator has a better proportionality of the light yield than the Eu-doped CsCaBrI₂ and CsSrBrI₂ scintillators.

Acknowledgments

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