

ENHANCING GAMMA-RAY SHIELDING EFFICIENCY OF ERBIUM OXIDE DOPED GERMANATE GLASS: A STUDY USING FLUKA AND XCOM PROGRAMS

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Abstract

Gamma (γ)-ray shielding materials are essential for reducing γ -ray exposure to safe levels for human safety. This study analyzed the γ -ray shielding characteristics of $x\text{Er}_2\text{O}_3$ ($x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0$ mol%) doped germanate glass utilizing FLUKA Monte Carlo simulations and XCOM theoretical programs across the energy range of 15 keV to 15 MeV. The parameters examined include mass (μm) attenuation coefficients, mean free path (MFP), half value layer (HVL), effective atomic number (Z_{eff}), and effective electron density (N_{eff}). The γ -ray shielding performance of the present glasses was assessed relative to standard shielding materials.

Keywords: Er_2O_3 ; Shielding materials; Germanate glass; FLUKA; XCOM

Introduction

Nowadays, radiation shielding materials are continuously being developed to protect against ionizing radiation. This type of radiation is generated from various sources, including nuclear power plants, research institutions, radiotherapy rooms, and naturally occurring radioactive materials (NORMs). The conventional materials commonly used for radiation shielding are lead and concrete (Gunoglu & Akkurt, 2021) due to their important properties, such as mechanical, physical, economic, workability, formability, and durability. However, lead has limitations such as toxicity (Eid & Zawia, 2016), while concrete has drawbacks like inconsistent composition (Rouihem *et al.*, 2024),

crack formation, and loss of density in the long run. Therefore, the primary focus of research is the improvement of innovative shielding materials. Many researchers have investigated and developed alternative shielding materials, including alloys (Alzahrani *et al.*, 2022), composites (Chaiphaksa *et al.*, 2023), and glass materials (Sangwaranatee *et al.*, 2021; Boontueng *et al.*, 2024; Cheewasukhanont *et al.*, 2024; Mutuwong *et al.*, 2025).

Glass materials provide numerous advantages when used as protective windows. They are transparent to visible light and provide protection against ionizing radiation. Additionally, the

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radiation shielding properties of glass can be enhanced by incorporating heavy oxides. High-density materials are essential for the production of γ -ray shielding glass due to their high cross-section. In a previous study, high-density glasses with a density ranging from approximately 4.612 to 4.9089 g/cm³ were successfully prepared (Wantana *et al.*, 2024). The physical, structural, optical, and luminescence properties of the 25Gd₂O₃–35B₂O₃–(40-x)GeO₂–xEr₂O₃ glass composition (where x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mol%) were investigated in their research. The erbium oxide (Er₂O₃) was added to improve the shielding properties due to its high molar mass (382.56 g/mol) when compared to others. Germanate glass doped with Er³⁺ emits photons at a wavelength of 1.5 μ m. These characteristics make germanate glass an ideal host material for Er³⁺ doped waveguides, which are crucial for light manipulation in photonic circuits. However, there is no information on the shielding properties of this material. In this work, FLUKA was used to investigate the γ -ray shielding properties of gadolinium borogermanate glasses. The results were validated using XCOM theoretical programs. A range of energy between 15 keV and 15 MeV was examined.

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Materials and Methods

FLUKA is a Monte Carlo-based simulation software that is both comprehensive and extremely versatile, and it is employed for the analysis of particle transport and interaction. It is widely applied in radiation physics, medical physics, high-energy physics, and engineering to simulate complex scenarios involving the interaction of particles with matter (Ahdida *et al.*, 2022). It requires defining essential parameters such as, geometry, materials, radiation sources, and scoring settings. The geometry setup was previously described (Mutuwong *et al.*, 2018). According to previous work (Wantana *et al.*, 2024), the glass formula: 25Gd₂O₃–35B₂O₃–(40-x)GeO₂–xEr₂O₃ (where x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mol%) was defined as the sample's materials.

The linear attenuation coefficient (μ) quantifies a material's ability to reduce radiation intensity based on its thickness. It is mathematically expressed as

$$\mu = \ln(I_0/I)/d \quad (1)$$

where I_0 and I denote the incident and transmitted γ -ray intensities, respectively, while d represents the sample thickness.

To further characterize the material's shielding properties, the mass attenuation coefficient (μ_m) was determined using FLUKA, following the equation:

$$\mu_m = \frac{\ln(I_0/I)/d}{\rho} \quad (2)$$

where ρ denotes the sample's density. The mass attenuation coefficient for material mixtures theoretically differs from the Monte Carlo-derived equation. Instead, it can be calculated using a weighted sum from the NIST database via the XCOM program (Gerward *et al.*, 2004):

$$\mu_m = \sum w_i (\mu_m)_i \quad (3)$$

where the variable w_i represents the normalized weight fractions of the i^{th} element. The $(\mu_m)_i$ is the mass attenuation coefficient of the i^{th} element.

In addition, the theoretical μ_m values are a summation of the partial interactions of μ_m (Photoelectric effect: $(\mu_m)_{\text{PE}}$, Compton scattering: $(\mu_m)_{\text{CS}}$, Pair production: $(\mu_m)_{\text{PP}}$), as calculated using the following equation:

$$\mu_m = (\mu_m)_{\text{PE}} + (\mu_m)_{\text{CS}} + (\mu_m)_{\text{PP}} \quad (4)$$

The mean free path (MFP) and half-value layer (HVL) can be mathematically expressed as follows:

$$\text{MFP} = \frac{1}{\mu}, \quad (5)$$

$$\text{HVL} = \frac{\ln(2)}{\mu} \quad (6)$$

The total atomic cross-section ($\sigma_{t,a}$) is equal to the summation of partial cross-sections associated with photon interactions with atoms. The relationship between $\sigma_{t,a}$ and μ_m is expressed by the following equation (Hubbell, 2006):

$$\sigma_{t,a} = \frac{(\mu_m)_{\text{sample}}}{N_A \sum_i^n (w_i/A_i)} \quad (7)$$

where N_A is Avogadro's number. The A_i is the atomic weight of the constituent elements of the mixture. The total electronic cross-section ($\sigma_{t,el}$) is the cross section by which photons interact with electrons, as expressed by the following equation:

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{z_i} (\mu_m)_i \quad (8)$$

where f_i denotes the fractional abundance of the element i with respect to the number of atoms ($\sum f_i = 1$) and z_i is the atomic number of i^{th} elements.

The effective atomic number (Z_{eff}) and the effective electron number or electron density (N_{eff}) of the composite material are calculated using the following relation:

$$Z_{\text{eff}} = \frac{\sigma_{t,a}}{\sigma_{t,el}}, \quad (9)$$

$$N_{\text{eff}} = \frac{\mu_m}{\sigma_{t,el}} \quad (10)$$

Results and Discussion

The μ and μ_m values of the glass samples are illustrated in Figure 1 and Figure 2, respectively. The values of μ and μ_m computed by FLUKA and XCOM are in good agreement. The addition of Er_2O_3 content results in a modest increase in μ and μ_m . The μ and μ_m values decrease as the photon energy increases, for the K absorption edge of Gd at approximately 0.05024 MeV. The photoelectric effect results in a significant increase in μ and μ_m at energy near the K-edge of Gd. The energy of the incident photon can be completely transferred to the k-orbital electron of Gd. The outcome of the phenomenon is a photoelectron, which is a charged particle that can be attenuated in the material. The μ and μ_m values of the 5Er sample are higher than others, indicating that the addition of the Er_2O_3 content can improve the shielding properties while affecting the color of the glass (Wantana *et al.*, 2024).

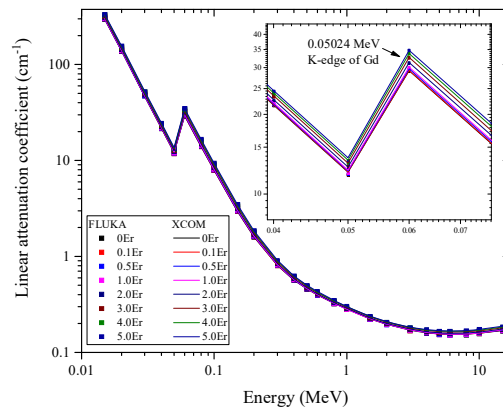


Figure 1. The μ of the $25\text{Gd}_2\text{O}_3\text{--}35\text{B}_2\text{O}_3\text{--}(40\text{--}x)\text{GeO}_2\text{--}x\text{Er}_2\text{O}_3$ (where $x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0$, and 5.0 mol%) glass

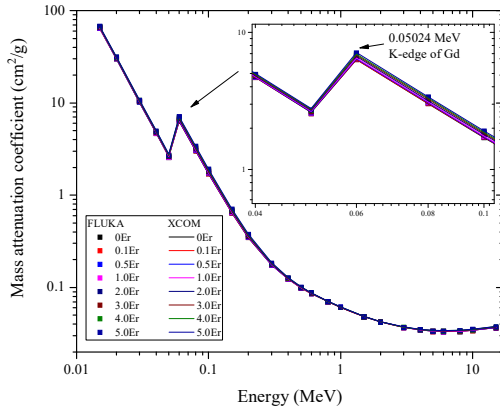


Figure 2. The μ_m of the 25Gd₂O₃-35B₂O₃-(40-x)GeO₂-xEr₂O₃ (where x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mol%) glass

The partial interactions of the 5Er (25Gd₂O₃-35B₂O₃-35GeO₂-5Er₂O₃) samples were analyzed for comprehensive interpretation, as depicted in Figure 3. The three principal photon interaction processes that occur in distinct energy regions with the 5Er glass can be attributed to the variation in μ_m as the energy of the incident photon changes. In the energy range of $E < 0.3$ MeV, the photoelectric effect is the primary interaction, as μ_m values are significantly influenced by $(\mu_m)_{pe}$. The Compton scattering process $(\mu_m)_{cs}$ is the primary interaction that contributes to the μ_m value when E is between 0.3 MeV and 7 MeV. The photoelectric effect $(\mu_m)_{pe}$ and Compton scattering $(\mu_m)_{cs}$ mechanisms are less influential at energies beyond 7 MeV when compared with pair production $(\mu_m)_{pp}$. Pair production becomes the primary interaction, leading to a modest increase in μ_m .

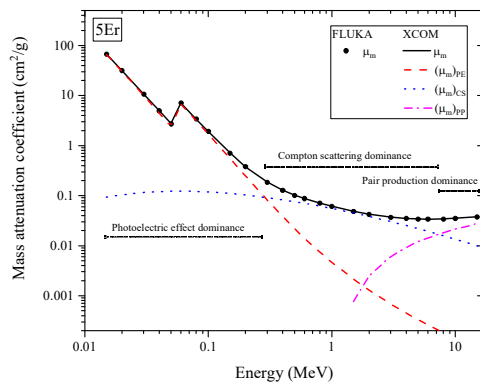


Figure 3. The partial interaction of the 5Er (25Gd₂O₃ - 35B₂O₃ - 35GeO₂ - 5Er₂O₃) sample

The average distance of incident photons before the first interaction with samples and the shortest thickness of the absorber that can attenuate the intensity of incident photons by half are shown in Figure 4 and Figure 5, respectively. The MFP and HVL of the glass reduce as the Er₂O₃ concentration is added while rising as photon energy increases. Furthermore, Figure 6 depicted the comparisons between the HVL of the current work and the HVL of conventional concrete (Singh *et al.*, 2018), such as ordinary, Hematite-Serpentine, Ilmenite-limonite, Basalt-Magnetite, and Ilmenite. The results indicated that the HVL of all samples in this study is lower than the HVL of concrete. Therefore, the synthesized glass samples can be used as shielding material instead of concrete.

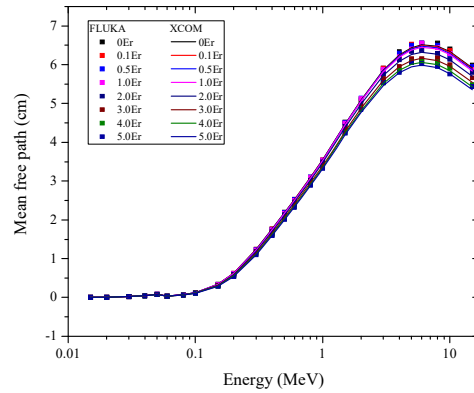


Figure 4. The MFP of the 25Gd₂O₃-35B₂O₃-(40-x)GeO₂-xEr₂O₃ (where x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mol%) glass

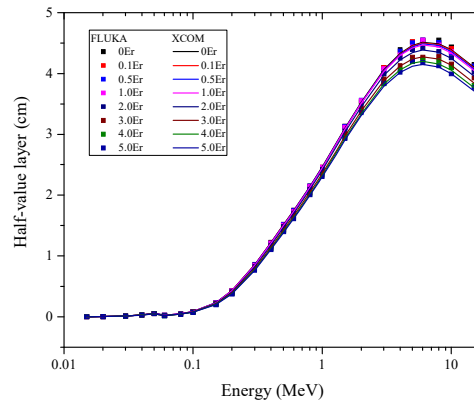


Figure 5. The HVL of the 25Gd₂O₃-35B₂O₃-(40-x)GeO₂-xEr₂O₃ (where x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mol%) glass

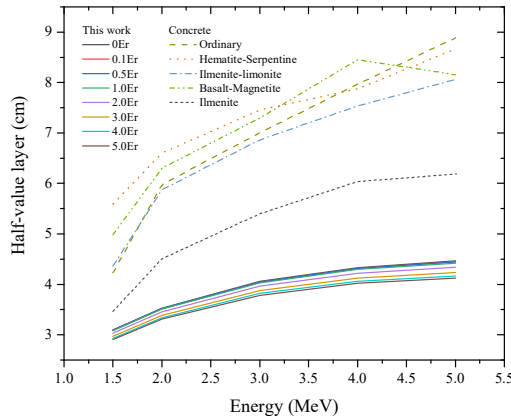


Figure 6. The comparisons between present work and standard concrete in terms of HVL

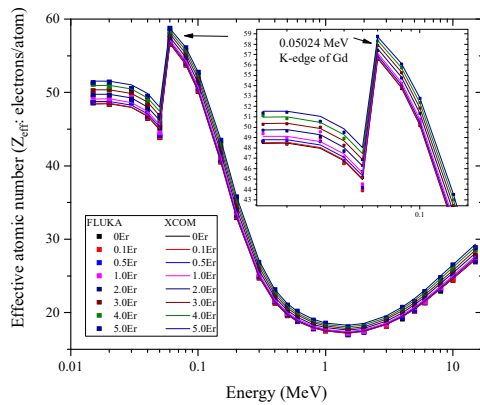


Figure 7. The Z_{eff} of the $25\text{Gd}_2\text{O}_3\text{-}35\text{B}_2\text{O}_3\text{-(}40\text{-x)GeO}_2\text{-xEr}_2\text{O}_3$ (where $x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0$, and 5.0 mol%) glass

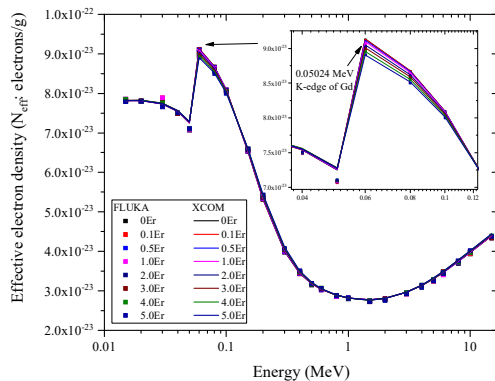


Figure 8. The N_{eff} of the $25\text{Gd}_2\text{O}_3\text{-}35\text{B}_2\text{O}_3\text{-(}40\text{-x)GeO}_2\text{-xEr}_2\text{O}_3$ (where $x = 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0$, and 5.0 mol%) glass

Figure 7 and Figure 8 demonstrate the Z_{eff} and N_{eff} of the glass, respectively. Z_{eff} is evidently subject to a significant fluctuation in photon energy, with a range of 16.97 to 58.75 (electrons/atom). The increase in Z_{eff} of the glass samples indicates higher probabilities of photon interaction. The N_{eff} values also show significant fluctuations depending on the photon energy, ranging from 2.74×10^{23} to 8.91×10^{23} electrons/g.

Conclusions

This study examines the gamma-ray shielding characteristics of xEr_2O_3 doped germanate glass using FLUKA Monte Carlo simulations and XCOM theoretical programs. The parameters examined include mass attenuation coefficients, mean free path, half value layer, effective atomic number, and effective electron density. The γ -ray shielding performance of the glasses was assessed and compared with standard shielding materials to ensure human safety by reducing γ -ray exposure.

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