

Influence of Eu_2O_3 incorporation on the gamma-ray shielding performance of germanoborate glasses

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ABSTRACT

Background: The widespread use of ionizing radiation in medical and industrial applications has increased the demand for effective and lead-free radiation shielding materials. Rare earth doped glass systems have attracted attention due to their optical transparency and favorable attenuation properties.

Objectives: This study investigates the physical and gamma-ray shielding properties of Eu_2O_3 -doped germanoborate glasses.

Materials and methods: Glasses with the composition $40\text{GeO}_2: 25\text{Gd}_2\text{O}_3: (35-x)\text{B}_2\text{O}_3: x\text{Eu}_2\text{O}_3$ ($x=0, 1, 3, 5, 7$ and 9 mol%) were prepared using the melt-quenching method. Density and molar volume were evaluated experimentally, while shielding parameters, including mass attenuation coefficients (μ_m), the effective atomic number (Z_{eff}), the effective electron density (N_{eff}), and half-value layers (HVL) and Pb equivalent thickness, were calculated using the WinXCom program.

Results: The density of the glasses increased with increasing Eu_2O_3 concentration, while the shielding parameters exhibited strong energy dependence according to dominant photon interaction mechanisms. Distinct K-absorption edges of Eu and Gd were observed near 0.04852 MeV and 0.05024 MeV, respectively. The incorporation of Eu_2O_3 slightly enhanced the attenuation parameters and reduced the HVL values, indicating improved gamma-ray shielding performance.

Conclusion: The developed Eu_2O_3 -doped germanoborate glasses demonstrate promising physical and radiation shielding properties, suggesting their potential as transparent and lead-free shielding materials for medical and industrial applications.

Introduction

Ionizing radiation plays an essential role in modern medical applications, particularly in diagnostic imaging and radiation therapy. Nevertheless, continuous exposure to ionizing radiation may cause harmful biological effects in both patients and medical personnel, thereby increasing the demand for effective radiation shielding materials in healthcare environments.¹ The attenuation capability of a shielding material strongly depends on its density, elemental composition, and atomic number. Materials containing high atomic number elements generally exhibit superior photon attenuation

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performance because they enhance the probability of photon interaction processes such as the photoelectric effect and Compton scattering.² Lead has long been utilized as a conventional radiation shielding material owing to its high density and excellent attenuation efficiency. However, the toxicity, heavy weight and environmental concerns associated with lead-based materials have motivated researchers to explore alternative eco-friendly shielding materials.¹

Concrete is another widely used shielding material because of its low cost and good mechanical strength. Despite its effectiveness in radiation protection, the opaque nature of concrete limits its application in environments where optical transparency is required, particularly in medical and diagnostic facilities. Consequently, transparent glass materials have attracted considerable attention as promising candidates for radiation shielding applications due to their optical transparency, compositional flexibility, chemical durability, and ease of fabrication.³ Significant attention has therefore been directed toward the development of lead-free materials for gamma-ray shielding applications.⁴ Among various glass systems, borate glasses are recognized as excellent host materials because of their superior glass-forming ability, thermal stability, and capability to accommodate different modifier oxides without significant crystallization. In addition, borate glasses exhibit good transparency and can be tailored to achieve desirable physical and shielding properties through compositional modification.⁵ The incorporation of GeO_2 into borate glass systems is known to improve structural connectivity, chemical stability, refractive index, and optical transparency. Owing to its relatively high density and low phonon energy, GeO_2 also enhances the physical and optical performance of germanoborate glasses, making them suitable for photonic and radiation shielding applications.⁶

For gamma-ray shielding applications, Gd_2O_3 is considered one of the most attractive heavy metal oxides because gadolinium possesses a high atomic number ($Z=64$) and high density, which significantly improve photon attenuation efficiency. Moreover, Gd_2O_3 incorporation can enhance radiation shielding performance while maintaining the optical transparency of the glass matrix.⁷ In addition, Eu_2O_3 has recently attracted interest as a rare earth dopant due to its unique optical and luminescent properties. Europium ions can modify the structural arrangement of glass networks and contribute to photon interaction behavior owing to their relatively high atomic number ($Z=63$). Furthermore, Eu^{3+} doped glasses are well known for their strong luminescence characteristics, narrow emission bands, and potential applications in photonic and scintillation materials.

Therefore, the incorporation of Eu_2O_3 into germanoborate glass systems may provide additional functionality while simultaneously contributing to

radiation attenuation performance.⁸ Glasses doped with rare earth and heavy metal oxides have been widely investigated as lead-free gamma-ray shielding materials. However, most reported systems are based on borate, phosphate, tellurite or silicate hosts and employ only a small amount of a single high- Z rare-earth modifier.

For example, the Eu -, Te - and Pb -containing telluroborate glasses⁹ and the Ce - and Gd -reinforced borosilicate glasses reported previously derive most of their attenuation from the heavy-metal or lead component of the host and incorporate the rare-earth oxide only as a minor dopant.¹⁰ In contrast, the present work combines a germanoborate host with a dual rare-earth design, in which a fixed 25 mol% Gd_2O_3 is reinforced with variable Eu_2O_3 (0-9 mol%), so that the rare-earth oxides act as the principal attenuating constituents rather than as minor dopants. This configuration also introduces two closely spaced K-absorption edges ($\text{Eu} \approx 48.52$ keV and $\text{Gd} \approx 50.24$ keV) that extend the high-attenuation region within the diagnostic energy range, while keeping the glass lead-free and optically active via Eu^{3+} luminescence.

In the present study, Eu_2O_3 -doped germanoborate glasses with the composition 40GeO_2 : $25\text{Gd}_2\text{O}_3$: $(35-x)\text{B}_2\text{O}_3$: $x\text{Eu}_2\text{O}_3$ were prepared using the conventional melt-quenching technique. The physical and gamma-ray shielding properties of the prepared glasses were systematically investigated through density, molar volume, mass attenuation coefficient, effective atomic number, effective electron density, half-value layer, and lead equivalent thickness analyses. The photon interaction parameters were theoretically evaluated using the WinXCom program based on the NIST photon cross section database.¹¹

Materials and methods

Glass sample preparation

The germanoborate glass system containing Eu_2O_3 was synthesized according to the composition 40GeO_2 : $25\text{Gd}_2\text{O}_3$: $(35-x)\text{B}_2\text{O}_3$: $x\text{Eu}_2\text{O}_3$, where $x=0, 1, 3, 5, 7$, and 9 mol%, using the conventional melt-quenching method. High purity chemical reagents were employed throughout the preparation process. Each batch was prepared with a constant total weight of 20 gm and measured using a high-precision analytical balance with an accuracy of four decimal places. The prepared mixtures were transferred into covered alumina crucibles and heated in an electric furnace at $1,400^\circ\text{C}$ for 3 hours until complete melting and homogenization were achieved. Subsequently, the molten glasses were cast into graphite molds at ambient conditions and annealed at 500°C for 3 hours to eliminate residual thermal stress before cooling gradually to room temperature. The fabricated glass samples were then shaped and polished into dimensions of approximately $1.0 \times 1.5 \times 0.3$ cm for subsequent analyses. The measured physical parameters, including density and molar volume, are illustrated in Figure 1.

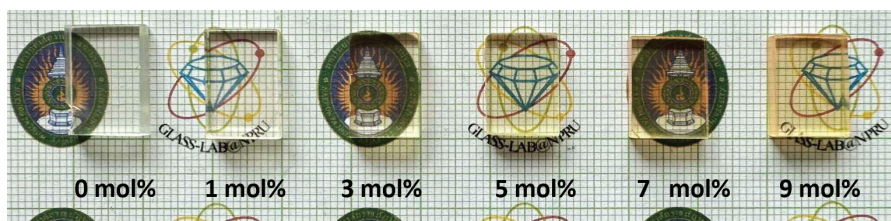


Figure 1. The glass samples of the Eu_2O_3 -doped germanoborate glasses.

Measurement of physical properties

The physical characteristics of the prepared Eu_2O_3 -doped germanoborate glasses were investigated through density and molar volume measurements. Density is considered a fundamental physical parameter in glass materials, as it provides important information regarding the structural compactness and atomic packing of the glass network. Furthermore, density plays a crucial role in determining the interaction probability between the material and incident gamma photons. In addition, the measured density values are required to determine several radiation shielding parameters, including the linear attenuation coefficient, effective atomic number, and electron density. The density (ρ) of the fabricated glass samples was experimentally determined at room temperature using the Archimedes method with distilled water as the immersion medium. All measurements were carried out using a high-resolution analytical balance (AND, HR-200). The density values were calculated using the following equation:

$$\rho = \left(\frac{W_{\text{air}}}{W_{\text{air}} - W_{\text{water}}} \right) \times \rho_w \quad (1)$$

Where W_{air} and W_{water} correspond to the weights of the sample measured in air and the immersion liquid, respectively, while ρ_w represents the density of the buoyant medium.

The molar volume was determined from the experimentally measured density values and the corresponding molecular weights of the glass compositions. This parameter provides useful information regarding the structural arrangement, packing efficiency, and spatial distribution within the glass network. Variations in molar volume are commonly associated with changes in bond configuration, network connectivity, and the formation of bridging oxygen (BO) and non-bridging oxygen (NBO) species in the glass structure. Consequently, molar volume is recognized as an important parameter for correlating the structural characteristics of glass systems with their physical and radiation shielding properties.¹² The molar volume (V_m) of the prepared glasses was calculated using the following equation:

$$V_m = \frac{M}{\rho} \quad (2)$$

Where M denotes the molecular weight of the glass composition and ρ represents the density of the corresponding glass sample.

Theoretical background

The attenuation of gamma rays passing through a material is governed by the exponential Beer-Lambert law, which describes the reduction in photon intensity as a function of material thickness and attenuation capability:

$$I = I_0 e^{-\mu x} \quad (3)$$

where I and I_0 represent the transmitted and incident photon intensities, respectively, μ is the linear attenuation coefficient (cm^{-1}), and x denotes the thickness of the absorber material (cm). The mass attenuation coefficient (μ_m) is obtained by normalizing μ to the density of the material, thereby providing a density-independent parameter for evaluating the gamma-ray attenuation capability of the investigated glasses:

$$\mu_m = \sum_i w_i \left(\frac{\mu}{\rho} \right)_i \quad (4)$$

When w_i represents the weight fraction of each constituent element, and μ_m corresponds to the mass attenuation coefficient of the individual elements within the glass composition. The theoretical attenuation parameters were calculated using the WinXCom program, which is based on the NIST photon cross-section database and provides photon interaction coefficients as a function of elemental composition and photon energy.¹²

The average atomic cross-section, (σ_a), can be evaluated from the mass attenuation coefficient using the following relation:

$$\sigma_a = \frac{\mu}{N_A \sum_i \frac{w_i}{A_i}} \quad (5)$$

Similarly, the average electronic cross-section (σ_e), can be determined using the following equation:

$$\sigma_e = \frac{1}{N_A} \sum_i \left(\sum_j \frac{f_j A_j}{Z_j} \right) w_i \quad (6)$$

where f_i and Z_i denote the fractional abundance and atomic number of the constituent element, respectively.

For composite glass materials, the effective atomic number (Z_{eff}) represents an equivalent atomic number that characterizes the material's photon interaction capability of the material.

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_{el}} \quad (7)$$

The effective electron density (N_{eff}) defines the number of electrons per unit mass, which is related to the Z_{eff} , and is formulated as follows.¹³

$$N_{\text{eff}} = N_A \frac{Z_{\text{eff}}}{\sum_i \frac{w_i}{A_i}} \quad (8)$$

The half-value layer (HVL) is defined as the thickness of a shielding material required to reduce the incident gamma-ray intensity to one-half of its original value, and it can be calculated using the following equation¹⁴:

$$HVL = \frac{0.693}{\mu} \quad (9)$$

where μ is the linear attenuation coefficient. HVL is a practical parameter for assessing and comparing the shielding effectiveness of different materials.

The lead equivalent thickness represents the thickness of lead required to provide the same radiation attenuation performance as the investigated shielding material under identical exposure conditions. This parameter is widely used to compare the shielding effectiveness of alternative materials with conventional lead-based shields. The equivalent lead thickness can be estimated from the relationship between the linear attenuation coefficient and the thickness of the material for a specific photon energy, and is expressed

by the following equation¹⁵:

$$d_{pb} = \frac{\mu_{\text{material}}}{\mu_{pb}} \times d_{\text{material}} \quad (10)$$

where μ_{pb} is the linear attenuation coefficient of lead, d_{pb} denotes the calculated lead equivalent thickness, μ_{material} represents the linear attenuation coefficient of the investigated material, and d_{material} corresponds to the thickness of the shielding sample.

WinXCom program

WinXCom is a computational program developed based on the NIST XCOM photon cross-section database and is widely used to evaluate photon interaction parameters in shielding materials. The software provides theoretical mass attenuation coefficients together with partial photon interaction cross sections, including photoelectric absorption, Compton scattering, and pair production, over a broad photon energy range from approximately 1 keV to 100 GeV, as illustrated in Figure 2. By specifying the elemental composition and photon energy range, the program can generate attenuation-related parameters for compounds, mixtures, and glass systems with high computational efficiency.

In addition to mass attenuation coefficients, WinXCom can also be used to derive important shielding parameters such as the effective atomic number (Z_{eff}) and effective electron density (N_{eff}), which are commonly utilized to evaluate gamma-ray shielding performance. Owing to its reliability, rapid calculation capability, and broad applicability, WinXCom has become a standard tool extensively used in radiation shielding investigations.¹⁶ It should be noted that the gamma-ray shielding parameters presented in this study were obtained from WinXCom calculations, without experimental validation through gamma-ray attenuation measurements.

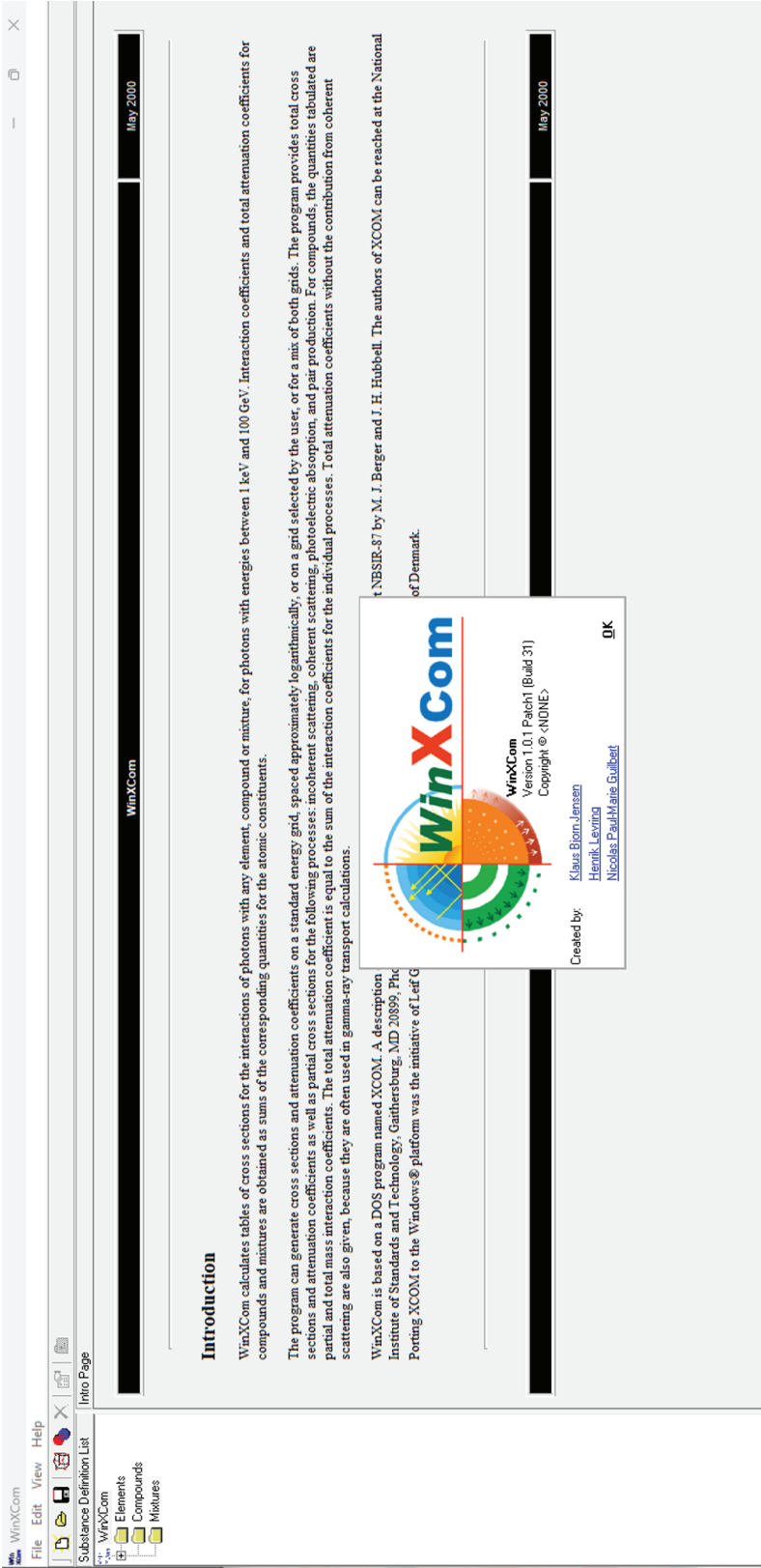


Figure 2. WinXCom program¹⁶

Results

Physical properties

The density and molar volume of the Eu_2O_3 -doped germanoborate glasses with the composition 40GeO_2 : $25\text{Gd}_2\text{O}_3$: $(35-x)\text{B}_2\text{O}_3$: $x\text{Eu}_2\text{O}_3$ were systematically investigated, as illustrated in Figure 3. The results reveal that the density of the prepared glasses gradually increased with increasing Eu_2O_3 concentration, rising from approximately 4.58 g/cm^3 for the undoped sample to 5.14 g/cm^3 for the glass containing 9 mol% Eu_2O_3 . This behavior can be attributed to the substitution of B_2O_3 , which possesses relatively low molecular weight and density, by Eu_2O_3 , which contains heavier europium ions with a high atomic mass. The incorporation of Eu^{3+} ions therefore enhances the overall density and compactness of the glass network. In contrast, the molar volume exhibits a slightly different trend with increasing Eu_2O_3 content. Initially, the molar volume decreased from approximately $34.7 \text{ cm}^3/\text{mol}$ to $34.5 \text{ cm}^3/\text{mol}$ with increasing Eu_2O_3 concentration up to

3 mol%, suggesting structural compaction and improved atomic packing within the glass matrix. This behavior may result from the occupation of interstitial positions by Eu^{3+} ions, reducing free volume and enhancing network connectivity. However, at higher Eu_2O_3 concentrations, the molar volume gradually increased and reached approximately $35.8 \text{ cm}^3/\text{mol}$ for the glass containing 9 mol% Eu_2O_3 . The increase in molar volume may be associated with the formation of non-bridging oxygen (NBO) sites and partial disruption of the borate glass network caused by the modifier role of Eu^{3+} ions. Such structural modifications can expand the glass network and increase interatomic spacing within the system.^{17,18}

The observed variations in density and molar volume confirm that Eu_2O_3 incorporation significantly influences the structural arrangement, packing efficiency, and network connectivity of the germanoborate glass system.

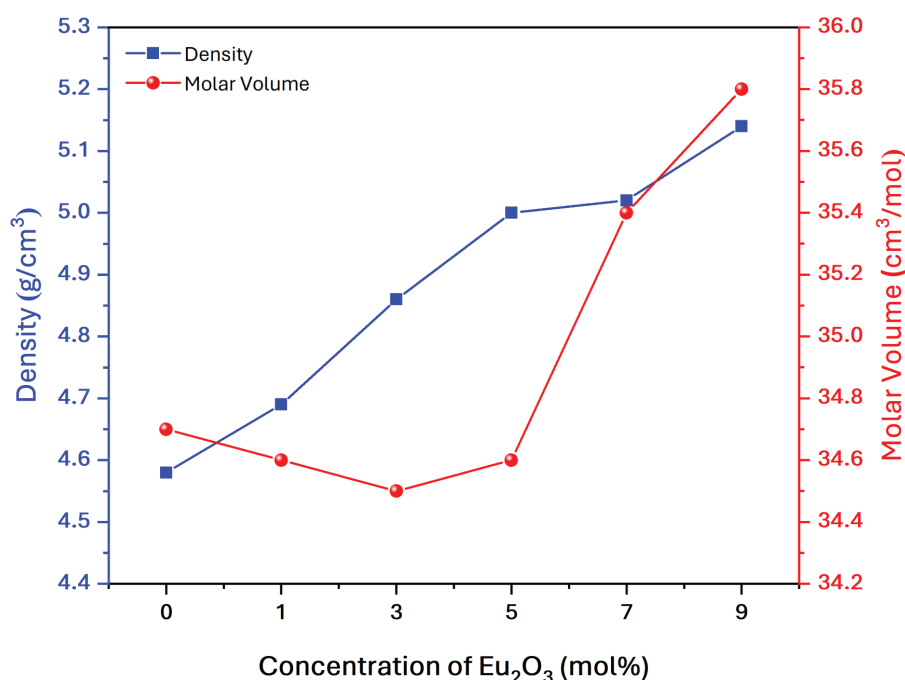


Figure 3. The density and molar volume of Eu_2O_3 -doped germanoborate glasses.

Radiations properties

Figure 4 illustrates the dominant photon interaction mechanisms of the Eu_2O_3 -doped germanoborate glass containing 9 mol% Eu_2O_3 over the photon energy range of 0.015-15 MeV. The attenuation processes can be classified into three principal interaction mechanisms: the photoelectric effect, Compton scattering, and pair production. In the low-energy region below approximately 0.1 MeV, the photoelectric effect is the dominant interaction process. This behavior is strongly associated with the presence of high atomic number elements such as gadolinium ($Z=64$) and europium ($Z=63$), which

significantly enhance the probability of photon absorption. In addition, two distinct absorption edges can be observed near 0.04852 MeV and 0.05024 MeV, corresponding to the K-absorption edges of Eu and Gd, respectively. These absorption discontinuities originate from the interaction between incident photons and K-shell electrons, resulting in a sudden increase in attenuation efficiency within this energy region. As the photon energy increases into the intermediate energy range (approximately 0.1-1.0 MeV), Compton scattering becomes the predominant interaction mechanism. This interaction mainly depends

on the electron density of the material and involves the inelastic scattering of photons by loosely bound electrons. Consequently, Compton scattering plays a major role in gamma-ray attenuation for medical diagnostic energies and industrial radiographic applications. At higher photon energies exceeding 1.02 MeV, pair production gradually becomes more significant. In this process, incident photons interact with the nuclear field and are converted into electron-positron pairs. The increasing contribution of pair production at high energies demonstrates the capability of the investigated glass system to attenuate

high-energy gamma photons, which is particularly important for shielding applications involving high-energy radiation facilities and linear accelerators.

The total attenuation behavior represents the combined contribution of all photon interaction mechanisms and exhibits strong energy dependence across the investigated energy range. The incorporation of Eu_2O_3 together with Gd_2O_3 contributes to enhanced attenuation performance, particularly in the low-energy region where the photoelectric effect and the characteristic K-absorption edges of Eu and Gd strongly influence photon interaction probability.

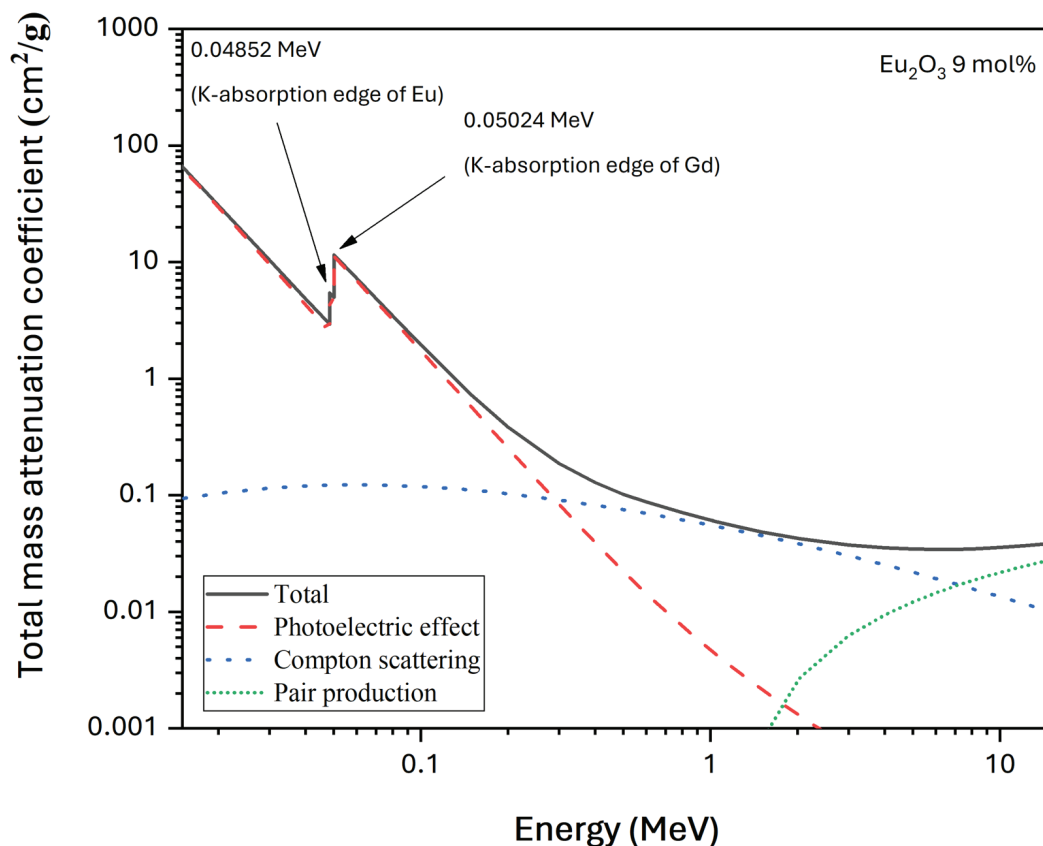


Figure 4. The partial interaction of Eu_2O_3 -doped germanoborate glasses.

Figure 5 presents the variation of the mass attenuation coefficient (μ_m) for Eu_2O_3 -doped germanoborate glasses with the composition $40\text{GeO}_2 : 25\text{Gd}_2\text{O}_3 : (35-x)\text{B}_2\text{O}_3 : x\text{Eu}_2\text{O}_3$ (where $x=0, 1, 3, 5, 7$, and 9 mol%) over the photon energy range of 0.015–15 MeV using the WinXCom program. The results demonstrate that the mass attenuation coefficient decreases continuously with increasing photon energy, which is consistent with the energy dependence of the dominant photon interaction mechanisms, including the photoelectric effect, Compton scattering, and pair production. In the low-energy region below approximately 0.2 MeV, the photoelectric effect is the predominant attenuation process, resulting in relatively high μ_m values. In this region, the attenuation coefficients decrease rapidly

as photon energy increases due to the strong energy dependence of the photoelectric absorption process. In other words, because the photoelectric interaction becomes far more probable as the photon energy decreases, μ_m attains its highest values in this low-energy region. Furthermore, two noticeable discontinuities can be observed near 0.04852 MeV and 0.05024 MeV, corresponding to the K-absorption edges of europium (Eu) and gadolinium (Gd), respectively. At these energies, incident photons possess sufficient energy to ionize K-shell electrons, leading to a sudden enhancement in photon absorption probability and attenuation efficiency. These jumps occur exactly where the photon energy just exceeds the K-shell binding energy of Eu and Gd, opening an additional photoelectric

absorption channel. As the photon energy increases into the intermediate region (approximately 0.2-1.0 MeV), the mass attenuation coefficient gradually decreases, and the dominant interaction mechanism shifts toward Compton scattering. In this energy range, photon interactions are mainly governed by electron density rather than atomic number, resulting in relatively small differences among the investigated glass compositions.

Hence, the μ_m curves of all compositions nearly coincide here, because Compton scattering depends on electron density rather than on atomic number.¹⁹ At higher photon energies exceeding 1.02 MeV, pair production gradually becomes the dominant interaction mechanism. This process involves the conversion of high-energy photons into electron-positron pairs in the vicinity of the atomic nucleus. Consequently, the attenuation behavior at high energies becomes less

dependent on elemental composition compared with the low-energy region. Comparative analysis of the investigated glass systems indicates that increasing Eu_2O_3 concentration slightly enhances the mass attenuation coefficient, particularly at low photon energies. This improvement can be attributed to the relatively high atomic number and density of europium ions, which increase photon interaction probability through the photoelectric effect. However, the influence of Eu_2O_3 concentration becomes less pronounced at intermediate and high photon energies because Compton scattering and pair production are less sensitive to atomic number. Overall, the obtained results confirm that Eu_2O_3 incorporation contributes positively to the gamma-ray attenuation capability of germanoborate glasses, demonstrating their potential for radiation shielding applications.

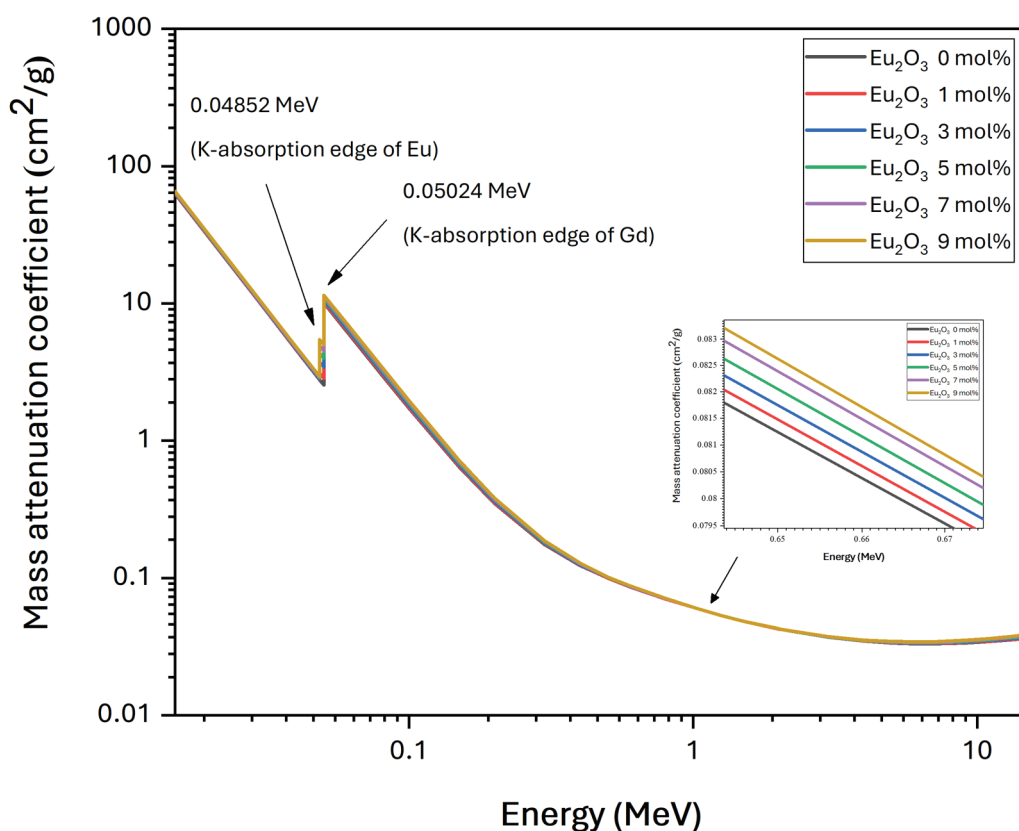


Figure 5. The mass attenuation coefficient of Eu_2O_3 -doped germanoborate glasses.

Figure 6 illustrates the variation of the effective atomic number (Z_{eff}) of Eu_2O_3 -doped germanoborate glasses with different Eu_2O_3 concentrations (0-9 mol%) over the photon energy range of 0.015-15 MeV. The obtained results demonstrate that the Z_{eff} values strongly depend on photon energy due to the dominant photon interaction mechanisms occurring within different energy regions. In the low-energy region below approximately 0.1 MeV, relatively high Z_{eff} values are observed for all investigated glass compositions.

This behavior is mainly attributed to the dominance of the photoelectric effect, which strongly depends on the atomic number of the constituent elements. Therefore, the incorporation of high atomic number oxides such as Gd ($Z=64$) and Eu ($Z=63$) significantly enhances the photon interaction probability and increases the effective atomic number of the glass system. The high atomic numbers of Gd and Eu enhance the photoelectric effect, resulting in the maximum Z_{eff} in the low-energy region. A distinct discontinuity in

the Z_{eff} curves can be observed near 0.04852 MeV and 0.05024 MeV, corresponding to the K-absorption edges of Eu and Gd, respectively. At these characteristic energies, incident photons possess sufficient energy to ionize K-shell electrons, resulting in a sudden increase in the atomic interaction cross-section and consequently producing sharp enhancements in the effective atomic number.

The presence of these absorption edges confirms the strong contribution of Eu and Gd ions to photon attenuation in the low-energy region. As photon energy increases beyond the absorption edge region, the Z_{eff} values gradually decrease and reach minimum values within the intermediate energy range of approximately 0.2-2.0 MeV. This trend is associated with the predominance of Compton scattering, where photon interactions depend mainly on electron density rather than atomic number. Consequently, the differences in Z_{eff} among the investigated glass compositions become

less pronounced within this energy region. At higher photon energies exceeding 1.02 MeV, the Z_{eff} values exhibit a slight increasing trend due to the increasing contribution of pair production. Since pair production probability is influenced by the atomic number of the absorber material, glasses containing higher Eu_2O_3 concentrations demonstrate slightly higher effective atomic numbers at high photon energies. Z_{eff} rises again in this region because pair production, like the photoelectric effect, is enhanced by the high-Z Eu and Gd atoms.²⁰

The energy-dependent variation of Z_{eff} closely follows the behavior observed for the mass attenuation coefficient, particularly within the photoelectric absorption region. The incorporation of Eu_2O_3 together with Gd_2O_3 therefore enhances the photon interaction capability of the germanoborate glass system across a broad photon energy range, indicating its potential applicability for gamma ray shielding applications.

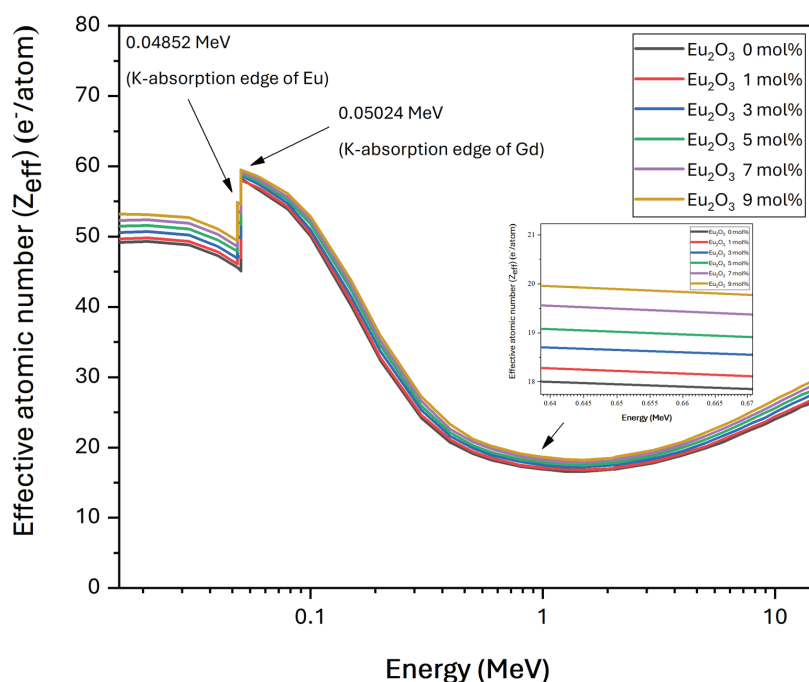


Figure 6. The effective atomic number of Eu_2O_3 doped germanoborate glasses.

Figure 7 illustrates the variation of the effective electron density N_{eff} of Eu_2O_3 doped germanoborate glasses over the photon energy range of 0.015-15 MeV. In the low-energy region, relatively high N_{eff} values are observed together with noticeable discontinuities near 0.04852 MeV and 0.05024 MeV, corresponding to the K-absorption edges of Eu and Gd, respectively. A slight inversion trend can also be observed below the absorption edge region, where glasses containing lower Eu_2O_3 concentrations exhibit slightly higher N_{eff} values compared with highly doped compositions. This behavior may be associated with the influence of the

Eu and Gd absorption edges, which produce abrupt changes in photon interaction probability and consequently affect the effective electron density response of the investigated glasses. As photon energy further increases, the N_{eff} values gradually rise again due to the increasing contribution of pair production interactions.

Glasses containing higher Eu_2O_3 concentrations exhibit slightly enhanced N_{eff} values at medium and high photon energies owing to the additional electron contribution introduced by europium ions into the glass network.²¹

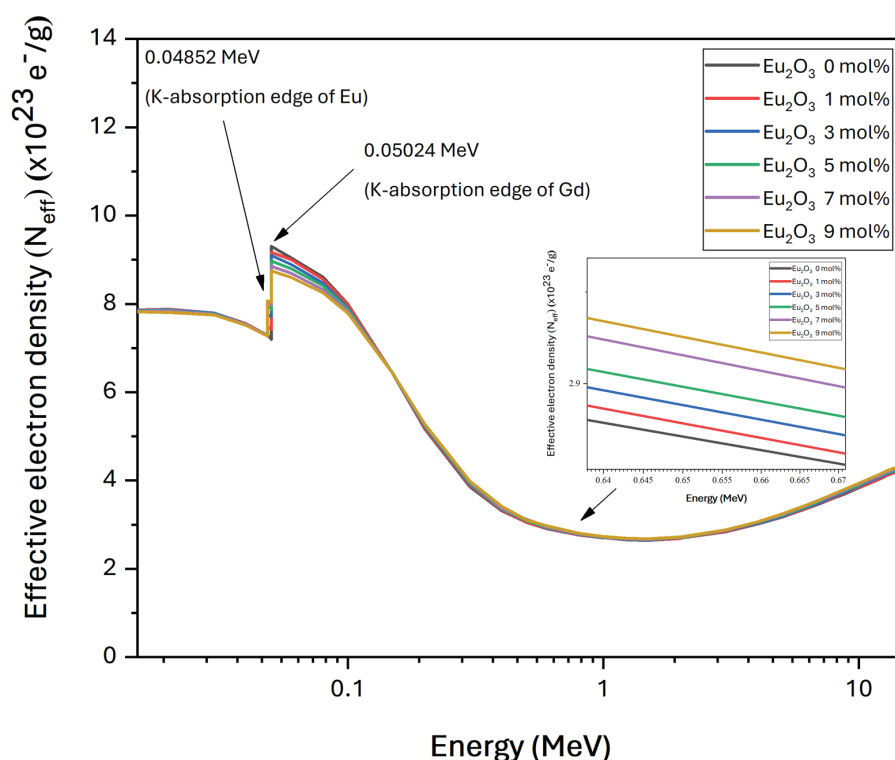


Figure 7. The effective electron density of Eu_2O_3 -doped germanoborate glasses.

Figure 8 presents the variation of the half-value layer (HVL) for Eu_2O_3 -doped germanoborate glasses at a photon energy of 0.662 MeV. It can be observed that the HVL values slightly decrease as the Eu_2O_3 concentration increases, reflecting the improved ability of the glasses to attenuate incident gamma photons. The reduction in HVL indicates that a thinner glass thickness is required to reduce the radiation intensity to half its initial value, confirming the enhanced shielding performance after Eu_2O_3 incorporation. To evaluate the shielding effectiveness, the obtained HVL values were compared with several conventional shielding materials, including commercial window glass,²² ordinary concrete,²³ and PbO-based glass (50% PbO).²⁴ The investigated glasses exhibit noticeably lower HVL values than those of commercial

window glass and ordinary concrete, indicating superior gamma-ray attenuation capability. Nevertheless, the HVL values remain moderately higher than those of PbO-based glass, which can be attributed to the superior attenuation efficiency of lead-containing materials resulting from the higher atomic number and density of Pb atoms. Among all investigated compositions, the sample containing 9 mol% Eu_2O_3 demonstrates the minimum HVL value, suggesting the highest shielding efficiency within the studied glass system.

These results indicate that the incorporation of Eu_2O_3 positively contributes to the radiation shielding characteristics of germanoborate glasses while maintaining the advantages of transparency and lead-free composition.

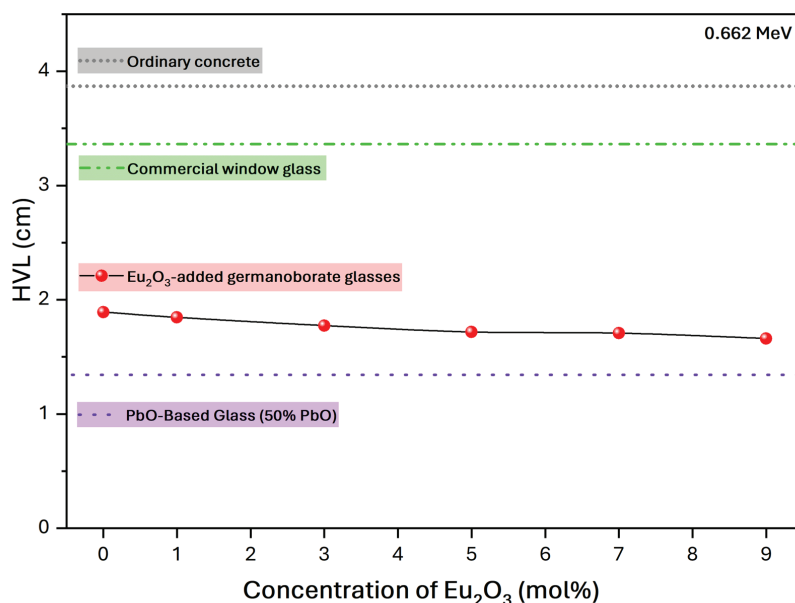


Figure 8. The half-value layer (HVL) values of Eu_2O_3 -doped germanoborate glasses.

Figure 9 presents the Pb equivalent thickness of Eu_2O_3 -doped germanoborate glasses at 0.662 MeV as a function of Eu_2O_3 concentration. The results indicate that the Pb equivalent values gradually increase with increasing Eu_2O_3 content, rising from approximately 0.094 cm for the undoped glass to about 0.107 cm for the glass containing 9 mol% Eu_2O_3 . This behavior suggests that the incorporation of Eu_2O_3 enhances the gamma-ray attenuation capability of the investigated glass system due to the contribution of high atomic number europium ions to photon interaction probability. In comparison with reference shielding materials, the Pb equivalent values of the

investigated glasses are significantly higher than those of commercial window glass,²³ demonstrating their superior radiation shielding performance. However, the obtained values remain slightly lower than those reported for PbO-based shielding glasses,²⁴ which is expected because lead possesses a higher atomic number and density. Nevertheless, the developed Eu_2O_3 -doped germanoborate glasses provide the additional advantages of lead-free composition, optical transparency, and improved environmental safety, making them promising candidates for practical radiation shielding applications.

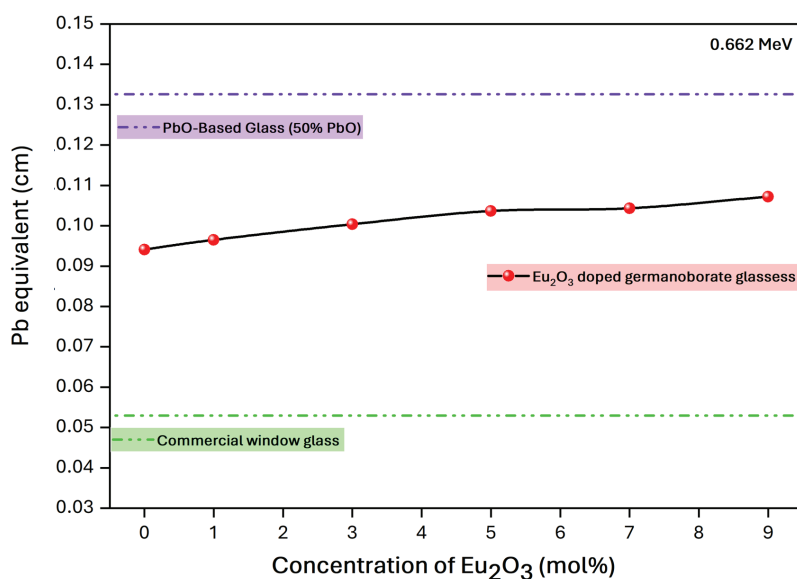


Figure 9. Pb equivalent of Eu_2O_3 -doped germanoborate glasses.

Limitation

This study has several limitations. The glass samples were successfully fabricated using the conventional melt-quenching technique, and their physical properties, including density and molar volume, were experimentally measured. However, all gamma-ray shielding parameters were theoretically calculated using the WinXCom program and were not validated by experimental attenuation measurements. Therefore, the reported shielding performance should be interpreted as theoretical predictions rather than direct experimental results.

Conclusion

In this work, the physical and gamma-ray shielding properties of Eu_2O_3 -doped germanoborate glasses with the composition $40\text{GeO}_2 \cdot 25\text{Gd}_2\text{O}_3 \cdot (35-x)\text{B}_2\text{O}_3 \cdot x\text{Eu}_2\text{O}_3$ ($x=0, 1, 3, 5, 7$ and 9 mol%) were systematically investigated. The glass samples were successfully fabricated using the conventional melt-quenching technique. The obtained results revealed that the density of the glasses gradually increased with increasing Eu_2O_3 concentration, while the molar volume exhibited slight structural variations associated with modifications in glass network packing and connectivity. The radiation shielding parameters, including the μ_m , Z_{eff} , N_{eff} , HVL and Pb equivalent thickness, were evaluated using the WinXCom program. The investigated parameters exhibited strong energy dependence corresponding to the dominant photon interaction mechanisms, namely the photoelectric effect at low energies, Compton scattering at intermediate energies, and pair production at high energies. Distinct discontinuities associated with the K-absorption edges of Eu and Gd were also observed near 0.04852 MeV and 0.05024 MeV, respectively. The incorporation of Eu_2O_3 slightly enhanced the attenuation capability of the investigated glasses, particularly in the low-energy region, due to the contribution of europium ions with relatively high atomic number. In addition, the Pb equivalent values increased with increasing Eu_2O_3 concentration, indicating improved shielding effectiveness compared with commercial window glass, although the performance remained slightly lower than that of PbO-based shielding glasses.

The developed Eu_2O_3 -doped germanoborate glasses exhibit favorable physical characteristics together with promising gamma-ray shielding performance. The combination of lead-free composition, optical transparency, and enhanced radiation attenuation capability suggests that these glasses are potential candidates for transparent radiation shielding applications in medical, industrial, and nuclear radiation environments.

Ethical approval

Not applicable. This study did not involve human participants, animals, or identifiable personal data.

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Conflict of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Natthakridta Chanthima: writing: original draft, validation, investigation, funding acquisition, conceptualization; **Supakit Yonphan:** writing: review and edit, resources, investigation; **Chalermpon Mutuwong:** methodology, investigation, software; **Wuttichai Chaiphaksa:** writing: review and edit, validation, conceptualization, supervision.

Generative AI and AI-assisted use

Not applicable

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