



Theoretical Evaluation of Enhanced Gamma Radiation Shielding Properties of Eu_2O_3 -Doped Silicate Glasses via WinXcom Simulations

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Abstract

This study investigates the radiation shielding properties of newly synthesized Eu_2O_3 -doped silicate glasses, specifically formulated as $40\text{Li}_2\text{O}-05\text{BaO}-05\text{Gd}_2\text{O}_3-(50-x)$ with doping concentrations of $x = 0.0, 0.1, 0.5, 1.0, 1.5,$ and 2.0 mol%. Utilizing the WinXcom program, we theoretically computed key parameters including mass attenuation coefficients (μ_m), effective atomic numbers (Z_{eff}), effective electron densities (N_e), mean free path (MFP), and half-value layers (HVL) across various photon energy levels. The results reveal that the radiation attenuation properties are significantly influenced by both photon energy and the chemical composition of the glass. Notably, as the gamma photon energy increases, the attenuation parameters consistently decrease, while an increase in the doping concentration of Eu_2O_3 is associated with enhanced radiation shielding capabilities. The Eu_2O_3 -doped glass not only avoids the hazardous effects of lead but also exhibits improved transparency and mechanical stability, making it a promising candidate for gamma radiation shielding applications. This research underscores the potential for developing effective, environmentally friendly materials for radiation protection, paving the way for further experimental validation and practical applications in safety-sensitive areas.

Subject Areas

Applied Physics

Keywords

Effective Atomic Numbers, Effective Electron Densities, Attenuation Parameters, Radiation Shielding, Half Value Layer

1. Introduction

The interaction of high-energy photons with matter is a field of concern in several disciplines, such as radiation medicine, nuclear engineering, and space technology. These interactions are very essential for developing applications in those fields [1]. The use of X-rays and gamma rays is increasing in different fields, especially in radiotherapy, imaging, and sterilization; however, leakage and scattering of these rays may cause potent health hazards to human beings. Proper shielding is one of the vital and essential precautions when dealing with such radiations [2]. Currently, the shielding against the two most frequently encountered types of indirectly ionizing radiation, namely photons and neutrons, has gained much attention due to the needs for proper measures to reduce the risks associated with radiation [3]. Glass, an inorganic material, is usually brittle and transparent to visible light [4] and can absorb gamma rays and neutrons to act as a radiation shield for observers and researchers [5].

The mass attenuation parameter (μ_m), effective atomic number (Z_{eff}) and effective electron density (N_{eff}) are convenient parameters with which the scattering and absorption of gamma rays can be characterized for a given material. For example, effective atomic numbers can be used to determine an approximate value of the chemical composition of an unknown compound or they can be used to substitute one chemical element by another in a complicated material [6]. It has to be taken into consideration that the atomic numbers of the elements making up the materials need to be weighted differently for every particular process by which gamma radiation interacts with matter. The effective atomic number of a given material, hence, is not a constant but depends on photon energy and depends on what interaction processes are involved [7].

Materials with high atomic numbers and high densities are primarily used for this purpose; however, because of their high prices, their use is limited [8]. The materials used in this experiment are stainless steel and lead. Silicate glass is one of the preferred choices to the other substances used in radiation shielding owing to its strength and low cost. Silicate glass is one of the better materials used for protection from radiation [9]. Glasses containing BaO belong to a specific glass system that has demonstrated considerable significance from both basic scientific and technological viewpoints [10] [11]. Silicate glasses are preferably used materials for many applications in optical devices. In modern era, the popularity of

silicate glass has grown significantly with the importance of optical components in communication technology. Now a days, forms of communication such as telephone, fax, and the Internet are almost completely dependent on optical fiber transmission, which has largely replaced the use of copper wiring [12].

A comparison between Eu_2O_3 -doped silicate glasses and other glass types, such as, borate and phosphate glass, indicates that silicates generally possess better mechanical stability and optical clarity while still retaining acceptable radiation shielding properties [13]. The incorporation of Eu_2O_3 into such glass matrices have proved to increase both the mechanical integrity and radiation shielding ability of the material significantly compared to conventional glass formulations. The observed effect may be attributed to the unique structural characteristics imparted by the rare-earth oxide, which increases the stability of the glass matrix and thus improves the performance of the glass in radiation protection properties [14].

Radiation shielding materials are necessary for the protection of human health and the environment from harmful ionizing radiation. The ideal design of these materials is to compromise effectively a group of mechanical properties, transparency, and shielding efficiency. A few recent studies have highlighted the potential of employing various glass compositions to achieve these goals. For example, [13] found that modified borate glasses exhibit significant abilities for radiation shielding, indicating their potential application in nuclear facilities and medicine.

Moreover, the developments in the manufacturing of composite materials have been seen to demonstrate higher efficiency in radiation shielding. Research by Kaur *et al.* (2022) determined the effective parameters of photon interactions in different oxide glasses, indicating that certain doping can enhance the attenuation properties considerably, hence rendering them more suitable for use in high-radiation fields [14]. These findings are in agreement with ongoing research on rare-earth oxide doped glasses, where doping with elements like europium can impart certain structural characteristics beneficial for radiation shielding. Likewise, a comparative investigation by Tow *et al.* (2020) on silicone-based materials highlighted the significance of hybrid composites in reducing the effective atomic number and enhancing electron density, which contributes to better shielding performance against gamma radiation [15]. While the use of materials like lead oxide has been prevalent in conventional glass formulations, the environmental issues related to lead have prompted research into more secure and eco-friendly substitutes.

In this article, the current study aims to further explore the radiation shielding potential of Eu_2O_3 -doped silicate glasses. The glasses not only show promising mechanical stability and transparency but also demonstrate enhanced radiation attenuation properties with the incorporation of europium oxide. Through the controlled modification of Eu_2O_3 concentration in the glass matrix, we aim to optimize the radiation shielding performance with a particular focus on the lack of toxic materials, such as lead. This study adds to the increasing literature concern-

ing eco-friendly materials for radiation protection applications, promoting the utilization of novel glass compositions with the fulfillment of safety and performance criteria.

Some researchers have measured absorption coefficients or have calculated effective atomic numbers or effective electron densities for glasses at energies around 1 MeV [15]-[21], but there is a lack of studies covering lower and higher energy regions. In the present study, we have calculated the effective atomic number and related parameters for photon energies between 0.001 MeV and 1 MeV for the 40Li₂O-05BaO-05Gd₂O₃-(50-x) glass formulations using photon interaction cross-sections obtained from the WinXCOM interpolation program [22].

2. Experimental Procedures

The glasses having composition 40Li₂O-05BaO-05Gd₂O₃-(50-x) (where “x” is the mole percent of Eu₂O₃) were prepared by the conventional melt quenching method. The reagent’s quantities were weighed as per the above formula and mixed to form a total of 10 grams for every sample, followed by loading the mixture in an alumina crucible. The crucibles were moved to the lower part of the electric furnace for heating. The temperature of the electric furnace is increased to 1500°C at the rate of 10 °C/min. The temperature had been maintained for 3 hours at 1500°C for the homogeneous melting of chemicals. The fluid is then quickly poured out on a steel sculpture and moved to some other electric oven which has already been kept at 500°C for further 3 hours to eliminate the thermal stress. The sample is polished carefully on the alumina polishing plate using high-quality diamond polishing powder to obtain a smooth, transparent, and parallel surface. The glass samples thus prepared and fine polished to sizes of (W × D × H) 1.0 cm × 0.3 cm × 1.5 cm for further analysis [14].

Physical Properties

The density of 40Li₂O-05BaO-05Gd₂O₃-(50-x) (where “x” is the mole percentage of Eu₂O₃) glasses were measured using Archimedes principle by the following equation [23].

$$\rho = \frac{W_{air}}{W_{air} - W_{water}} \quad (1)$$

Where W_{air} represents weight of in air and W_{water} , represents weight of samples in water and density of water is $\frac{1g}{cm^3}$. The molar volumes V_m were obtained by dividing the total molecular weight (M) of each sample by its density as shown in the following Eq. (2) [24] [25].

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

where V_m is the molar volume, M is the molar weight and ρ is the density of samples.

The composition of glass together with the concentration of dopant and the glass code is given below in **Table 1**.

Table 1. Glass composition, glass code and dopant concentration of the glass under investigation.

Glass Code	Eu ₂ O ₃ mol%	Composition (mol%)
LBGS (Host)	0	40Li ₂ O-05Gd ₂ O ₃ -05BaO-50SiO ₂
LBGS-0.1Eu	0.1	40Li ₂ O-05Gd ₂ O ₃ -05BaO-49.9SiO ₂ :0.1 Eu ₂ O ₃
LBGS-0.5Eu	0.5	40Li ₂ O-05Gd ₂ O ₃ -05BaO-49.5SiO ₂ :0.5 Eu ₂ O ₃
LBGS-1.0Eu	1.0	40Li ₂ O-05Gd ₂ O ₃ -05BaO-49SiO ₂ :1.0 Eu ₂ O ₃
LBGS-1.5Eu	1.5	40Li ₂ O-05Gd ₂ O ₃ -05BaO-48.5SiO ₂ :1.5 Eu ₂ O ₃
LBGS-2.0Eu	2.0	40Li ₂ O-05Gd ₂ O ₃ -05BaO-48SiO ₂ :2.0 Eu ₂ O ₃

3. Result and Discussion

3.1. Mass Attenuation Coefficient

The mass attenuation coefficient (μ_m) of the proposed glasses system were theoretically investigated by WinXCOM program developed by Gerward *et al.* [26]. The mass attenuation coefficients were calculated according to the measured incident and transmitted gamma-ray intensities for a range of photon energies from 0.001 MeV to 1 MeV, along with the thickness (x) and density (ρ) for each sample.

The dependence of the absorption coefficients (μ) on energy for various glass samples is studied in detail and shown in **Figure 1(a)-(f)**. These figures show the energy-dependent behavior of the absorption properties, which reveal some strong peaks which indicate particular electronic transitions occurring in the material [27]. The L-peak occurs as the L-shell electrons jump and is located at lower energy than the K-peak. It presents a moderate increase in absorption. This peak shows how the glass interacts with lower-energy radiation, which is important for some applications shown in **Figure 1**. The M-peak is due to the change in outer-shell electrons and occurs at much lower energies than the K and L peaks. It shows how the glass interacts with low-energy radiation, which is very important for understanding its behavior in low-energy photon environments [28].

The Beer-Lambert law, an essential exponential law behind narrow beam attenuation, was used to explain this experiment. Thus, it describes an exponential relationship between the incident, I_0 and the transmitted I , intensity with the thickness of target material, x to be given as below. [29] [30]. Theoretical values calculated using the WinXcom program for the given glass system are listed in **Table 2**. From the table, it can be seen that mass attenuation coefficients depend on both photon energy and chemical composition. **Figure 2(a)** shows the dependence of the mass attenuation coefficient for the LBGS-2.0Eu glass as a function of energy.

A higher value of mass attenuation coefficient has been reported for LBGS-2.0Eu, which indicates its good shielding properties.

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

3.2. Effective Atomic Number (Z_{eff})

The effective atomic number (Z_{eff}) signifies that the radiation attenuation in the absorbing medium is associated with the interaction of radiations with matter and varies with energy. Effective atomic number is one of the most important parameters providing a measure of the ability of a material to absorb or scatter ionizing radiation. In the context of Eu_2O_3 -doped silicate glasses, the glass composition primarily dictates Z_{eff} , especially concerning the heavy metal oxides and rare-earth elements such as europium. This relation also underlines the importance of the material composition in evaluating the effectiveness of radiation shielding for these glass compositions.

The theoretical values of Z_{eff} are presented in Fig. 2b that the Z_{eff} of Eu_2O_3 -doped silicate glasses is observed to decrease significantly with the increase in energy of gamma rays, characteristic of the higher penetration at high energies. A decrease in Z_{eff} can be explained by the relative importance of different interaction mechanisms such as photoelectric effect, coherent, and incoherent scattering. At lower energies of the photons, it is dominated by the photoelectric effect, and this absorption mechanism defines higher Z_{eff} . As the energy increases above 0.1 MeV, the number of scattering and pair production events also increases; hence, it reduces the relative importance of the photoelectric effect and decreases Z_{eff} . Specifically, pair production is only possible for energies greater than 1.02 MeV; but below this energy (up to 0.1 MeV), the photoelectric effect causes very high values of Z_{eff} . In the intermediate energy interval (0.1 to 1 MeV), where scattering processes dominate, Z_{eff} is smaller indicating that, in this energy range, incident photons are more attenuated by materials with high Z_{eff} values. It was seen that the effective atomic number, Z_{eff} , increases with increasing dopant concentration. Indeed, LBGS-2.0Eu has the largest value of Z_{eff} among the studied samples, which means that high dopant concentration levels improve the capacity of the material to attenuate incident gamma radiation. The relationship observed underlines the crucial role of dopant concentration on enhancing the radiation shielding properties of Eu_2O_3 -doped silicate glasses.

3.3. Effective Electron Densities

Figure 3(a) depicts the effective electron density (N_e) of the glass systems. Similar trends obtained in the Z_{eff} and mass attenuation coefficient (μ_m) also exist in the energy dependence of the energy absorption dose (EED). It is worthwhile to note that EED values have a tendency to decrease with an increase in photon energy. This observation indicates a higher cost per unit mass at lower incident energies, suggesting that the material has more potential to absorb energy at these lower

energy levels.

In addition, EED is quite sensitive to the chemical composition of the glass systems and tends to increase with increasing dopant concentration [31]. The relation shows that the material composition significantly affects the radiation absorption characteristics. Interestingly, the N_e values are relatively higher for LBGS-2.0Eu, which essentially means this particular composition has more chances of interacting with photons. This may further imply that LBGS-2.0Eu exhibits improved radiation shielding compared to other formulations.

The above remarks provide strong evidence showing that the dopant concentration and glass composition are crucial factors in the optimization of radiation attenuation in such materials. Moreover, similar dependencies of N_e on gamma-ray energy were also reported in the literature for a variety of materials, hence the importance of the findings in different contexts [32] [33]. These results have significant implications in the design and optimization of the materials to be used for radiation shielding applications, drawing attention to the importance of careful composition parameter consideration in order to enhance performance [34].

3.4. Half Value Layer

The phenomenon of exponential decay in photon intensity can be quantitatively described by the concept of half thickness, often referred to as the half-value layer (HVL) or The HVL is also defined as that thickness of a material necessary to reduce the radiation intensity to fifty percent of its original value. This is an important property since it characterizes the intrinsic capability of high-energy photons penetrating a medium, which generally increases with photon energy. Hence, HVL is one of the most important measures of shielding effectiveness of various materials against radiation, which provides crucial information about their ability in attenuation of photons of different energies. The HVLs obtained from theoretical calculations are plotted as a function of energy and shown in **Figure 3(b)**. From the data as shown in **Table 2**, it was observed that the HVL values for the studied glass systems increase with increasing gamma-ray energies. Moreover, the results show a decrease in HVL values as dopant concentration increases, meaning that materials with higher concentrations of dopants have better shielding characteristics. More significantly, LBGS-2.0Eu has the lowest HVL value among the studied glass systems, indicating that it has better shielding characteristics compared to other studied systems. This trend puts the dopant concentration at an equally important position as the glass composition in optimizing the radiation attenuation characteristics. The results show that it is possible to improve the performance of materials used in radiation shielding applications through tuning these parameters. Therefore, understanding the interaction of these parameters gives very relevant information necessary for both the development and selection of materials tailored for a given radiation protection need.

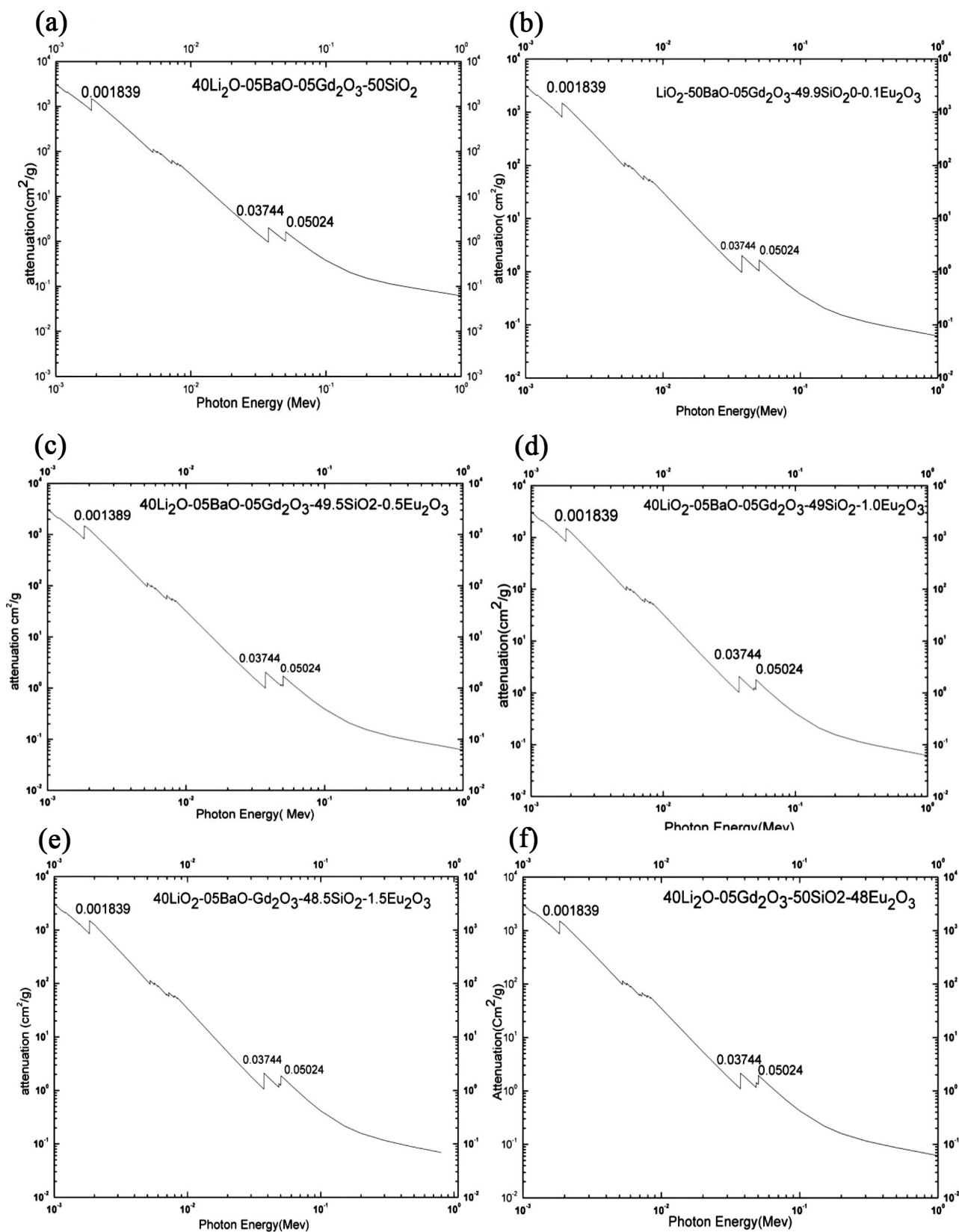


Figure 1. (a)-(f) All indicate the variation of μ as a function of energy. The K-peak of all the glass samples occur at 0.05024 Mev, similarly L-peak at 0.03744 and M-peak at 0.001839 Mev.

Table 2. Variation of μ_m with photon energy.

Energy keV	LBGS Host	LBGS 0.1Eu	LBGS 0.5Eu	LBGS 1.0Eu	LBGS 1.5Eu	LBGS 2.0Eu
	μ_m (cm ² /g)					
662	0.07567	0.07568	0.07571	0.07575	0.07578	0.07582
569.74	0.08142	0.08143	0.08149	0.07575	0.08163	0.0817
482.4	0.08836	0.08838	0.08849	0.07575	0.08875	0.08887
409.42	0.09598	0.09602	0.0962	0.07575	0.09664	0.09686
338.83	0.1062	0.1063	0.1066	0.07575	0.1074	0.1078
290.98	0.1161	0.1162	0.1167	0.07575	0.118	0.1186
257.48	0.1256	0.1258	0.1265	0.07575	0.1283	0.1292
229.96	0.1362	0.1365	0.1374	0.07575	0.1398	0.1411

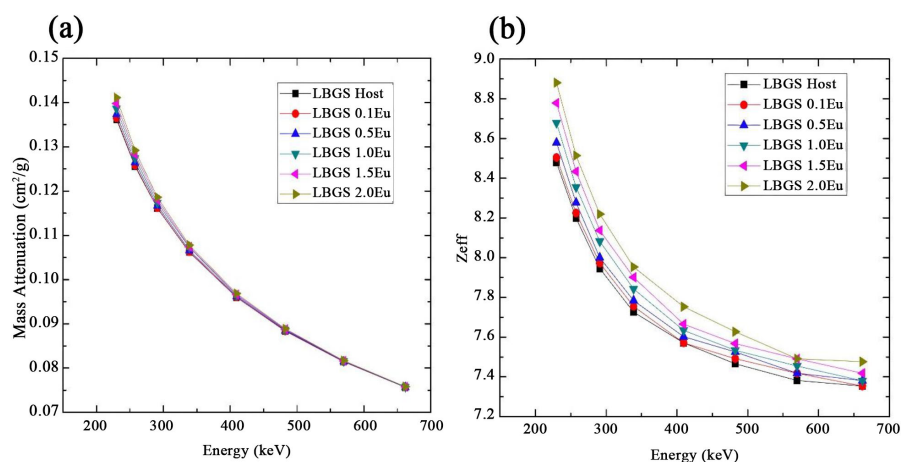


Figure 2. (a): Variation of μ_m with concentration of energy and dopant. (b): Z_{eff} variations with energy and dopants of concentration.

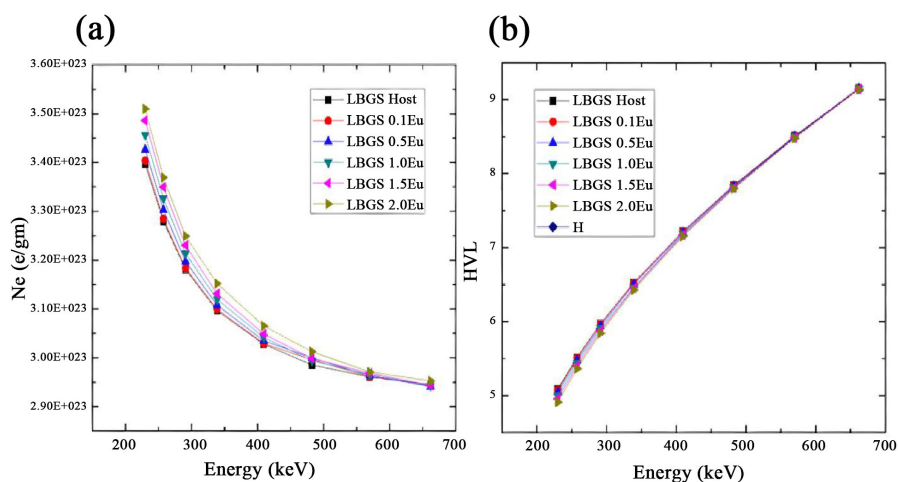


Figure 3. (a): EED trend with energy and dopant concentration. (b): Variation of HVL as an energy function.

4. Conclusions

The investigation of the structural properties and radiation shielding capabilities of Eu_2O_3 -doped silicate glasses has yielded useful information on their prospective applications in radiation protection. The research was directed at a specific glass composition of $40\text{Li}_2\text{O}-05\text{BaO}-05\text{Gd}_2\text{O}_3-(50-x)$, which was prepared by the melt-quenching technique, with Eu_2O_3 concentrations ranging from 0.0 to 2.0 mol%. The results indicated an exceptional improvement in the mass attenuation coefficient (μ_m) with rising concentrations of Eu_2O_3 , signifying an improved capacity for photon absorption. This correlation follows the Beer-Lambert law, describing the exponential decrease of the radiation as a function of the thickness of the material and the absorption coefficients. The rise in μ can be ascribed to the higher electron density of the glass matrix, allowing for more intense photon interactions, especially via the photoelectric effect at lower photon energies. Additionally, the research recognized abduction in the effective atomic number (Z_{eff}) with increasing photon energy, a trend largely determined by the composition of the glass. The presence of europium, a high-atomic-number element, increases radiation shielding at lower photon energies because of its intense photoelectric absorption behavior, consistent with traditional models of radiation interaction. Besides, the effective electron density (N_e) presented an increasing behavior regarding the increase in the concentration of Eu_2O_3 , hence increasing the potential for photon interactions within the glass medium.

The study also pointed out a decrease in half-value layer (HVL) with higher dopant concentration, which is an indication of enhanced shielding ability. This is in line with theoretical principles which assert that materials of higher attenuation coefficients need less thickness to cut down radiation by 50%. The results highlight the necessity of customization of silicate glass compositions to optimize their radiation shielding performance. By precise control of dopant concentrations, these materials can be optimized for use in radiation medicine, nuclear engineering, and aerospace applications. Experimental verification is required to support the theoretical predictions and facilitate practical implementation of Eu_2O_3 -doped silicate glasses in radiation shielding.

Conflicts of Interest

The authors declare no conflicts of interest.

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