Investigation of X-rays and Gamma-ray Shielding Properties of Heavy Metal Oxide Glass Materials

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Abstract. Exposure to high levels of ionizing radiation poses serious health risks, especially for workers in medical, industrial, and nuclear environments. Traditional shielding materials like lead have significant drawbacks, including toxicity and environmental concerns. This study focuses on developing lead-free heavy metal oxide glass materials that offer effective X-ray and gamma-ray attenuation while maintaining transparency, structural durability, and cost efficiency. In this work, the radiation shielding parameters of the glass system, with the chemical composition $\mathrm{xBi_2O_3} - (55 - x)\mathrm{B_2O_3} - 15\mathrm{BaO} - 10\mathrm{ZnO} - 18\mathrm{SiO_2} - 2\mathrm{Nd_2O_3}$ (where x =15, 20, 25, 30, and 35 mol%) was investigated. The radiation shielding properties were investigated through simulations using XCOM software over a photon energy range of 0.03 to 0.3 MeV. The results show that increasing $\mathrm{Bi_2O_3}$ content significantly increases the mass attenuation coefficient (MAC), indicating better shielding performance compared to similar glass compositions reported in the literature.

1 Introduction

As technology advances, ionizing radiation has become an essential tool across numerous industries, including medical diagnostics, nuclear research, and mining. However, exposure to high levels of ionizing radiation can severely affect biological systems, leading to long-term illnesses such as cancer and other health complications [1, 2]. Traditionally, materials like lead (Pb) and concrete have been widely used to shield against X-rays and gamma rays due to their high density and attenuation properties [3]. Lead, in particular, has long been favored for its effective radiation absorption capabilities. However, it poses several significant drawbacks, including low material strength, handling difficulties, lack of transparency, and high costs [4]. Moreover, lead is toxic and non-biodegradable, raising environmental and health concerns due to its persistence in nature and the risk of inhalation, skin absorption, or ingestion [4]. Concrete is another commonly used shielding material, valued for its affordability, ease of manufacture, and structural durability [5]. Yet, its effectiveness can be compromised by structural cracking, variations in water content, and long-term degradation, which may allow ionizing radiation to penetrate through damaged sections [6]. Therefore, the proper design, composition, and maintenance of concrete structures are vital to ensure their long-term shielding performance.

Due to the environmental and safety drawbacks of conventional materials like lead and concrete, there is a growing need to develop alternative shielding materials that are safer, more effective, cost-efficient, and environmentally friendly. Among the promising alternatives are heavy metal oxide glass systems, which combine high density and excellent attenuation properties with desirable mechanical, thermal, and optical characteristics.

In this study, a new lead-free heavy metal oxide glass system composed of $Bi_2O_3 - B_2O_3 - BaO - ZnO - SiO_2 - Nd_2O_3$ is investigated for its potential as an effective radiation shielding material. Bismuth oxide (Bi_2O_3) is a key component due to its high atomic number (Z = 83) and density, which increase the probability of photoelectric absorption and enhance X-ray attenuation [7, 8]. Boron trioxide (B_2O_3) acts as a network former, providing structural stability, chemical durability, and thermal resistance, while also contributing to neutron shielding [9, 10]. Barium oxide (BaO), with a high atomic number (Z = 56), further increases the glass density and shielding effectiveness while lowering the melting temperature and improving workability [11, 12, 13]. Zinc oxide (ZnO) improves the optical properties, mechanical strength, and chemical durability of the glass, making it suitable for medical and industrial applications requiring transparency [14, 15]. Silicon dioxide (SiO_2) serves as the primary glass former, contributing to a strong, thermally stable, and mechanically robust glass network [16]. Additionally, neodymium oxide (Nd_2O_3), a rare earth oxide, enhances the optical performance by absorbing specific wavelengths and improves resistance to radiation-induced damage, which is particularly valuable in medical imaging environments [17, 18].

The aim of this research is to develop and assess this Bi_2O_3-based glass system to achieve a high mass attenuation coefficient and robust structural performance, providing an effective, transparent, and environmentally sustainable alternative for shielding against X-rays and gamma rays.

2 Simulation Methods

The XCOM program, developed by the National Institute of Standards and Technology (NIST), is a widely used database and computational tool for calculating X-ray interaction cross-sections and related properties. It provides detailed information on photoabsorption, coherent scattering, and Compton (incoherent) scattering, and it offers reliable attenuation and absorption coefficients for elements, compounds, and mixtures across a broad energy range from 1 keV to 100 GeV [19]. In this study, XCOM was used to evaluate the X-ray shielding performance of the glass system with the composition $xBi_2O_3 - (55 - x)B_2O_3 - 15BaO - 10ZnO - 18SiO_2 - 2Nd_2O_3$ (where x =15, 20, 25, 30, and 35 mol%). The mass attenuation coefficient (MAC) was determined by inputting the weight fractions of each compound (see Table1) in the glass and calculating their interaction with photons in the energy range of 0.03 to 0.3 MeV.

Table 1: Weight fractions (%) of different compounds in the prepared glass samples (S1–S5).

Compounds	Weight fractions (%)				
	S1	S2	S3	S4	S5
Bi_2O_3	0,477	0,561	0,626	0,679	0,723
B_2O_3	0,190	0,147	0,112	0,085	0,062
BaO	0,157	0,138	0,124	0,112	0,102
ZnO	0,056	0,049	0,044	0,040	0,036
SiO_2	0,074	0,065	0,058	0,053	0,048
Nd_2O_3	0,046	0,040	0,036	0,033	0,030

The mass attenuation coefficient (MAC) describes how effectively a material reduces the intensity of a radiation beam as it passes through it. It is calculated by dividing the linear attenuation coefficient (LAC) by the material's density and represents the rate of attenuation per unit mass [20, 21]. Mathematically, it is defined as

$$\mu_m = \frac{\mu}{\rho}, \tag{1}$$

where μ is the linear attenuation coefficient (in cm^{-1}), which measures the likelihood of photon interactions within the material depending on its thickness, and ρ is the material's density. The MAC is a key parameter for comparing the shielding performance of different materials.

3 Results and Discussion

The performance of the glass samples was evaluated in terms of their mass attenuation coefficients (MAC) across the selected photon energy range. Figure 1 illustrates how the MAC varies for the glass compositions S1–S5 within 0.03–0.3 MeV. The results show that all samples maintain high attenuation at lower photon energies, with

MAC values ranging from 16.07 to 22.09 cm^2/g at 0.03 MeV. As the photon energy increases, a exponentail reduction in MAC is observed, which aligns with the decreased probability of interaction between the radiation and atomic electrons. At higher energies, radiation is less effectively attenuated because interactions shift from the electron shells to the atomic nucleus, which generally results in lower attenuation overall. A slight peak near 0.0375 MeV is linked to the K-absorption edges of Neodymium (Nd) and Barium (Ba), where incoming photons have sufficient energy to eject K-shell electrons. The K-edge energies for Nd and Ba are approximately 0.04356 MeV and 0.037 MeV, respectively, which supports the observed increase in attenuation. Similarly, the sharp feature around 0.09 MeV corresponds to the K-edge of Bismuth (Bi), which occurs at 0.090 MeV, further enhancing photon absorption due to increased interaction probability at this energy The inset graph in Figure1 clearly demonstrates that increasing the Bi_2O_3 concentration leads to consistently higher MAC values, confirming that a higher bismuth content improves shielding efficiency in these lead-free glasses.

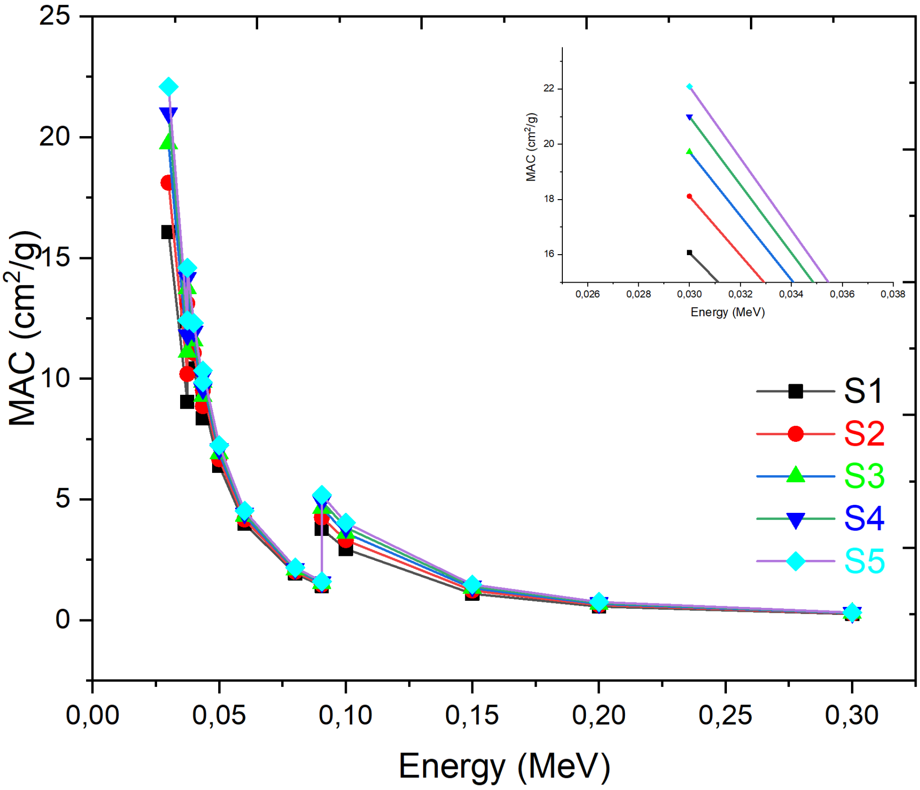

Figure 1: Mass attenuation coefficients of $Bi_2O_3 - B_2O_3 - BaO - ZnO - SiO_2 - Nd_2O_3$ glass system as a function of energy.

To further evaluate the performance of the prepared glasses, Figure 2 compares the MAC values of the S1–S5 samples with those reported for similar glass systems in previous studies [4, 22, 23] at 0.1 MeV and 0.3 MeV. At both energies, the new glasses display noticeably higher MAC values than the reference glasses (BiTeEu-3,BiTeEu-4, BSABa25, BSABa28, LiBPTe0 and LiBPTe10 compositions), demonstrating the enhanced shielding capability of the developed materials. For example, at 0.1 MeV, the S-series samples achieve MAC values between 2.946 and 4.033 cm^2/g, whereas the literature samples remain below 2.6 cm^2/g. A similar trend is observed at 0.3 MeV, where the S1–S5 glasses consistently outperform the reference systems. This improvement is directly linked to the optimized Bi_2O_3 content, which increases the glass density and the probability of photon interaction [24]. Overall, these results highlight that the proposed glass system offers superior attenuation characteristics and is a promising lead-free alternative for effective radiation shielding applications.

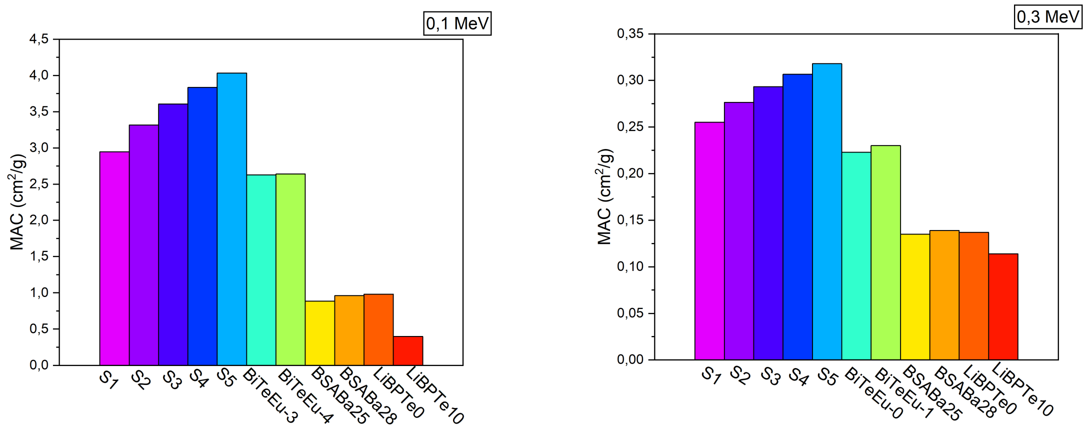

Figure 2: The mass attenuation coefficients of the selected glasses in comparison with six radiation shielding glasses reported in the literature (BiTeEu-3,BiTeEu-4, BSABa25, BSABa28, LiBPTe0 and LiBPTe10) at 0,1 and 0,3 MeV.

4 Conclusion

The MAC results confirm that the developed heavy metal oxide glasses demonstrate excellent X-ray attenuation performance across the investigated energy range. The continuous MAC curves indicate that increasing Bi_2O_3 content significantly improves the shielding effectiveness, especially at lower photon energies where photoelectric absorption dominates. The comparative analysis with previously reported glass systems further validates the improved performance of the new compositions, which consistently achieve higher MAC values at both 0.1 MeV and 0.3 MeV. These findings highlight that the proposed lead-free glasses are strong candidates for replacing conventional shielding materials, offering a safer, transparent, and effective solution for radiation protection in medical, industrial, and nuclear applications.

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