

EXPERIMENTAL AND THEORETICAL EVALUATION OF GAMMA-RAY ATTENUATION IN Bi₂O₃ DOPED SILICO BORO TELLURITE GLASS SHIELDING

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Abstract

A multifunctional glass with the composition 20TeO₂: 20Bi₂O₃: (25-x)SiO₂: 15BaO: 10Na₂O: 5Tb₂O₃: 5Eu₂O₃: xBi₂O₃ (x = 0, 1, 2, 5, 10 and 20 mol%) was synthesized via the melt-quenching method to investigate gamma-ray shielding performance and physical properties. Density increased from 4.998 g/cm³ to 5.999 g/cm³ with increasing Bi₂O₃ content, while molar volume increased from 28.99 to 35.65 cm³/mol. The mass attenuation coefficient (μ_m) measured using the Compton scattering technique over the photon energy range of 0.223-0.662 MeV, showed good agreement with theoretical values from WinXCom. At 0.223 MeV, the μ_m value increased from 11.5 to 13.0 cm²/g as Bi₂O₃ content increased from 0 to 20 mol%. Additionally, the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) increased with Bi₂O₃ concentration, reaching maximum values of 54.34 and 3.18×10^{24} electrons/g, respectively. The half-value layer (HVL) and mean free path (MFP) decreased with Bi₂O₃ addition, indicating enhanced attenuation capability. For example, at 0.223 MeV, the HVL value decreased from 0.060 cm (0 mol% Bi₂O₃) to 0.053 cm (20 mol% Bi₂O₃). The glasses containing ≥ 10 mol% Bi₂O₃ exhibited HVL values lower than ordinary concrete, confirming their potential as lightweight, transparent, and lead-free radiation shielding materials suitable for low- to medium-energy applications.

Keywords: Glass shielding; WinXCom; Compton; Bismuth Oxide

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Introduction

Radiation is widely used in medical, industrial, and research fields; however, it can pose significant health and environmental risks if not properly controlled. Exposure to high-energy radiation such as X-rays and gamma rays may lead to cellular damage, genetic mutations, or long-term illnesses. Therefore, the development of efficient and safe radiation shielding materials is crucial for minimizing radiation exposure to workers, patients, and the general public (Cheewasukhanont *et al.*, 2024). Traditional shielding materials like lead and concrete are commonly used, but they have limitations such as toxicity, heavy weight, and lack of transparency. In recent years, glass-based shielding materials have attracted increasing attention due to their unique advantages, such as optical transparency, ease of fabrication, and the ability to incorporate various heavy metal oxides to enhance their shielding effectiveness (Sayyed *et al.*, 2020). Silicate-based glasses (SiO₂) are widely used as a host matrix due to their excellent thermal stability, chemical durability, and mechanical strength. The addition of B₂O₃ improves the glass-forming ability, lowers the melting point, and enhances transparency (Kirdsiri *et al.*, 2019). Moreover, boron has high neutron absorption capability, making borate glasses a good candidate for shielding both photons and neutrons (Monisha *et al.*, 2021). Tellurite glasses (TeO₂) are also promising due to their high density and refractive index, which improve gamma-ray attenuation properties (Yasaka and Kæwkhao, 2016; Wongwan *et al.*, 2022; Thanyaphirak *et al.*, 2024; Khondara *et al.*, 2025). Additionally, TeO₂-based glasses have good infrared transmission and the ability to host rare-earth ions, making them suitable for multifunctional shielding applications (Boonin *et al.*, 2020). The incorporation of Na₂O and BaO further enhances glass performance. Na₂O serves as a flux, reducing the melting temperature and modifying the network structure for better processability. (Singkiburin *et al.*, 2024). BaO contributes significantly to increasing glass density and stability, which improves radiation attenuation and mechanical strength (Tuscharoen *et al.*, 2012). Rare-earth oxides such as Tb₂O₃ and Eu₂O₃ are also beneficial (Krongkitsiri *et al.*, 2023; Mangthong *et al.*, 2024; Wongwan *et al.*, 2024). In this work, these oxides were incorporated based on our previous study on luminescence glass systems (Ruamnikhom *et al.*, 2025). While the primary focus of this study is radiation shielding, the inclusion of Tb₂O₃ and Eu₂O₃ aims to explore multifunctional aspects, as these dopants can also

contribute to glass density and compactness, indirectly influencing shielding performance. The present study focuses solely on the radiation shielding performance of these Bi₂O₃ doped glasses. These dopants can enhance luminescence, improve glass compactness, and may participate in energy absorption and emission mechanisms, thus adding functional versatility to the shielding glass. Among various heavy metal oxides, bismuth oxide (Bi₂O₃) is considered one of the most effective alternatives to lead oxide because of its high atomic number, high density, low toxicity, and excellent gamma-ray absorption capability. Bi₂O₃ enhances not only the shielding efficiency but also the optical basicity and polarizability of the glass network (Yasaka *et al.*, 2014). In this study, a multi-component glass system was developed by 20TeO₂: 20B₂O₃: (25-x)SiO₂: 15BaO: 10Na₂O: 5Tb₂O₃: 5Eu₂O₃ xBi₂O₃ (x = 0, 1, 2, 5, 10 and 20 mol%) to optimize both physical and radiation shielding properties. Main parameters including the mass attenuation coefficient (μm), half-value layer (HVL), mean free path (MFP), effective atomic number (Z_{eff}), and effective electron number (N_{eff}) were analyzed in the photon energy range of 0.20 to 1.00 MeV. To validate the theoretical data obtained from WinXCom software, experimental measurements were performed using Compton scattering with various energy sources, including ¹³⁷Cs, to provide reliable comparisons. Theoretical calculations of radiation shielding commonly employ the WinXCom database, developed by Hubbell and Berger, and later expanded by Gerward *et al.* (Gerward *et al.*, 2004). This database allows for the calculation of attenuation characteristics for elements, compounds, and mixtures over a photon energy range of 1 keV to 100 GeV. Based on the mass attenuation coefficients obtained from WinXCom, other shielding parameters can be determined using standard equations. To validate the theoretical data obtained from WinXCom software, experimental measurements were performed using Compton scattering with various energy sources, including ¹³⁷Cs, to provide reliable comparisons (Kurtulus *et al.*, 2020).

Experiment

Glasses preparation

The 20TeO₂: 20B₂O₃: (25-x)SiO₂: 15BaO: 10Na₂O: 5Tb₂O₃: 5Eu₂O₃ xBi₂O₃ (x = 0, 1, 2, 5, 10 and 20 mol%) glasses were prepared by the melt quenching technique. The high-purity chemicals

TeO₂ (Sigma Aldrich 99.8%), H₃BO₃ (ANALYTICAL REAGENT, 99.8%), SiO₂ (SIGMA-ALDRICH, 99.8%), Na₂CO₃ (ANALYTICAL REAGENT, 99.8%), BaCO₃ (HIMEDIA, 99.0%), Tb₂O₃ (REacton, 99.99%), Eu₂O₃ (REacton, 99.99%) and Bi₂O₃ (QRc, 99.95%) were put into the alumina crucible for 15 g and melted at 1100°C. The melt was then quickly poured into a preheated graphite mold and annealed at 500 °C for 3 hours before being left to cool down slowly to room temperature. The process diagram for preparing these glass samples is shown in Figure 1. The prepared glasses were cut and polished to sizes of 1×1.5×0.3 cm³ as shown in Figure 2 for measurements such as density, molar volume and Compton scattering. The specific Bi₂O₃ concentrations (0, 1, 2, 5, 10, and 20 mol%) were selected to systematically investigate the impact of increasing heavy metal oxide content on the glass properties and gamma-ray shielding performance. This range aligns with common practices in radiation shielding studies, where high heavy metal

oxide concentrations are typically used to improve attenuation capabilities (Elsafi *et al.*, 2021). The 20 mol% upper limit was due to solubility constraints during the melt-quenching process.

Compton Scattering Technique for Attenuation Measurement

The mass attenuation coefficient (μ_m) of the prepared glasses was determined using the Compton scattering technique, as illustrated in Figure 3. The CST system was designed to cover the photon energy range from approximately 0.225 MeV to 0.662 MeV, based on monoenergetic gamma rays emitted by a ¹³⁷Cs radioactive source (15 mCi), provided by the Office of Atoms for Peace (OAP), Thailand. The experimental setup was aligned according to the Compton scattering equation (Tsoulfanidis and Landsberger, 2019):

$$E_{\gamma'} = \frac{E_{\gamma}}{1 + (1 - \cos \theta) E_{\gamma} / mc^2} \quad (1)$$

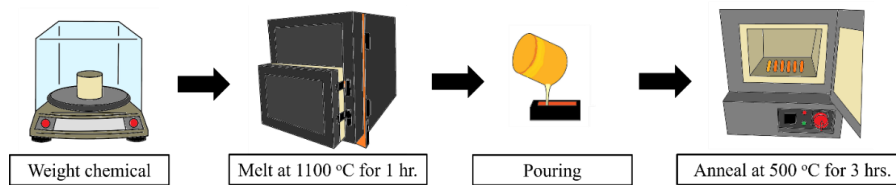


Figure 1. Schematic preparation of TeO₂: B₂O₃ SiO₂: BaO: Na₂O: Tb₂O₃: Eu₂O₃ Bi₂O₃ glasses by melt quenching technique

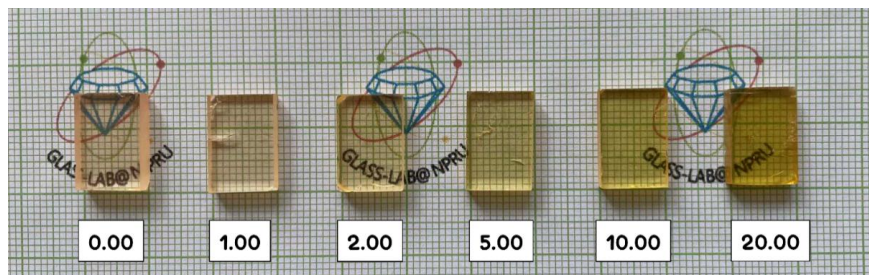


Figure 2. The TeO₂: B₂O₃ SiO₂: BaO: Na₂O: Tb₂O₃: Eu₂O₃ Bi₂O₃ glasses at different concentrations of Bi₂O₃

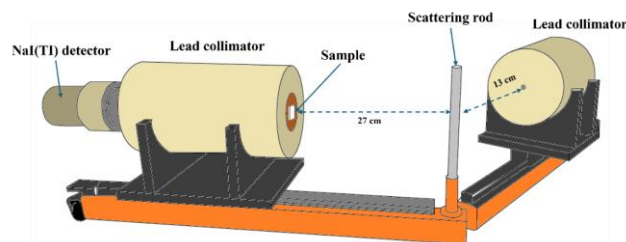


Figure 3. The experimental setup for the transmission method using the Compton scattering technique

Where $E_{\gamma'}$ is the scattered gamma-ray energy, E_{γ} is the incident gamma-ray energy, θ is the scattering angle, and m is the rest mass of the electron. This equation is derived under the assumption of a relativistic collision between a gamma-ray photon and a stationary electron. While electrons in matter are typically bound, if the photon energy is in the keV range or higher compared to the eV-scale binding energies electrons can be approximated as free. The collision is inelastic, where an incoming photon is scattered, resulting in another photon with different energy and momentum. An adjustable stand was used to secure and align the ¹³⁷Cs source, while an aluminum rod served as the scattering medium. The scattered gamma rays were detected using a 2" × 2" NaI(Tl) scintillator detector (BICRON model 2M2/2) with an energy resolution of 8% at 662 keV. The detector was coupled with a CANBERRA photomultiplier tube base (model 802-5), and spectra were recorded using a CANBERRA PC-based multichannel analyzer (MCA) with 1024 voltage-divided bins. The distances between the source, scatterer, and detector were each optimized to 20 cm. The system was calibrated using known gamma-ray sources to accurately assign energy values to MCA channel numbers. Measurements were conducted by varying the detector angle from 0° to 120°, with each angle corresponding to a specific scattered photon energy. This experimental design enabled precise selection of photon energies and reliable measurement of μ_m . The validity of the Compton scattering setup was confirmed by comparing the experimental photon energies with theoretical predictions, and the relative differences (%RD) are summarized in Table 1. To evaluate the uncertainty in the measurement, statistical errors were calculated based solely on the ray-sum measurement, which involves the product of the linear attenuation coefficient (μ) and sample thickness (x). The intensity values were obtained from Gaussian fitting of the full-energy peaks in the MCA spectra. The standard deviation (σ) of each peak was estimated using the full width at half maximum (FWHM) and the relation:

$$FWHM = 2\sqrt{2\ln 2}\sigma \quad (2)$$

$$\sigma = \frac{FWHM}{2.355} \quad (3)$$

This σ value reflects the spread of the photopeak due to counting statistics and system resolution. The propagated error in the energy of photons was used to estimate the final uncertainty in the mass attenuation coefficient. This approach

follows the methodology reported by Limkitjaroenporn *et al* (Limkitjaroenporn *et al.*, 2012).

Table 1. The energies are generated by changing angles from the CST technique (experiment) and Compton equation (theory) (Cheewasukhanont et al., 2024)

Scattered angles (θ)	E_{γ} /Theory (MeV)	E_{γ} /Experiment (MeV)	%RD (%)
30	0.557	0.582±0.014	0.866
60	0.402	0.409±0.010	1.741
90	0.288	0.291±0.014	1.041
120	0.225	0.227±0.002	0.888

Results and Discussion

Density and Molar volumes

The 20TeO₂: 20B₂O₃: (25-x)SiO₂: 15BaO: 10Na₂O: 5Tb₂O₃: 5Eu₂O₃: xBi₂O₃ (x = 0, 1, 2, 5, 10 and 20 mol%) glasses were measured density using the Archimedes principle from Equation 4. The uncertainty in density measurements was estimated to be ± 0.0023 - 0.0045 g/cm³, based on repeated measurements and balance precision

$$\rho_{glass} = \frac{W_{air}}{W_{air}-W_{water}} \times \rho_{water} \quad (4)$$

Where W_{air} is the weight of glass in the air (g), W_{water} is the weight of glass in distilled water (g), and ρ_{water} is the density of distilled water, which is about 1 g/cm³. Then, the molar volume (V_m (mol/cm³)) of each glass sample was calculated using the measured density by applying Equation 5:

$$V_m = \frac{M_t}{\rho} \quad (5)$$

Where M_t is the total molar mass (g/mol) of the glass composition and ρ is the measured density (g/cm³). This value helps to understand how the glass structure changes when Bi₂O₃ replaces SiO₂. Figure 4 shows the variation of density and molar volume of the 20TeO₂: 20B₂O₃: (25-x)SiO₂: 15BaO: 10Na₂O: 5Tb₂O₃: 5Eu₂O₃: xBi₂O₃ glass system as a function of Bi₂O₃ concentration (x = 0-20 mol%). From the graph, both the density and molar volume increase steadily with increasing Bi₂O₃ content. This increase is primarily because Bi₂O₃ has a significantly higher molecular weight (465.96 g/mol) compared to SiO₂ (60.08 g/mol). As Bi₂O₃ replaces SiO₂ in the glass network, the total mass of the glass per unit volume increases, leading to higher density. In addition to increased density,

previous studies have confirmed that Bi_2O_3 also contributes to increased molar volume in glass systems. The expansion of the glass network was confirmed by the parallel increase of both parameters. Because Bi_2O_3 replaces SiO_2 in the glass structure, it begins to function as a network modifier as opposed to the network-forming function that SiO_2 previously performed. Consequently, the expansion of the glass network is amplified as the quantity of Bi_2O_3 increases, leading to a concomitant escalation in V_m values (Stalin *et al.*, 2021; Kurtuluş *et al.*, 2022; Mutuwong *et al.*, 2024).

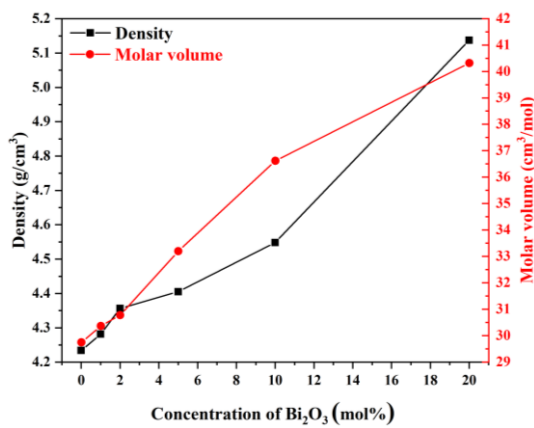


Figure 4. The density and molar volumes of prepared glasses at different concentrations of Bi_2O_3

Gamma-ray shielding properties

Figure 5 shows that the mass attenuation coefficient (μ_m) decreases with increasing photon energy and increases with higher Bi_2O_3 content. This is because Bi_2O_3 has a high atomic number ($Z = 83$) and high molecular weight, which enhances the probability of photon interaction in the glass matrix (Tuscharoen *et al.*, 2012). Comparison between the experimental results and the theoretical values from WinXCom, as shown in Table 2, shows good agreement across most compositions and energy ranges. Slight deviations, particularly at 20 mol% Bi_2O_3 and low photon energy, are likely due to experimental errors during the measurement process. Figure 6 presents the effective atomic number (Z_{eff}), which increases as the Bi_2O_3 content increases. Since Bi is a high- Z element, substituting SiO_2 with Bi_2O_3 significantly raises the average atomic number of the glass matrix. Additionally, Z_{eff} tends to decrease slightly as photon energy increases, consistent with the dominance of the

photoelectric effect at lower energies and Compton scattering at intermediate energies (Tsoulfanidis and Landsberger, 2019). Figure 7 shows the trend of effective electron density (N_{eff}), which correlates with Z_{eff} and μ_m . As Bi_2O_3 content increases, N_{eff} also increases, indicating a higher number of electrons available per gram of material to interact with incoming photons. Similar to Z_{eff} , N_{eff} decreases with increasing photon energy due to reduced interaction efficiency at higher energies (Limkitjaroenporn *et al.*, 2012).

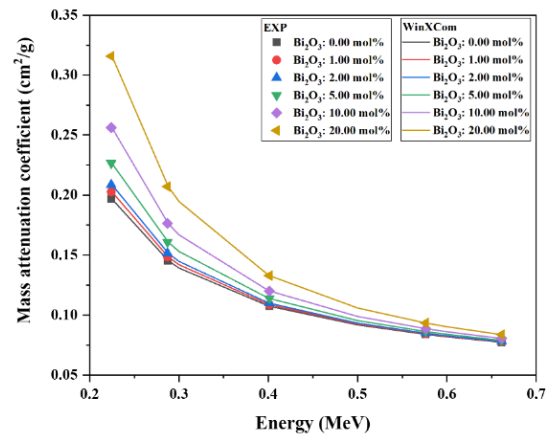


Figure 5. Experimental and theoretical (WinXCom) mass attenuation coefficients (μ_m) of the glasses at different photon energies

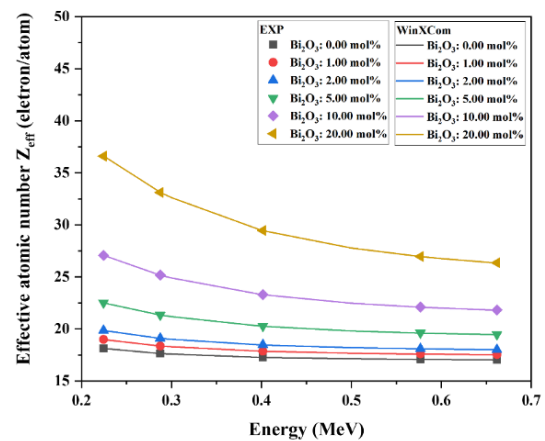
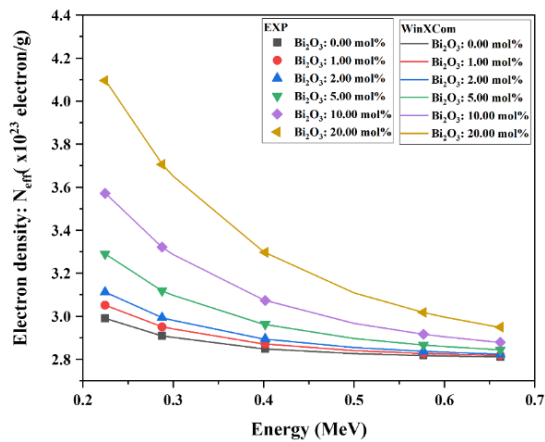


Figure 6. Effective atomic number (Z_{eff}) of the glasses at different photon energies

Table 2. Comparative of μ_m between the experiment and WinXCom

RHA glasses	Energy (MeV)	Total mass attenuation coefficients (μ_m) (cm ² /g)		
		EXP	WinXCom	%Error
Bi ₂ O ₃ : 0 mol%	0.255	0.19667	0.19667	0.000
	0.288	0.14532	0.14531	0.007
	0.402	0.10733	0.10731	0.019
	0.577	0.08393	0.0839	0.036
	0.662	0.07731	0.07729	0.026
Bi ₂ O ₃ : 1 mol%	0.255	0.2026	0.20263	0.015
	0.288	0.14835	0.14839	0.027
	0.402	0.10855	0.10858	0.028
	0.577	0.08434	0.08437	0.036
	0.662	0.07763	0.07761	0.026
Bi ₂ O ₃ : 2 mol%	0.255	0.20854	0.20858	0.019
	0.288	0.15149	0.15148	0.007
	0.402	0.10987	0.10985	0.018
	0.577	0.08483	0.08484	0.012
	0.662	0.0779	0.07793	0.038
Bi ₂ O ₃ : 5 mol%	0.255	0.22642	0.22644	0.009
	0.288	0.16076	0.16075	0.006
	0.402	0.11366	0.11365	0.009
	0.577	0.08623	0.08625	0.023
	0.662	0.07885	0.07888	0.038
Bi ₂ O ₃ : 10 mol%	0.255	0.25615	0.25621	0.023
	0.288	0.17628	0.17619	0.051
	0.402	0.11995	0.11999	0.033
	0.577	0.08859	0.08861	0.023
	0.662	0.08047	0.08046	0.012
Bi ₂ O ₃ : 20 mol%	0.255	0.31568	0.31575	0.022
	0.288	0.20704	0.20707	0.014
	0.402	0.1327	0.13267	0.023
	0.577	0.0933	0.09331	0.011
	0.662	0.08364	0.08362	0.024

**Figure 7.** Effective electron density (N_{eff}) of the glasses as a function of photon energy

Mean free path and half-value layer

Figure 8 and Figure 9 show the HVL and MFP values, respectively, for the prepared glass. Both parameters show a decrease with increasing Bi₂O₃

content and an increase with photon energy. This is consistent with the inverse relationship between attenuation efficiency, HVL and MFP. A higher Bi₂O₃ concentration increases the density and atomic number of the glass, leading to shorter distances required for gamma-ray absorption. At low photon energies (~0.223 MeV), the HVL and MFP values of the 20 mol% Bi₂O₃ glass are the lowest among all samples, indicating superior shielding capability. At higher energies (~0.662 MeV), the differences become less pronounced, but the trend remains. Importantly, the experimental results show good agreement with the theoretical values calculated using WinXCom, confirming the reliability of the measurement method. This consistency also aligns with the trends observed in the mass attenuation coefficient and effective atomic number results discussed earlier. Furthermore, Figure 8 compares the HVL values of the prepared glasses with standard shielding materials. The glasses with ≥ 10 mol% Bi₂O₃ show HVL values lower than concrete (Bashter, 1997) and within the range of commercial window glass

(Kaewjang *et al.*, 2015), highlighting their potential as lightweight and transparent radiation shielding materials.

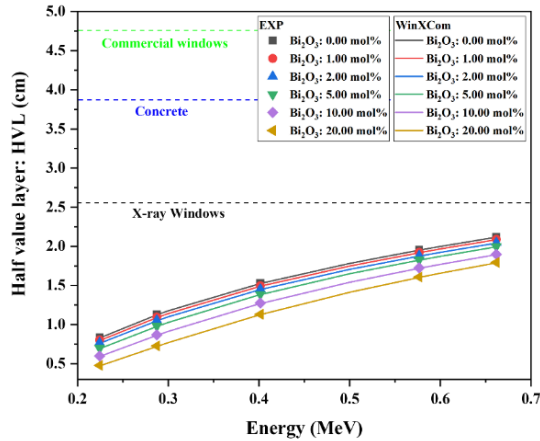


Figure 8. Half-value layer (HVL) as a function of photon energy for different Bi_2O_3 concentrations

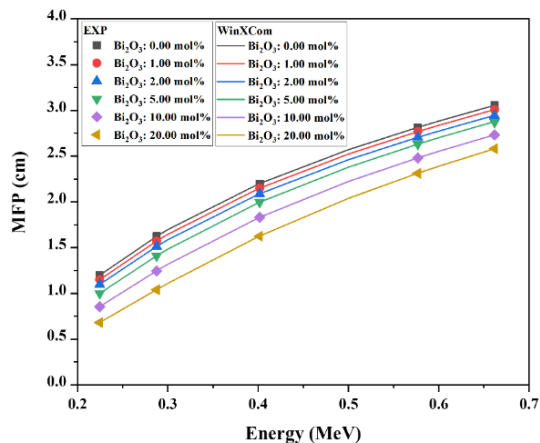


Figure 9. Mean free path (MFP) as a function of photon energy at various Bi_2O_3 contents

Conclusions

The TeO_2 : B_2O_3 : SiO_2 : BaO : Na_2O : Tb_2O_3 : Eu_2O_3 : Bi_2O_3 glasses were successfully synthesized and investigated for gamma-ray shielding performance. Increasing Bi_2O_3 content from 0 to 20 mol% led to a continuous rise in glass density (from 4.998 to 5.999 g/cm^3) and molar volume (from 28.99 to 35.65 cm^3/mol), primarily due to the high atomic mass of bismuth. The mass attenuation coefficient (μ_m), effective atomic number (Z_{eff}), and effective electron density (N_{eff}) increased with higher Bi_2O_3

concentrations, while the half-value layer (HVL) and mean free path (MFP) decreased, indicating improved attenuation capacity. At 0.223 MeV, the μ_m value increased from 11.5 to 13.0 cm^2/g , and the HVL decreased from 0.060 to 0.053 cm when Bi_2O_3 increased from 0 to 20 mol%. These trends reflect enhanced interaction probability due to the addition of high-Z elements. The experimental results obtained using the Compton scattering technique closely matched theoretical values from WinXCom across all energy levels, confirming the accuracy and reliability of the measurement approach. Furthermore, glass samples with ≥ 10 mol% Bi_2O_3 showed superior shielding performance compared to conventional concrete, while maintaining transparency and lead-free composition. These findings demonstrate the potential of Bi_2O_3 -doped silico-boro-tellurite glass as a promising alternative to conventional shielding materials, offering an effective, lightweight, and lead-free solution for radiation protection in medical and industrial applications.

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