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Investigation of TeO_2-Based Borotellurite Glass as a Radiation Shield: Effects of Composition on Attenuation Parameters

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ABSTRACT

The development of lead-free glass materials as radiation shielding has gained significant attention due to environmental concerns and the need for transparent shielding alternatives. This study investigates the effectiveness of TeO_2-based borotellurite glass as a potential radiation shielding material. Glass samples with compositions of TeO_2-(60-x) B_2O_3-20Bi_2O_3-15ZnO-5CaO (x = 0, 5, 10, 15 mol%) were synthesized and analyzed. The radiation shielding performance was evaluated using parameters attenuation within the energy range of 0.01–1.5 MeV. The obtained values were compared with those of commercial shielding materials, including RS-253-G18 glass and 40% synthetic borax. The results indicate that increasing TeO_2 concentration enhances the glass density and improves radiation attenuation capability. The TeB4 sample (15 mol% TeO_2) exhibited the highest MAC value of 3.372 cm^2/g at 0.06 MeV, which is significantly higher than that of TeB1 (2.814 cm^2/g), TeB2 (3.011 cm^2/g), and TeB3 (3.197 cm^2/g). Additionally, the HVL values at 0.6 MeV for TeB1, TeB2, TeB3, and TeB4 were 1.390 cm, 1.359 cm, 1.329 cm, and 1.300 cm, respectively, confirming that higher TeO_2 concentration leads to a reduction in HVL and an overall improvement in shielding efficiency. Moreover, the absorption edge of Bi_2O_3 at 0.0905 MeV contributed to a sudden increase in attenuation efficiency at specific energy levels. The findings confirm that TeO_2-based borotellurite glass is a promising candidate for radiation shielding applications, offering both high attenuation performance and optical transparency

Keywords: TeO_2-based glass, radiation shielding, mass attenuation coefficient, borotellurite glass, and lead-free shielding materials

INTRODUCTION

The utilization of ionizing radiation in various fields, including the medical industry (1) and food preservation (2), continues to increase. Along with this development, efforts to enhance protection for radiation workers have become highly important. Although ionizing radiation, such as gamma rays, offers various benefits, its uncontrolled use can negatively impact workers' health. There are three primary strategies for controlling ionizing radiation exposure: reducing exposure time, increasing the distance between workers and radiation sources, and using radiation shielding materials with optimal performance (3).

The combination of concrete and lead has long been used as a radiation shielding material due to its effectiveness in providing protection for radiation workers. However, this material has several limitations, such as significant thickness, making it unsuitable for applications requiring limited space, its non-transparent nature, which hinders observation into radiation areas, and the toxic properties of lead, which pose potential health hazards to workers and the environment (4). Thus, glass-based radiation shielding emerges as a promising alternative as it is thinner, transparent, and allows for the use of lead-free fillers that are more environmentally friendly.

Numerous studies have been conducted to evaluate the effectiveness of glass as a radiation shielding material. Almuqrin et al. (2024) conducted a study on glass-based radiation shielding with a composition of B_2O_3–PbO–ZnO–CaO, where variations in ZnO concentration significantly increased the linear attenuation coefficient (LAC), with the highest value reaching 11.136 cm^{-1} at a radiation energy of 0.060 MeV (5). Meanwhile, research by Sayyed (2025) developed glass shielding with a composition of 15BaO–10Na_2O–5Al_2O_3–(70-x)B_2O_3–xCaO (where x = 5, 10, 15, and 20 mol%). The results indicated that increasing CaO concentration contributed to a reduction in the Half-Value Layer (HVL), leading to thinner glass shielding with more optimal radiation protection performance (6).

Tellurium dioxide (TeO_2) is one of the materials used in glass systems for radiation shielding, primarily due to its superior physical and nuclear characteristics. With an atomic number of 52 and an atomic mass of 127.6, TeO_2 effectively absorbs high-energy radiation, such as gamma rays. Additionally, its high density makes it more efficient in shielding against radiation exposure compared to materials with lower atomic numbers. Other advantages include excellent thermal stability and chemical resistance, preventing degradation even in environments with high radiation exposure. Besides its radiation shielding properties, TeO_2 maintains transparency within the glass structure and possesses high mechanical strength, making it ideal for radiation protection applications without compromising visibility or resistance to physical impacts (7).

This study aims to evaluate the effect of TeO_2 concentration variations on the performance of glass-based radiation shielding. The type of glass used in this study is borotellurite glass with a composition of TeO_2-(60-x)B_2O_3-20Bi_2O_3-15ZnO-5CaO, where x = 0, 5, 10, and 15 mol%. Each oxide in this composition has a specific role in determining the physical, optical, and radiation shielding properties of the glass. TeO_2 serves as the primary glass former, increasing the density and optical transparency of the glass while also enhancing thermal stability and resistance to radiation exposure (7). B_2O_3 acts as a network former, contributing to the glass structure, reducing melting temperature, and improving chemical stability and transparency. Bi_2O_3 is added to enhance radiation shielding capability due to its high atomic number, making it effective in absorbing gamma radiation (8). According to Singh et al. (2023) and Alomayrah et al. (2024), ZnO changes the chemical stability of the glass and makes it more durable, while CaO changes the chemical stability of the glass and makes it stronger, more resistant to humidity, and helps make a more stable glass network (9) (10).

To assess the effectiveness of borotellurite glass as a radiation shield, various radiation absorption parameters were comprehensively calculated. The mass attenuation coefficient (MAC), the linear attenuation coefficient (LAC), the half-value layer (HVL), the tenth-value layer (TVL), and the mean free path (MFP) are all calculated in the energy range of 0.01 to 1.5 MeV. Simulations were conducted using XCOM software, which allows for the prediction of shielding characteristics based on physical parameters and material composition. The obtained results were then compared with various commercial shielding materials, including conventional glass shielding and concrete shielding, to evaluate the effectiveness of borotellurite glass in radiation protection applications. This research is expected to serve as a primary reference in the development of glass shielding materials for future experimental applications.

MATERIALS & METHODS

Materials

The effect of TeO_2 concentration variations on the performance of glass-based radiation shielding was numerically evaluated using the XCOM software from the National Institute of Standards and Technology (NIST). This software provides mass attenuation coefficient (MAC) data, which is then developed through analytical calculations to obtain other radiation absorption parameters, such as linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP). This study involved four glass samples with varying TeO_2 concentrations, where each sample was analyzed within an energy range of 0.01–1.5 MeV. The chemical composition of each sample follows the general molecular formula TeO_2-(60-x)B_2O_3-20Bi_2O_3-15ZnO-5CaO, with x = 0, 5, 10, and 15 mol%, while the mol% fraction and density of each sample are detailed in Table 1 and Figure 1.

Table 1. Fraction of the Component (mol.%) and density of each sample

Sample	TeO_2	B_2O_3	Bi_2O_3	ZnO	CaO	Density (g/cm^3)
TeB1	0	60	20	15	5	4.923
TeB2	5	55	20	15	5	5.071
TeB3	10	50	20	15	5	5.221
TeB4	15	45	20	15	5	5.370

Analysis based on Table 1 shows a correlation between the increase in TeO_2 concentration and the increase in the density of the shielding material, although there is a simultaneous decrease in B_2O_3 fraction. TeB4, which has the highest TeO_2 concentration of 15 mol%, exhibits the highest density of 5.370 g/cm^3, whereas the densities of the other samples, TeB1, TeB2, and TeB3, are 4.923 g/cm^3, 5.071 g/cm^3, and 5.221 g/cm^3, respectively. Information regarding the molar fraction of each element in the glass composition for each sample is presented in Table 2, which is then used as input in the XCOM software.

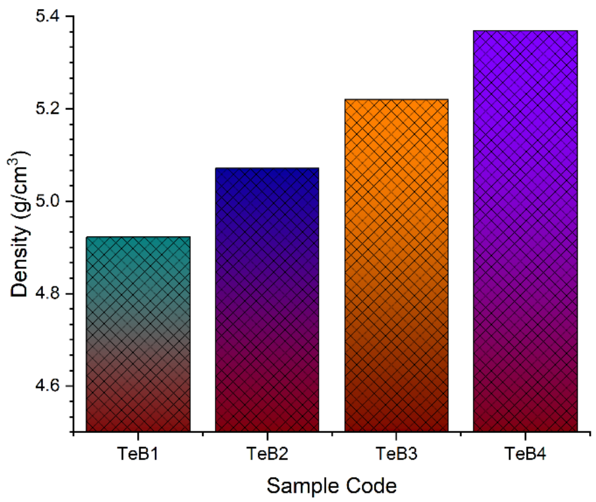

Figure 1. Density of each sample

Methods

The XCOM software, developed by NIST, is a data-based program used to calculate scattering, photoelectric absorption, and pair production, as well as to determine the mass attenuation coefficient in the energy range of 0.001 MeV to 20 MeV theoretically (11). This program serves as the basis for calculating radiation shielding parameters, which are then compared among samples to evaluate the effectiveness of shielding against ionizing radiation.

Table 2. Fraction of the element (wt.%) of each element

Sample	Te	O	B	Bi	Zn	Ca
TeB1	0	0.2774	0.0865	0.5574	0.0654	0.0133
TeB2	0.0413	0.2641	0.0769	0.5412	0.0635	0.0129
TeB3	0.0803	0.2516	0.0680	0.5258	0.0617	0.0126
TeB4	0.1171	0.2398	0.0595	0.5112	0.0601	0.0123

The radiation absorption parameters analyzed in this study include LAC, MAC, HVL, TVL, and MFP. LAC is a measure of how quickly ionizing radiation intensity decreases as it passes through a material, directly related to the material's ability to absorb or block radiation. The higher the LAC value, the more effective the material functions as radiation shielding. The LAC value can be obtained by applying Lambert-Beer's equation (12) as follows:

$$I = I_O e^{-\mu x} \quad (1)$$

where I_0 and I represent the initial and attenuated radiation intensities, μ is the LAC (cm^{-1}), and x is the thickness of the shielding material (cm).

The MAC parameter indicates how much a material can absorb radiation per unit density (13). Unlike LAC, which measures absorption based on the radiation path length in the material, MAC considers material density, providing a more general perspective in comparing the effectiveness of various shielding materials. The larger the MAC value, the better the material's quality in absorbing radiation. The MAC value is calculated by dividing LAC by the density of the material and considering the contribution of each component in the material based on its mass fraction. The MAC calculation formula is given as (10):

$$MAC = \frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

Additionally, other important parameters in evaluating shielding material performance are HVL and TVL, which indicate the thickness of the material required to reduce radiation intensity to half and one-tenth of its original value, respectively (14). The equations for calculating HVL and TVL are given as follows:

$$HVL = \frac{\ln 2}{\mu} \quad (3)$$

$$TVL = \frac{\ln 10}{\mu} \quad (4)$$

MFP represents the average distance traveled by radiation particles before interacting with atoms in the shielding material. The smaller the MFP value, the higher the material's ability to attenuate radiation exposure, as radiation interactions with the material occur over shorter distances. The MFP value can be determined using the following equation (15):

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

Evaluation of these parameters enables the determination of shielding material effectiveness in absorbing and reducing ionizing radiation intensity, as well as providing a basis for comparing various types of materials used in radiation protection applications.

RESULT AND DISCUSSION

Effect of TeO_2 Concentration Variations on Radiation Shielding Performance

The higher the mass attenuation coefficient (MAC) of a radiation shield, the more effective the material is in attenuating gamma rays (5). The MAC value is influenced by two primary factors: material density and radiation energy. The first factor, shielding material density, plays a crucial role in enhancing radiation shielding effectiveness. The higher the density of a material, the greater the number of available electrons, thereby increasing the probability of interaction between photons and electrons in the material. Figure 2 shows that the TeB4 sample has the highest density, which directly contributes to the increased MAC value. At 0.06 MeV radiation energy, the MAC value for TeB4 is recorded at 3.372 cm^2/g, which is higher than the MAC values of other samples, namely TeB1 (2.814 cm^2/g), TeB2 (3.011 cm^2/g), and TeB3 (3.197 cm^2/g).

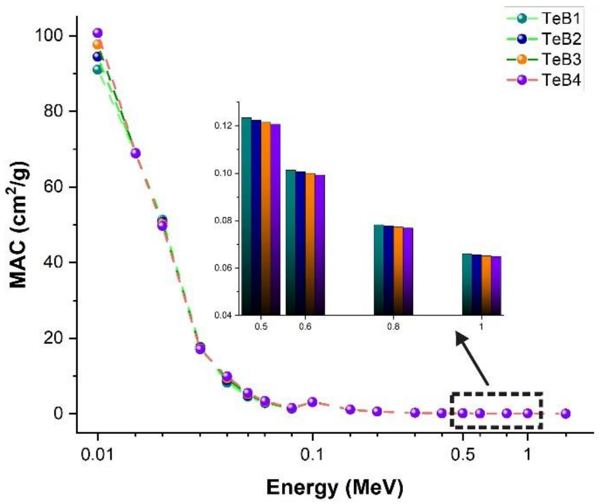

Figure 2. Mass attenuation coefficient (MAC) in the radiation energy range of 0.01 – 1.5 MeV

The second factor influencing MAC values is radiation energy. From Figure 2, it is evident that in the same sample, such as TeB2, the MAC value initially measures 94.430 cm^2/g at 0.01 MeV, but then decreases to 0.051 cm^2/g at 1.5 MeV. This reduction in MAC is attributed to the varying types of radiation-matter interactions, which differ based on energy levels. At low energy levels, the dominant interaction is the photoelectric effect (PE), where photons disappear after transferring their entire energy to electrons within the material. The effectiveness of the photoelectric effect in attenuating radiation follows an inverse relationship with radiation energy ($\sigma PE \propto 1/E$) (16). At moderate energy levels, the dominant interaction shifts to Compton scattering (CS), which is influenced by the effective atomic number (Zeff) with the relationship ($\sigma CS \propto Zeff$) (8). As radiation energy increases further, the dominant interaction becomes pair production, which occurs when photons possess energy exceeding 1.022 MeV, resulting in the formation of electron-positron pairs (17).

Additionally, Figure 2 also shows a sudden increase in MAC values at 0.1 MeV, which is caused by the absorption edge of bismuth (Bi) in Bi_2O_3, located at the K-shell energy level of 0.0905 MeV. The absorption edge plays a crucial role in determining how effectively a material absorbs X-rays and gamma rays, particularly at low-to-medium energy levels where photoelectric interactions are more dominant.

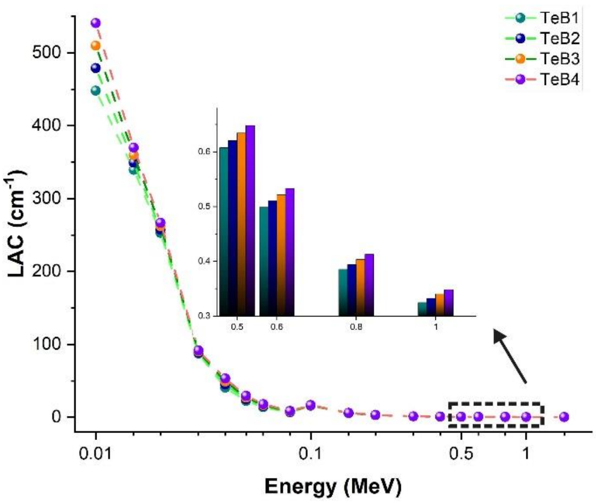

Figure 3. Linear attenuation coefficient (LAC) in the radiation energy range of 0.01 – 1.5 MeV

The MAC values obtained from numerical calculations using XCOM software were subsequently used to compute the linear attenuation coefficient (LAC) using Equation (2). The LAC values exhibit a trend similar to MAC, where an increase in radiation energy corresponds to a decrease in LAC (12). Figure 3 illustrates that for the TeB2 sample, the LAC initially measures 478.901 cm^{-1} at 0.01 MeV, but declines to 0.258 cm^{-1} at 1.5 MeV. Unlike MAC, the LAC values are not influenced by material density, but rather by the molar fraction of TeO_2 compounds in the composition of the glass radiation shield. At 0.5 MeV, the LAC values for each sample are recorded as follows: TeB1 (0.607 cm^{-1}), TeB2 (0.621 cm^{-1}), TeB3 (0.634 cm^{-1}), and TeB4 (0.648 cm^{-1}), indicating that increasing TeO_2 concentration contributes to an increase in LAC values.

Thus, the results of the analysis demonstrate that MAC and LAC values are influenced by a combination of material density, molar fraction of constituent components, and received radiation energy, with TeB4 exhibiting the best performance in absorbing low-to-medium energy radiation. This finding suggests that Bi_2O_3-TeO_2-based glass could be a potential candidate for high-efficiency radiation shielding.

Effect of Material Density and Radiation Energy on Half-Value Layer (HVL) and Tenth-Value Layer (TVL) in Glass-Based Radiation Shielding

The smaller the half-value layer (HVL) of a material, the more effective it functions as a radiation shield (14). HVL is influenced by two main factors: material density and photon radiation energy. The first factor is shielding material density, where the higher the density of a material, the greater the probability of interaction between gamma radiation and electrons within the material. This leads to a decrease in HVL values, as radiation weakens more rapidly when passing through denser materials (16). Based on Figure 4, at a radiation energy of 0.6 MeV, the HVL values for the samples TeB1, TeB2, TeB3, and TeB4 are 1.390 cm, 1.359 cm, 1.329 cm, and 1.300 cm, respectively. These results indicate that increased density due to the addition of TeO_2 contributes to the reduction in HVL values, demonstrating that Te plays an essential role in improving the effectiveness of radiation shielding. However, on the other hand, an increase in the molar fraction of TeO_2 also leads to a decrease in the molar fraction of B_2O_3, which may affect the physical and optical properties of the material.

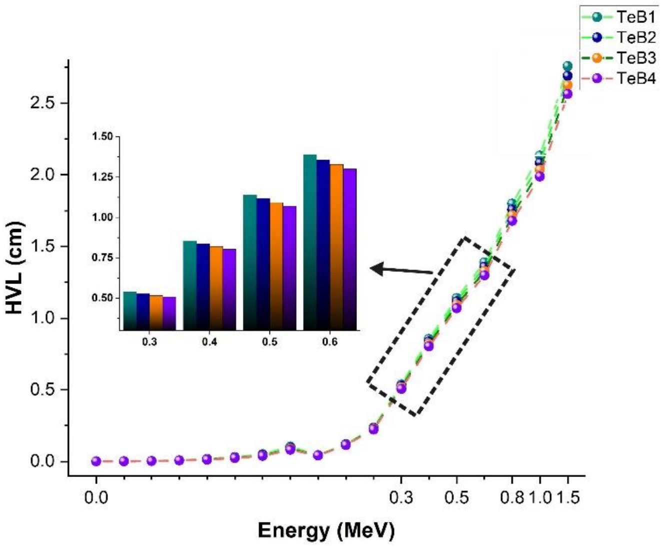

Figure 4. Half-value layer (HVL) in the radiation energy range of 0.01 – 1.5 MeV

The second factor affecting HVL values is radiation energy. The higher the radiation energy, the thicker the material required to reduce radiation intensity to half, resulting in an increase in HVL values. For instance, in the TeB4 sample, HVL increases with the rise in received radiation energy. At 0.01 MeV, the HVL value is only 0.001 cm, but it increases to 2.564 cm at 1.5 MeV. This data indicates that thicker shielding materials are required to maintain effective protection against high-energy radiation.

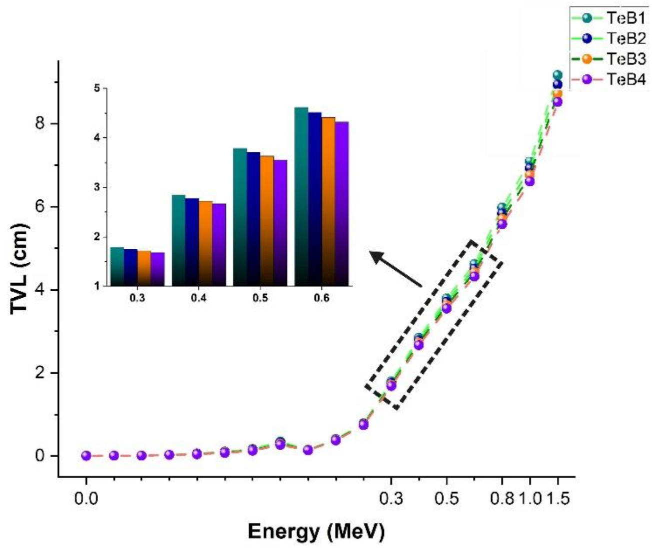

Figure 5. Tenth-value layer (TVL) in the radiation energy range of 0.01 – 1.5 MeV

Apart from HVL, another parameter with similar characteristics is the tenth-value layer (TVL). TVL represents the thickness of a material required to reduce radiation intensity to one-tenth of its initial value (18). In Figure 5, the TVL trend is similar to HVL, where TVL increases as radiation energy increases. However, at the same energy level, TVL values decrease as the material density and TeO_2 concentration increase, indicating improved radiation shielding effectiveness due to the addition of Te elements in the glass material.

Evaluation of Mean Free Path (MFP) in TeO_2-Based Glass Radiation Shielding Compared to Commercial Shielding Materials

To evaluate the mean free path (MFP) of TeO_2-based shielding, a comparison was made with commercial glass RS-253-G18 (19) and 40% synthetic borax (20). The analysis was conducted at two photon energy levels, 0.662 MeV and 1.332 MeV, to assess the effect of TeO_2 concentration on radiation shielding performance. At 0.662 MeV, an increase in TeO_2 concentration in the shielding material resulted in a decrease in MFP values, indicating improved radiation shielding effectiveness. According to Figure 6, the TeB1 sample, which does not contain TeO_2, has the highest MFP value of 2.203 cm, while the MFP values for the TeO_2-containing samples are TeB2 (2.153 cm), TeB3 (2.105 cm), and TeB4 (2.059 cm), respectively. Compared to other radiation shielding materials, such as RS-253-G18 glass (4.800 cm) and 40% synthetic borax (5.500 cm), all TeO_2-based samples exhibit lower MFP values, indicating that TeO_2-based shielding is more effective in attenuating radiation. The smaller the MFP value, the better the material quality as a radiation shield (15). Additionally, simulation results indicate that TeO_2-based shielding glass exhibits superior quality compared to other commercial shields. An additional advantage of TeO_2-based glass is its transparent and flexible characteristics, making it more favorable for various applications compared to conventional radiation shields, which tend to be more rigid.

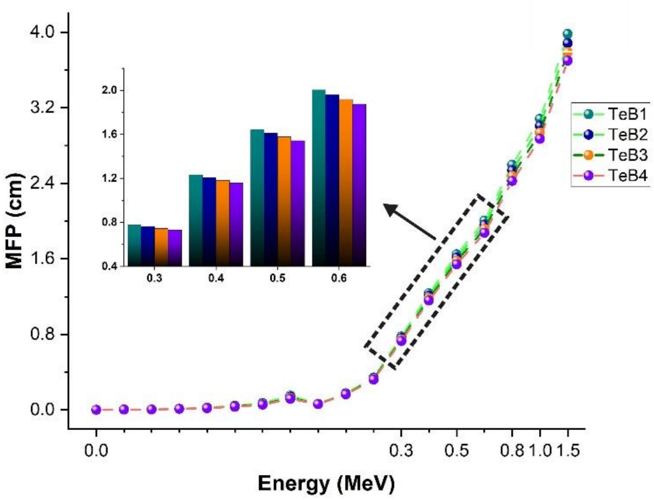

Figure 6. Mean free path (MFP) in the radiation energy range of 0.01 – 1.5 MeV

At 1.332 MeV, a similar trend is observed, where MFP decreases as the TeO_2 concentration increases in the shielding material. TeB4 has the lowest MFP value of 3.468 cm, which is smaller than other samples, specifically TeB1 (3.728 cm), TeB2 (3.637 cm), and TeB3 (3.550 cm). The MFP values of commercial RS-253-G18 glass (7.800 cm) and 40% synthetic borax (8.200 cm) remain significantly higher than TeO_2-based shielding, confirming that TeO_2-based glass is more effective in absorbing radiation. This effectiveness is primarily attributed to the increase in material density due to TeO_2 addition, which enhances the probability of interaction between radiation photons and electrons within the material.

When analyzing a single sample, such as TeB3, the MFP value increases as the incident radiation energy rises. At 0.01 MeV, the MFP value is initially only 0.002 cm, but it increases to 3.789 cm at 1.5 MeV. This increase in MFP values indicates that radiation particles travel longer distances before interacting with the shielding material, signifying a decline in radiation shielding effectiveness at higher energy levels. Therefore, these results confirm that TeO_2-based glass demonstrates high efficiency in absorbing low-to-medium energy radiation, whereas for higher energy levels, materials with greater density may be required to maintain radiation protection effectiveness.

CONCLUSION

The results demonstrated that increasing TeO_2 concentration enhances the density of the glass and significantly improves its ability to attenuate radiation. The TeB4 sample (15 mol% TeO_2) exhibited the highest mass attenuation coefficient (MAC) of 3.372 cm^2/g at 0.06 MeV, which was higher than the values obtained for the other samples. Additionally, the half-value layer (HVL) at 0.6 MeV showed a decreasing trend with increasing TeO_2 concentration, with values of 1.390 cm, 1.359 cm, 1.329 cm, and 1.300 cm for TeB1, TeB2, TeB3, and TeB4, respectively. These findings confirm that TeO_2 incorporation contributes to better radiation attenuation, making the glass an effective alternative for radiation shielding. The presence of Bi_2O_3 in the glass composition resulted in an absorption edge at 0.0905 MeV, leading to a sudden increase in attenuation efficiency at lower energy levels. Moreover, a comparison with commercial shielding materials, including RS-253-G18 glass and 40% synthetic borax, showed that TeO_2-based borotellurite glass exhibited lower mean free path (MFP) values, confirming its superior shielding capability. The material also offers the advantage of optical transparency, making it suitable for applications requiring both radiation protection and visibility. Based on these results, TeO_2-based borotellurite glass emerges as a promising lead-free alternative to conventional shielding materials, offering high radiation attenuation, reduced HVL, and improved transparency. Future research should focus on experimental validation, mechanical stability assessments, and optimization of glass compositions to further enhance its performance for practical applications in medical, nuclear, and industrial settings.

Declaration by Authors

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