

THE BEHAVIOR OF BISMUTH OXIDE ON TELLURITE BORATE OXIDE BASED GLASS SYSTEM FOR IONIZING RADIATION SHIELDING

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Abstract

This research, the photons shielding parameters such as mass attenuation coefficients (μ_m), effective atomic number (Z_{eff}) and Kerma relative to air (K_a) for Bi_2O_3 based TeO_2 - B_2O_3 - Bi_2O_3 glass system have been simulated by WinXCom software program at energies of 10^{-3} - 10^5 MeV. Also, buildup factors (BFs) have been estimated in wide energy ranging 15 keV-15 MeV for penetration depths (PD) until 40 mean free path (mfp). The results of the glass system in formula $(70-x)TeO_2$ - $30B_2O_3$ - xBi_2O_3 at $x = 10, 20, 30, 40$ and 50 mol% exhibited that Bi_2O_3 partial replacement of TeO_2 adjusts photons attenuation behaviors for get better. In addition, charged particles (proton: H^+ and alpha particles: He^{2+}) shielding parameters such as mass stopping power (MSP) and projected range (PR) were evaluated using SRIM software program at kinetic energy ranging 10 keV-10 MeV. The results found that the $20TeO_2$ - $30B_2O_3$ - $50Bi_2O_3$ glass sample which had the highest Bi_2O_3 content showed the largest μ_m , Z_{eff} and BFs values, while the MSP and the PR were the lowest values. These results indicated that glass sample with high Bi_2O_3 content is superb for photons attenuation while low Bi_2O_3 content is excellent for H^+ and He^{2+} shielding glass. The results of this research can be useful in enhancing the optimization of ionizing radiation shielding materials.

Keywords: Ionizing radiation shielding; Telluroborate glass; Build-up factors

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Introduction

In sectors of ionizing radiation (IR) like X/γ rays, proton, alpha and electron particles shielding materials, there are many materials like concrete, alloys, lead, glass, ceramic and polymer used for absorbing IR (Sharifi *et al.*, 2013; Halimah *et al.*, 2019; Asal *et al.*, 2021; Rammah *et al.*, 2021a; Akman *et al.*, 2022; Elsafi *et al.*, 2022). Concrete and lead (Pb) are basic photon shielding materials. Whereas they have a number of limitations, for example concrete is an opaque material, difficult to modify and cracks caused by water loss within concrete due to prolonged exposure to high energy radiation, while lead is expensive, toxic and heavy. Therefore, these problems are of great importance to scientists to develop new materials for IR shielding (Zaid *et al.*, 2012; Susoy *et al.*, 2020; Aboalatta *et al.*, 2021).

Glass is one of the favorite materials for IR shielding because of its transparency, easy processing, homogeneity, cheapness, thermal resilience and chemical durability (Mhareb *et al.*, 2021; Sayyed *et al.*, 2022a). Generally, chemical functions in glass structure can separate three types: glass network formers, like GeO_2 , B_2O_3 , TeO_2 , SiO_2 , Sb_2O_3 and P_2O_5 , glass intermediate and glass modifiers. Boron oxide (B_2O_3) favors the glass network former because of high thermal stability, low melting temperature, high thermal stability and ease of preparing glass. Tellurium oxide (TeO_2) is a heavy glass network former and excellent IR shielding due to its properties like high density, low melting point, and high thermal stability. In addition, the improved glass materials for IR shielding have been made by mixing heavy metal oxides (HMOs) in the structures like BaO , WO_3 , and Bi_2O_3 (Dwaikat *et al.*, 2021; Sayyed *et al.*, 2022b). Bismuth oxide (Bi_2O_3) which heavy metal oxides modifiers has been processed with high atomic number, high density, non-toxic, low softening point, high refractive index (RI), large polarizability, and strong non-linear optical properties these important properties for the development of IR shielding (Fong *et al.*, 2021; Jat *et al.*, 2021; Kaewjaeng *et al.*, 2021).

In this study, glass systems on formula $(70-x)\text{TeO}_2-30\text{B}_2\text{O}_3-x\text{Bi}_2\text{O}_3$ at $x = 10-50$ mol% were evaluated in terms of IR shielding. The parameters of uncharged particles (photons) like the mass attenuation coefficients (μ_m), the effective atomic number (Z_{eff}) and the Kerma relative to air (K_a) values have been determined at photon energy range from 10^{-3} - 10^5 MeV using the WinXCom software program. While the energy absorption and exposure buildup factor (EABF and EBF) have been simulated at widely energy range from 15 keV-15 MeV until deep penetration to 40 mean free path (mfp) at a specific energy. In addition, charged particles (proton: H^+ and alpha particles: He^{2+}) shielding parameters such as the mass stopping power (MSP) and the projected range (PR) have been simulated by the SRIM software at kinetic energy range from 10 - 10^4 keV.

Materials and Methods

Glasses Description

The Bi_2O_3 based on the TeO_2 - B_2O_3 glass system in this study has been adjusted Bi_2O_3 concentrations differently in formula $(70-x)\text{TeO}_2-30\text{B}_2\text{O}_3-x\text{Bi}_2\text{O}_3$ at $x = 10, 20, 30, 40$ and 50 mol% and exhibited in Table 1. From Table 1, Bi_2O_3 had maximum content at 50 mol% while TeO_2 and B_2O_3 concentration which glass network formers as combined at 50 mol%. This glass formula is designed based on concentration of former (TeO_2 and B_2O_3) not less than the rest component.

Mass Attenuation Coefficients (μ_m), Effective Atomic Number (Z_{eff}) and Kerma Relative to Air (K_a)

The theoretical of μ_m (cm^2/g) value for $(70-x)\text{TeO}_2-30\text{B}_2\text{O}_3-x\text{Bi}_2\text{O}_3$ where $x = 10, 20, 30, 40$ and 50 mol%) glass system was evaluated by mixture law which was simulated by WinXCom as exhibited in equation (1) (Kilicoglu *et al.*, 2019; Kamislioglu 2021(a)).

Table 1. The abbreviation and the chemical composition of glass samples (mol%)

Compound	Glass abbreviation and composition (mol%)				
	TBB1	TBB2	TBB3	TBB4	TBB5
TeO_2	60	50	40	30	20
B_2O_3	30	30	30	30	30
Bi_2O_3	10	20	30	40	50

$$\mu_m = \sum w_i (\mu_m)_i \quad (1)$$

here w_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of the sample, respectively, of i^{th} constituent elements.

The Z_{eff} and the K_a parameters have been simulated by equation (2) and (3) (An *et al.*, 2021; Kamislioglu 2021(a); Kamislioglu 2021(b); Turhan, 2021; Zaid *et al.*, 2021):

$$Z_{\text{eff}} = \frac{\sum_i f_i A_i (\mu_m)_i}{\sum_i f_i \frac{A_i}{Z_i} (\mu_m)_i} \quad (2)$$

here f_i , A_i and Z_i are mole fractions, atomic weight and number, respectively, of i^{th} constituent elements.

$$K_a = \frac{(\mu_m)_{\text{compound}}}{(\mu_m)_{\text{air}}} \quad (3)$$

Buildup Factors (BFs)

The BFs are fundamental parameters used to develop a medium for radiation shielding. This value can be divided into two types: energy absorption and exposure buildup factor (EABF and EBF). These parameters have been evaluated by the geometric progression (G-P) fitting method at energies range 15 keV-15 MeV which is referred to in several articles and have been simulated by equation (4)-(6) (Kavaz and Yorgun; 2018; Agar *et al.*, 2019; Mhareb *et al.*, 2020; Yonphan *et al.*, 2021):

$$B(E,x) = 1 + \frac{b-1}{b+1} (K^x - 1) \text{ for } K \neq 1 \quad (4)$$

$$B(E,x) = 1 + (b-1)x \text{ for } K = 1 \quad (5)$$

$$K(E,x) = cx^a + d \frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)} \text{ for } x \leq 40 \text{ mfp} \quad (6)$$

here E and x are the incident photon energy and the penetration depth in mfp (cm), a , b , c , d and X_k are the G-P fitting parameters, B is the buildup factor at 1 mfp. The parameter K is mentioned as the dose multiplication factor.

Mass Stopping Power (MSP) and Projected Range (PR)

The MSP and the PR quantities of the proton (H^+) and alpha (He^{2+}) particles for the TBB glass system were simulated using the SRIM-2013

software program. Many pieces of research explained the equations and concepts that using evaluated the MSP and the PR values which have been calculated by equation (7) and equation (8), respectively (Kavaz *et al.*, 2019; Rammah *et al.*, 2020a; Rammah *et al.*, 2021b; Alsaif *et al.*, 2022):

$$-\frac{dE}{dx} = S_e + S_n \quad (7)$$

here the minus sign is the charged particle will lose its E_k . dE/dx , S_e and S_n are the stopping power, electronic stopping power and nuclear stopping force, respectively.

$$PR = \left(\frac{M}{Z^2}\right) R_p(\beta) \quad (8)$$

here M , Z and $R_p(\beta)$ are mass, atomic number and the projected range for particles, respectively.

Results and Discussion

Mass Attenuation Coefficients (μ_m), Effective Atomic Number (Z_{eff}) and Kerma Relative to Air (K_a)

The uncharged (photons) attenuation behaviors can be discussed on several parameters such as the μ_m and the Z_{eff} . The μ_m value of the TBB glass system is exhibited in Figure 1. From the figure, the μ_m can separate on three energy regions as low energy range; photoelectric effect (PE) is major interaction, while at intermediated and high energy range; Compton scattering (CS) and pair production (PP) are major interaction, respectively. At the low energy range, the graph of the μ_m value exhibited a large value and it decreased rapidly. While at intermediated energy ranging, the graph increased slowly. Finally, at high energy ranging, the graph is nearly constant. These characteristics are due to photons interacting with substances depending on $E^{-3.5}$, E^{-1} and $\log E$ for PE, CS and PP processes, respectively. It was also found that the graph was not continuous. This event occurred from the K-, L- and M-absorption edges of Te and Bi in samples. In addition, the result displayed that the TBB5 glass sample had the largest μ_m . These events occurred because this sample had the highest Bi content, which indicated that the TBB5 sample had excellent photon shielding efficiency (Agar *et al.*, 2019; Mahmoud *et al.*, 2020; Ravangvong *et al.*, 2022a).

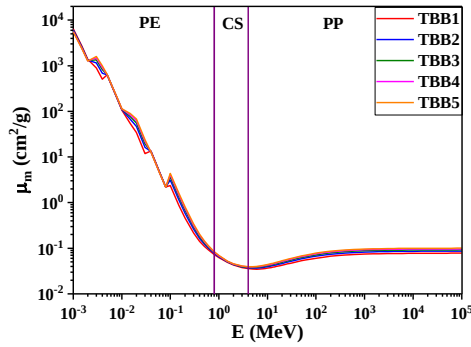


Figure 1. The μ_m versus energy for the glass system

The Z_{eff} is parameter using discussed the efficiency of medium for photons shielding. The medium which high Z_{eff} value means excellent photon shielding and exhibited in Figure 2. It found that the graph Z_{eff} values of the TBB glass system were higher at a low energy range because PE is the main interaction and depending on Z^{4-5} , and then decreased at intermediate energy range which CS is main interaction and $\propto Z$, while at high energy ranging, graphs increased nearly constant due to PP is main process and $\propto Z^2$. In addition, at low energy ranges appear three peaks around 4.00×10^{-3} , 2.00×10^{-2} and 1.50×10^{-1} due to the absorption edges of elements in the TBB glass system. Finally, the TBB5 graph has the highest value due to this sample had the largest Bi_2O_3 content which indicated that the Z_{eff} value depends on the composition of glass and this sample had the highest probability for occurring the interaction of photons with medium (Turhan 2021; Ravangvong *et al.*, 2022b; Sriwongsa *et al.*, 2022).

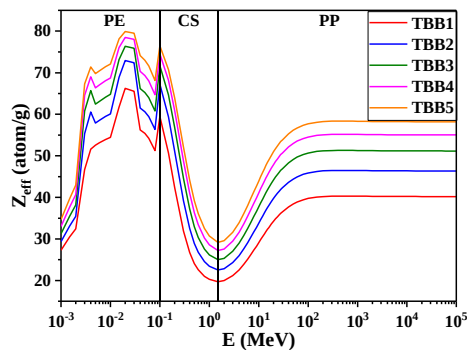


Figure 2. The Z_{eff} versus energy for the glass system

The Energy dependency of the K_a for the TBB glass system is exhibited in Figure 3. The result was observed that the K_a for the TBB glass

system increased with increasing energy until 0.02 MeV and then decreased rapidly to 1.00 MeV, after that it increased almost constantly. These events due to PE, CS and PP were the main processes. In addition, the graphs had three peaks at energy 0.02, 0.04 and 0.10 MeV because of the absorption edges of the element in the TBB glass system. Lastly, the TBB5 glass sample processed the highest K_a value due to this sample having the largest Bi content. It indicated that this value depends on the chemical composition (Kurtuluş *et al.*, 2021; Turhan 2021).

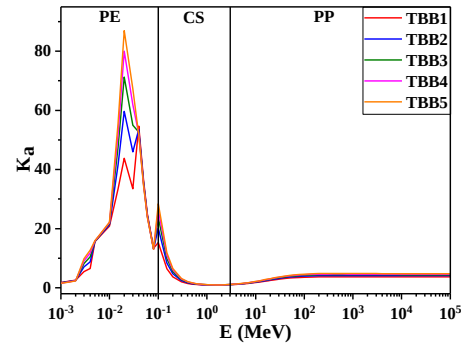


Figure 3. The K_a versus energy for the glass system

Buildup Factors (BFs)

The equivalent atomic number (Z_{eq}) parameter is the first parameter for simulating the BF's value and exhibited in Figure 4. It found that, at a low energy, the Z_{eq} also displays a low value and increases until $E < 100$ keV and the graph exhibited change around K absorption edge of elements in the TBB glass system and then slowly increases at intermediate energy while at high energy, it decreases. These results are because of PE, CS and PP are major interactions in each energy range, respectively (Issa *et al.*, 2020).

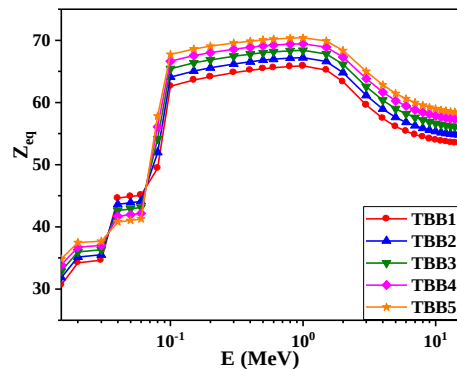


Figure 4. The Z_{eq} versus energy for the glass system

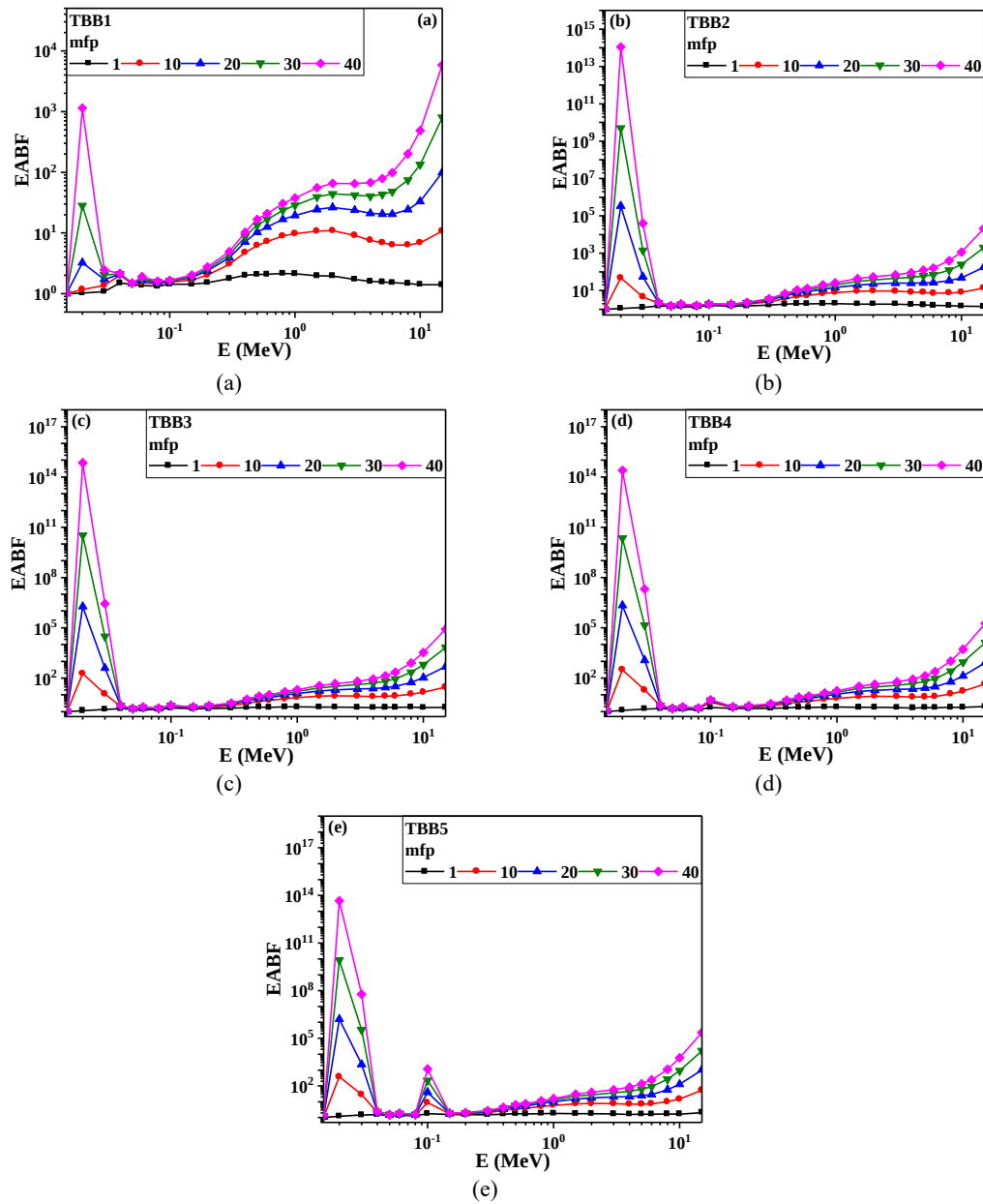


Figure 5. (a-e) The EABF versus energy from 15 keV-15 MeV until 40 mfp

The EBF and EABF are favor quantities for design materials for radiation shielding. Figure 5 and Figure 6 displayed EBF and EABF quantities for TBB glass system versus different penetration depths (PD) with energy until 15 MeV. The results found that, at low energy range, both values were lowest values due to PE being a major process and appearing at a sharp peak. This event has been explained by the absorption edges of elements in the TBB glass system. And then, at intermediate

energy, both values increased until the highest values with increased energy which CS is a major process. These events are due to photons losing energy from collisions and occurred accumulating energy within material for a long time. An increasing PD, these values increased because of the photons scattering increased with increased path length. At high energy, PP is major interaction.

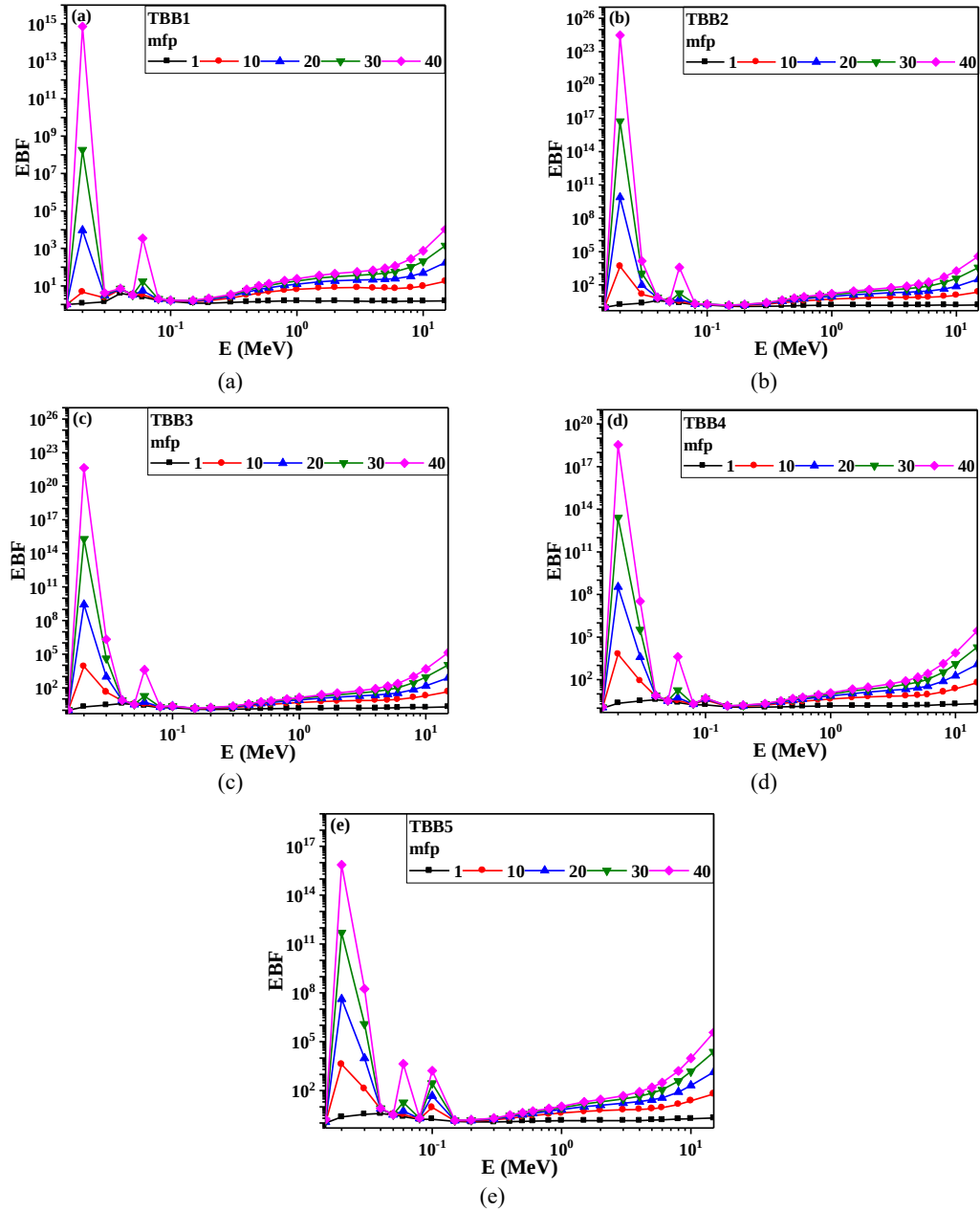


Figure 6. (a-e) The EBF versus energies from 15 keV-15 MeV until 40 mfp

The EABF and EBF values at specific energies of 0.15-15 MeV are exhibited in Figure 7 (a-d) and Figure (a-d). The EABF and EBF are small and grow until the maximum values with increasing depth from 1-40 mfp. These events

occur as more photons collided in glasses as depth increases. These things lead to increase numbers of low energy photons which accumulated in glasses (Rammah *et al.*, 2020b).

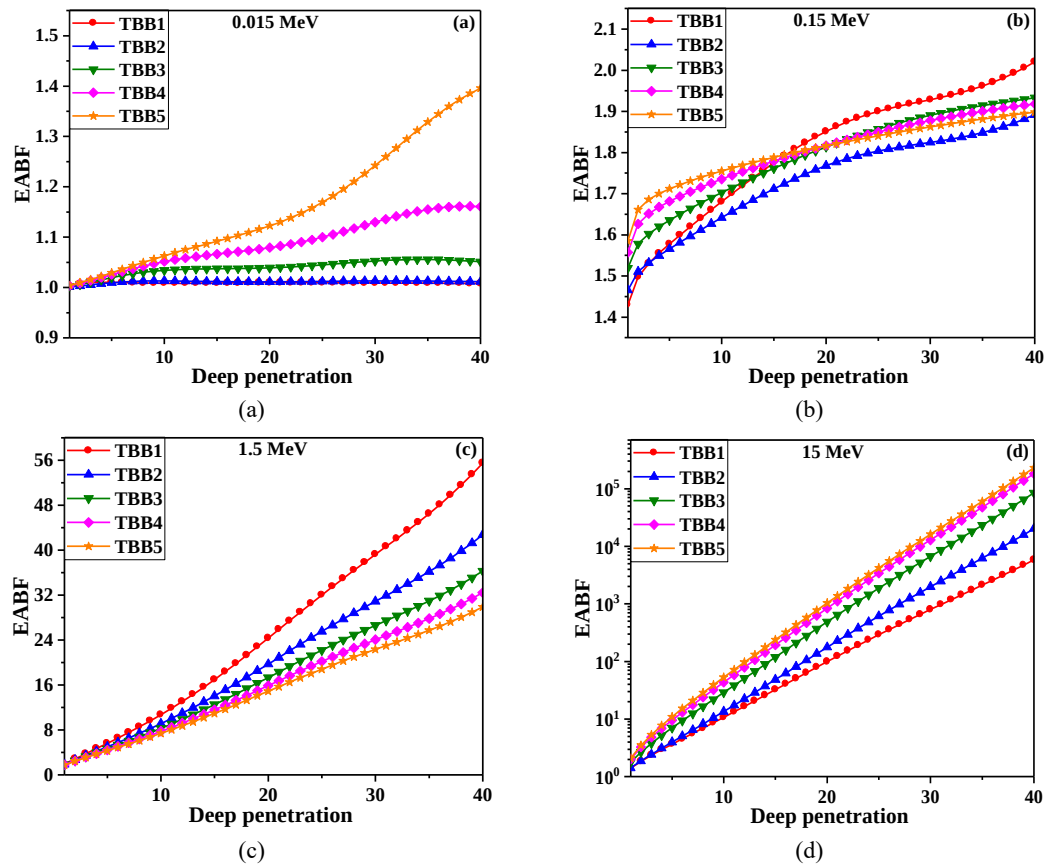


Figure 7. (a-d) The EABF until 40 mfp at 0.015, 0.15, 1.5 and 15 MeV

Mass Stopping Power (MSP) and Projected Range (PR)

The MSP of TBB glass system for proton and alpha particles have been simulated by the SRIM program at E_k ranging 10 keV-10 MeV. The MSP is a parameter representing the decrease in kinetic energy (E_k) as they travel through a material. Figure 8 exhibited that that glass samples TBB1, TBB2, TBB3, TBB4 and TBB5 which TBB5 had the lowest value of MSP for proton and alpha particles, respectively. From Figure 9, TBB1 glass sample had the largest value of MSP for removal of proton and alpha particles at E_k 90 keV and 700 keV about 1.93×10^{-1} and 5.57×10^{-1} MeV cm^2/g , respectively (Kilicoglu *et al.*, 2019).

For the TBB glass system, the projected range (PR) quantities were simulated in H^+ and He^{2+} at E_k ranging 10 keV-10 MeV as exhibited in Figure 10. From the figure, the removal of H^+ and He^{2+} for TBB1 at 10 MeV energy having the largest about 498.53 μm and 56.96 μm , respectively. The results indicated TBB1 glass sample has excellent value. The simulation results have deduced that the Bi_2O_3 in glass system is superior for H^+ and He^{2+} shielding (Kilicoglu *et al.*, 2019).

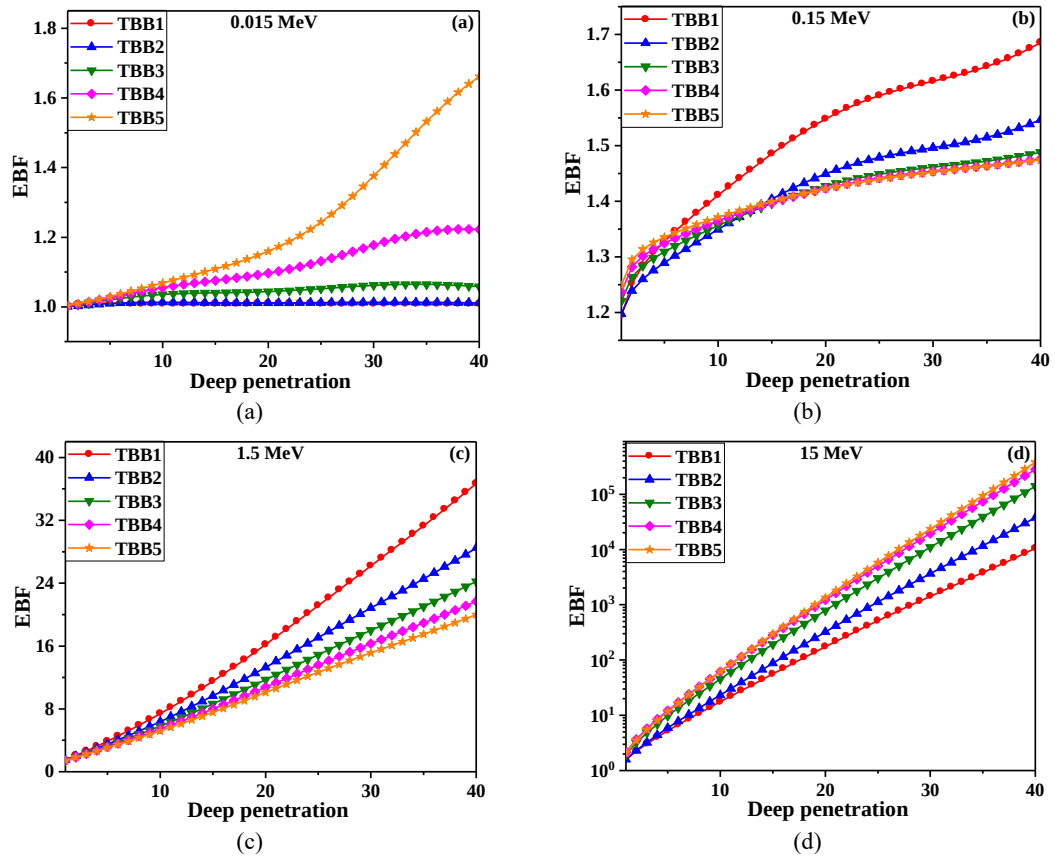


Figure 8. (a-d) The EBF until 40 mfp at 0.015, 0.15, 1.5 and 15 MeV

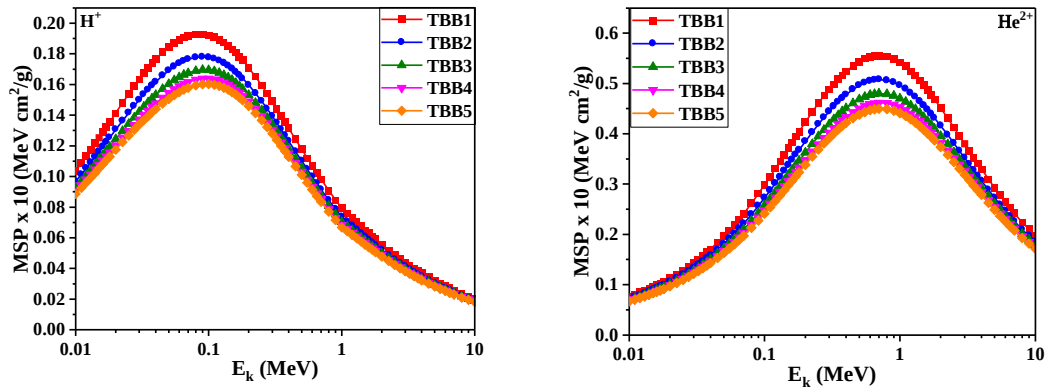


Figure 9. The MSP for H^+ and He^{2+} versus E_k .

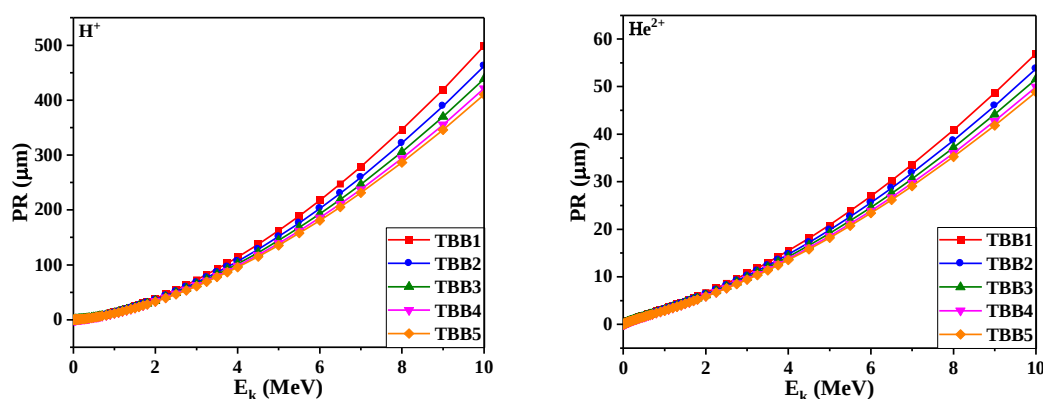


Figure 10. The PR of H^+ and He^{2+} versus E_k .

Conclusions

The behavior of Bi_2O_3 contents for ionizing radiation shielding of $(70-x)TeO_2-30B_2O_3-xBi_2O_3$ at $x = 10-50$ mol% glass system were illustrated. The uncharged particles (photons) shielding of glass system properties were simulated at $10^{-3}-10^5$ MeV using the WinXCom program and the parameters like the μ_m , the Z_{eff} and the K_a were explained. Also, the buildup factors (BFs) were estimated in the wide energy range of 15 keV-15 MeV for penetration depths (PD) until 40 mean free path (mfp). While the charged particles (proton and alpha) shielding properties were evaluated using the SRIM software program at E_k energy range 10 keV-10 MeV, MSP and PR were discussed. The results exhibited that the $20TeO_2-30B_2O_3-50Bi_2O_3$ glass sample which contained the highest Bi_2O_3 content showed the largest the μ_m , the Z_{eff} , the K_a and the BFs values, while the MSP and the PR were the lowest values. These results referred that glass sample with high Bi_2O_3 content is superb for photons attenuation while low Bi_2O_3 content is excellent for H^+ and He^{2+} shielding. The results of this research indicated that this glass system can be developed and used as IR shielding materials.

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