EVALUATION OF RADIATION SHIELDING PARAMETERS FOR OPTICAL MATERIALS

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In this work, we have evaluated the mass attenuation coefficient (μ/ρ), half value layer (HVL) and exposure buildup factors (EBF) for Bi-doped tellurite glass, and Dy-doped borate glass. The results show that the Bi-doped tellurite glass has higher μ/ρ and HVL than Dy-doped borate glass. These results could be useful in the construction of active shielding against hazardous gamma radiation.

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Keywords: Amorphous materials; Radiation damage; Mass attenuation coefficient; Half value layer; Exposure buildup factors

1. Introduction

It is well known that the existing optical glass systems can be divided into two groups: (i) low-melting glass systems like borate glass, tellurite glass and phosphate glass which possess a softening temperature lower than 600 °C and (ii) high-melting glasses mainly silicate glasses with a softening point higher than 600 °C. Borate glasses possess large glass forming ability, high optical transparency, good thermal and radiation stability, and good solubility of rare-earth (RE) or transition metal (TM) elements [1, 2]. Particularly, borate glasses doped with RE ions show significant applications for solid state lighting, sensors, optical data storage devices, and optical fibers etc. [1]. Borate glasses require the incorporation of modifiers such as alkali (Li_2O, Na_2O etc.) or alkaline (MgO, CaO etc.) oxides to improve the mechanical stability and reduce the hygroscopic nature of their glass network [3]. Further, TeO_2 based glasses are of scientific and technological interest due to their attractive physical and optical properties such as high refractive indices ($n \geq 2$), high dielectric constants, good transparency in the visible and infrared regions (0.4–6 μm), and low phonon energy (~750 cm^{-1} [4]. In addition, these glasses are stable against devitrification, non-toxic and are moisture resistant for relatively longer periods. Due to their above excellent features, RE-doped tellurite glasses found potential applications in lasers, optical fiber amplifiers, and planar waveguides etc. [4-7].

Though Pb-based glasses are useful for γ-ray radiation shielding device applications because of their enhanced physical and chemical properties, their toxic nature is the main concern for the environment. Thus, very recently, there is an increasing interest in evaluating Pb-free glasses such as borate, tellurite and boro-tellurite glasses suitable for radiation shielding applications [8–10]. In this article, we report some γ-ray shielding parameters such as mass attenuation coefficient (μ/ρ), half value layer (HVL) and exposure buildup factors (EBF) for heavy metal/transition metal (Bi_2O_3) doped tellurite glass, and RE (Dy_2O_3) doped borate glass. The chemical composition of the studied glasses is 59 B_2O_3-10 WO_3- 10 ZnO- 10 Li_2O- 10 Na_2O-1.0 Dy_2O_3 (mol %), and 69 TeO_2- 10WO_3-10 ZnO- 5 Na_2O-5 TiO_2- 1.0 Bi_2O_3 (mol %).

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2. Theory

2.1. Mass attenuation coefficient

The mass attenuation coefficient μ/ρ is a measure of the probability of interactions of photon with a material and measure in unit of cm^2/g. It is fundamental tool used to derive other photon interaction quantities such as half value layer. The μ/ρ of the Bi-doped tellurite and Dy-doped borate glasses can be calculated using the mixture rule [11]

$$\mu/\rho = \sum_i w_i(\mu/\rho)_i \tag{1}$$

here $(\mu/\rho)_i$ and w_i represent the total mass attenuation coefficient and the fractional weight of the *i*th constituent in the glass system, respectively. The linear attenuation coefficient, μ (cm^{-1}) was calculated by multiplying (μ/ρ) by the density of the glass. Mass attenuation coefficient (μ/ρ) of an element was determined by using WinXCom computer software [12].

2.2. Half value layer

Half value layer (HVL) is defined as the thickness of the material that reduces the photon beam intensity to half of its initial value and measured in (cm). The lower HVL indicates many interaction gamma rays with the material and hence the better gamma ray shielding effectiveness can be obtained. The following relation was used to calculate the HVL of the selected glasses [13]:

$$\text{HVL} == \frac{0.693}{\mu} \tag{2}$$

where μ represents the linear attenuation coefficient.

2.3. Exposure buildup factors

The computational work of the exposure buildup factors (EBF) for Dy doped borate and Bi doped Te glasses is carried out in three steps:

a. Calculation of equivalent atomic number Z_{eq}
b. Calculation of the G-P fitting parameters (b, c, a, X_k and d)
c. Calculation of the exposure buildup factors

The procedure of Z_{eq} calculation by logarithmic interpolation method has been discussed elsewhere [14, 15]. The G-P fitting parameters were calculated in a similar fashion of logarithmic interpolation procedure for Z_{eq}. The values of Z_{eq} for the selected glasses were then utilized to calculate the G-P fitting parameters (b, c, a, X_k and d). Finally, the G-P fitting parameters used to compute the EBF using the following formula [14]:

$$B(E,x) = \begin{cases} 1 + \frac{b-1}{K-1}(K^x - 1), & K \neq 1 \\ 1 + (b-1)x, & K = 1 \end{cases} \tag{3}$$

The function *K(E, x)* represents the photon dose multiplication factor, *E* is the incident photon energy, *x* is source to detector distance in the medium in unit of mean free path (mfp) and b is the buildup factor at 1 mfp.

3. Results and discussion

Fig. 1 shows the calculated μ/ρ values of Dy-doped borate and Bi-doped tellurite glasses. It can be seen from fig. 1, the μ/ρ values of glasses decrease rapidly, from 3.14×10^3 to 8.07×10^{-2} cm^2/g and 6.29×10^3 to 8.23×10^{-2} cm^2/g for Dy-doped borate and Bi-doped tellurite glasses, respectively, as the incident photon energy increases up to 0.6 MeV. In this photon energy range, discontinuities in μ/ρ values were observed at different energies due to M-, L- and K-absorption edge of the elements Ti, Zn, Te, Dy, W and Bi as tabulated in Table 1. It is deducible that in the lower energy region ($E<0.6$ MeV), the drastic decrease in μ/ρ of glasses may be attributed to the photoelectric absorption cross-section which is relative to $E^{3.5}$. In the moderate energy range $0.6 < E < 4$ MeV, the values of μ/ρ for the selected glasses decrease slowly, from 0.0807 to 0.0312 cm^2/g and 0.0823 to 0.03422 cm^2/g for Dy-doped borate and Bi-doped tellurite glasses, respectively. However, the μ/ρ for both glasses is almost the same and independent of chemical composition as shown in Figure 1. This behavior of μ/ρ in this energy region could be attributed to the Compton scattering which is predominant. Compton scattering varies linearly with atomic number therefore the difference between μ/ρ values becomes about zero. Furthermore, from Fig. 1 it is observed that as the photon energy increase from 4 MeV, the μ/ρ increase slowly up to 100 MeV then becomes constant thereafter. These results show the Bi-doped tellurite glass has higher μ/ρ than and Dy-doped borate glass.

Table 1. Photon energies (in KeV) of absorption edges for elements

Element	Z	M5	M4	M3	M2	M1	L3	L2	L1	K
Ti	22	-	-	-	-	-	-	-	-	4.966
Zn	30	-	-	-	-	-	1.020	1.043	1.194	9.659
Te	52	-	-	-	-	1.006	4.340	4.612	4.939	31.180
Dy	66	1.295	1.332	1.676	1.842	2.047	7.790	8.581	9.046	53.790
W	74	1.81	1.87	2.28	2.58	2.82	10.21	11.54	12.10	69.53
Bi	83	2.580	2.688	3.177	3.696	3.999	13.420	15.710	16.390	90.530

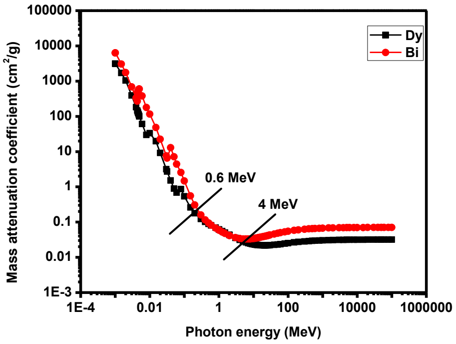

Fig. 1. Variation of mass attenuation coefficient as a function of photon energy for Bi -doped tellurite and Dy- doped borate glasses for total photon interaction from1 keV–100 GeV

Fig. 2 presents the variation of HVL values with incident photon energy in the range 1 keV -100 GeV. The HVL values, in the energy range 1-500 keV, are nearly photon energy and composition samples independent, and the values of HVL in this energy region are very small (<1 cm). Thereafter, the values of HVL increase rapidly with the increment in the energy and reach its maximum values of 10.29 cm and 3.75 cm at 20 MeV and 6 MeV for Dy-doped borate and Bi-doped tellurite glasses, respectively. With further increase of incident photon energy, decrement in the values of HVL was observed and after 3000 MeV the HVL values are almost constant. The values of HVL of Bi-doped tellurite glass are lower than that Dy-doped borate glass.

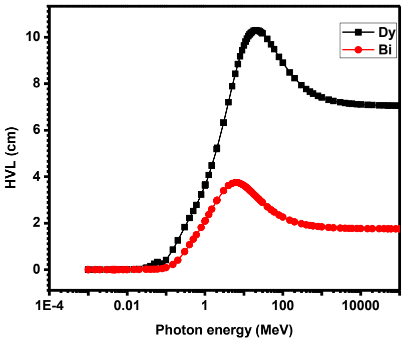

Fig. 2. Variation of half value layer as a function of photon energy for Bi-doped tellurite and Dy-doped borate glasses for total photon interaction from1 keV–100 GeV

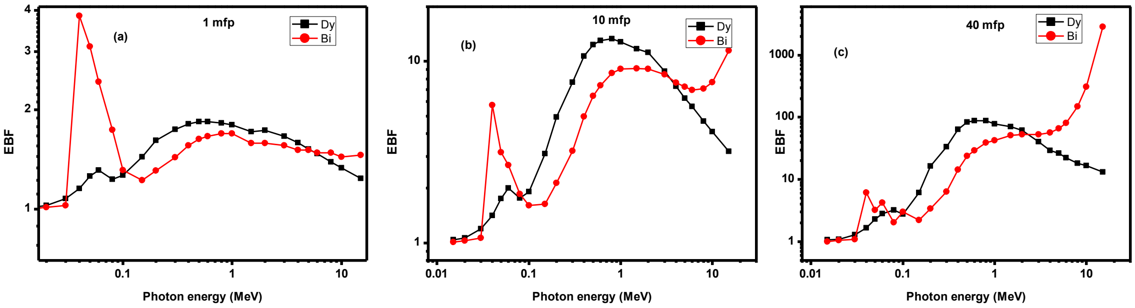

Fig. 3. Variation in exposure buildup factors for Bi-doped tellurite and Dy-doped borate glasses with photon energy at selected penetration depths 1, 10 and 40 mfp

The variation of EBF values with photon energy at 1, 10, and 40 mfp of Dy-doped borate and Bi- doped tellurite glasses have been plotted and the results are shown in Fig. 3 (a-c). The EBFs are found to be increasing with mean free path of the glasses. Also, it is clear that in the low energy region and for all penetration depths, the EBF values are almost unity up to 0.03 MeV for both glass samples. The EBF values are small due to the great number of photons were absorbed or removed because the predominant interaction processes is the photoelectric effect. While, the EBF at penetration depth 40 mfps were 42.79581 and 78.66555 at 1 MeV for Dy-doped borate and Bi-doped tellurite glasses, respectively. A critical peak in the EBF was seen at 0.04 MeV for Bi-doped Te glass which may be attributed to k-absorption edges of Te. The EBF at photon energy of 0.6 MeV (^{137}Cs equivalent) were in the range of 1.84 to 87.75 and 1.66 to 29.26 for Dy-doped borate and Bi-doped tellurite glasses, respectively. However, the EBF shown at photon energy 6 MeV (^{16}N equivalent) were 1.47 to 22.46 and 1.48 to 80.82 for Dy-doped borate and Bi-doped tellurite glasses, respectively. The analysis showed that the EBFs of Bi-doped tellurite glass at higher energy are found to be very high. This can be explained according to the dominance of pair production process in the higher energy region.

4. Conclusions

The gamma-ray shielding properties for Bi_2O_3 doped tellurite glass, and Dy_2O_3 doped borate glass have been studied using WinXCom program and G-P fitting method. It is shown that Bi_2O_3 doped tellurite glass have shown higher values of (μ/ρ) and HVL than Dy_2O_3 doped borate glass. The EBF of Bi-doped tellurite glasses at higher energy are found to be very high and this can be explained according to the dominance of pair production process in the higher energy region.

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