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Effect of Er^{3+} ions on Bismuthate Glasses for Radiation Shielding Applications

Dhyan Rajani[1], Dr. Seema Thakur[2]*
[1]Aditya Birla World Academy, J D Road Tardeo, Mumbai, Maharashtra, 400007, India.
E-mail ID: dhyanrajani1@gmail.com
[2*]Department of Humanity and Science, A.C. Patil College of Engineering, Kharghar, Navi Mumbai, Maharashtra, 410210, India. E-mail ID: seemathakurphy@gmail.com

Abstract

The radiation shielding effect of Er_2O_3-doped bismuthate glasses has been studied. These transparent glasses are considered environmentally safe due to its non-toxic nature and thus, can be used for windows installed in radiation zones. Various γ-ray attenuation parameters such as mass and linear attenuation coefficients (MAC, LAC), half and tenth-value layers (HVL, TVL) and mean free path (MFP) were evaluated by using Phy-X/PSD. A highly erbium-doped glass sample found to be a better performer than many commercially available glasses and ordinary concretes. The calculated results also indicated great potentials of the glasses in radiation shielding applications.

Keywords: *Er_2O_3-doped glass, Radiation Shielding, Phy-X/PSD*

1. Introduction

The applications of glasses requiring gamma-ray attenuation and high mechanical strength can be achieved by using heavy metal oxide-based glasses such as Pb_3O_4, Bi_2O_3, WO_3 etc. [1-3]. Nowadays, Bi_2O_3 has gained vast attention due to its applications in various fields and its tendency to provide host glass network. Additionally, this glass system is considered as an environmentally safe option for gamma radiation attenuation [4].

$BaTiO_3$ is a well-known ferroelectric perovskite oxide having remarkable properties such as high dielectric constant and mechanical strength, exhibits low dielectric loss etc. therefore, it is widely used in glass and glass-ceramics [5,6].

Researchers have been drawn to erbium oxide (Er_2O_3) because of its high thermal stability, chemical longevity, mechanical robustness, and excellent transparency in the visible light spectrum [7]. Additionally, it exhibits strongly intense spectral characteristics in 4f transitions [8].

Therefore, the present study evaluates the γ-ray shielding performance of Er_2O_3-doped glass system. While Pb-based glasses effectively block radiation, their high toxicity has created a growing demand for safer and environmentally suitable alternatives for shielding against radiation. Therefore, present work explores the theoretical approach for calculating various radiation shielding parameters using Phy-X/PSD simulation method [9-13].

2. Experimental

The glass samples are synthesized by employing the melt-quenching technique having composition $(80\text{-}x)Bi_2O_3$-$20(BaTiO_3)$-$x(Er_2O_3)$ where x = 1, 2, and 3 (*wt.* %). The high quality chemicals such as (99.9%) analar-grade Bi_2O_3, (99.9%) Sigma Aldrich $BaTiO_3$ and (99.9%) Otto Er_2O_3, were measured to make a suitable composition [14]. The glass synthesis procedure has been reported in our previous work [14]. A software Phy-X/PSD is used to evaluate the radiation shielding effectiveness of synthesized Er_2O_3-doped glasses [11,12].

3. Results and Discussions

3.1 Gamma Radiation Simulation

A software Phy-X/PSD has been employed to evaluate the theoretical parameters for photon attenuation in synthesized Er^{3+} ions doped bismuthate glass system. Various shielding parameters are computed in the photon energy of (0.015 to 15 MeV) such as mass and linear attenuation coefficients (μ_m, μ), half and tenth value layers (HVL, TVL), mean free path (MFP) [11-13].

3.1.1 Mass and Linear Attenuation Coefficients (MAC, LAC)

Mass attenuation coefficient, MAC (μ_m), depicts the glass system (mass per unit area) interacting with incident γ-ray photons computed in cm^2/g. A software Phy-X/PSD has been employed to calculate the values of MAC for the presently studied glass system [11].

$$\mu_m = \mu\rho^{-1} = \sum_i w_i(\mu_m)_i \quad (1)$$

where w_i indicates the weight fraction of i^{th} element.

Figure 1 illustrates a typical MAC behavior in the photon energy of (0.015-15) MeV. Upon increasing the photon energy, an intense decrease in MAC values has been observed, which further remained constant for all the high energy values. This typical behavior is assigned to the absorption cross-section due to photoelectric effect (PE) in low energy area, Compton scattering (CS) at intermediate energy and at high energy region pair production (PP) dominates (5-15MeV) [11,12,15-19].

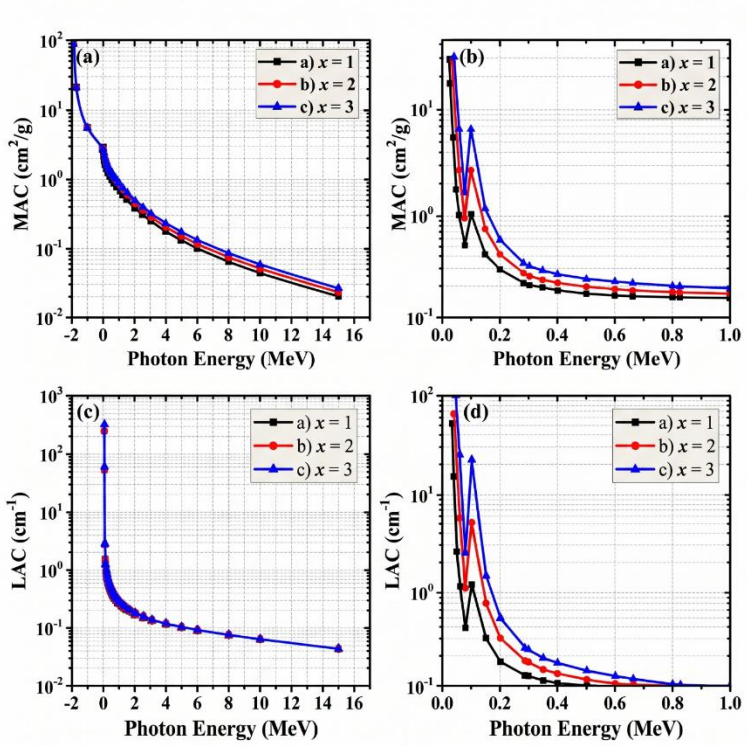


Figure 1. Variation of MAC & LAC parameters with respect to photon energy of Er_2O_3-doped bismuthate glasses.

PE absorption defined by PE∝ Z^4, typically dominates at low energies and most effective for the elements having high atomic numbers (Z). The Figure 1 also shows an abrupt peak upon increasing the energy ranging from (0.03-0.2) MeV. This particular peak represents energy absorbed by the photon at K-absorption edge of Bi element [11,17]. On the other hand, CS-cross section defined by CS ∝ Z/E is most effective in (0.5-5) MeV energy range. As a result, by surpassing the PE interaction CS becomes the principal mechanism in mid energy region. Figure 1 depicts that a similar attenuation trend has been followed by all the glass samples and a constant graph is observed only after 0.5 MeV. This specific trend is attributed to the dependency of PE absorption on electron density of glass sample and independent of Z [11]. Additionally, the constant trend of MAC values in mid-energy regions is observed due to linear dependence of CS cross-section on Z in all glass samples [17]. However, PP cross-section defined by PP ∝ Z^2 is predominantly active in high energy region (E > 1.02 MeV) [11]. Interestingly, apart from other properties of Er_2O_3-doped bismuthate glasses [19], Er_2O_3-doped glasses have the tendency to attenuate harmful gamma radiation and is considered to provide better shielding when compared with other glasses and commercial concretes [11,15,18].

Another important radiation shielding parameter is linear attenuation coefficient (LAC), indicated by (μ). To determined LAC parameter equation (2) i.e. Lambert-Beer rule is employed [11].

$$I = I_{\circ}e^{-\mu t} \quad (2)$$

where, $I_{\circ}$ and I are incident and transmitted gamma-ray intensity whereas, "t" represents the thickness (in cm) of glass.

LAC and MAC both the parameters are influenced by glass density and governed by radiation-matter interaction mechanisms [11-12]. The density increased with increasing Er_2O_3 content, resulting in higher LAC values in the presently studied glass system [14]. Since during LAC analysis, photon interactions occur with the glass material per unit thickness, their values also depend on three fundamental radiation absorption mechanisms: PE, CS and PP. Figure 1 shows the variation of parameter LAC in Er_2O_3-doped glasses as a function of photon energy. A prominent peak lies in energy ranging from (0.03-0.2) MeV is depicted in inset of Figure 1. This peak is assigned to K-absorption edge in bismuth, activated from PE absorption process [11,18,20].

Therefore, overall, the MAC and LAC results show a rising trend with increasing amount of Er_2O_3 in glasses as depicted in Figure 1.

3.1.2 Half-Value Layer (HVL) and Tenth-Value Layer (TVL)

Half value layer (HVL) and tenth value layer (TVL) are two important parameters and have been derived from LAC by using equations (3) and (4). These parameters represent the thickness of the attenuating material required to minimize the intensity of approaching γ-ray photons to one-half and one-tenth of their original intensity. Both the parameters indicate the shielding effectiveness of glasses against harmful gamma radiations. The performance of these parameters entirely depends upon the density of glasses and energy of the incident photons [11].

$$\mathrm{HVL} = 0.693 \times \mathrm{LAC}^{-1}\ (\mathrm{cm}) \quad (3)$$

$$\mathrm{TVL} = 2.303 \times \mathrm{LAC}^{-1}\ (\mathrm{cm}) \quad (4)$$

The variation of HVL and TVL parameters as a function of photon energy for the studied glasses is illustrated in Figure 2. The behavior of both the parameters with respect to the incident photon energies comes out to be similar [11]. It has been observed that both the parameters rapidly increase in low and mid-energy regions ranging from (0.015 to 6) MeV and stabilizes there-after in high energy regions. This specific trend has been attributed to various matter-radiation interactions such as PE, CS and PP [15]. Figure 2 also demonstrate the compositional effect on both the parameters and it has been observed that the increase in Er_2O_3 content drastically reduces the values of HVL and TVL parameters in studied glasses. This decline is assigned to the reported increase in density with increase in Er_2O_3 content [14]. Therefore, it has been concluded that the glass sample with highest Er_2O_3 content (x=3%) provides better radiation shielding due to the lowest values of (HVL and TVL) parameters and highest density [11,12,18].

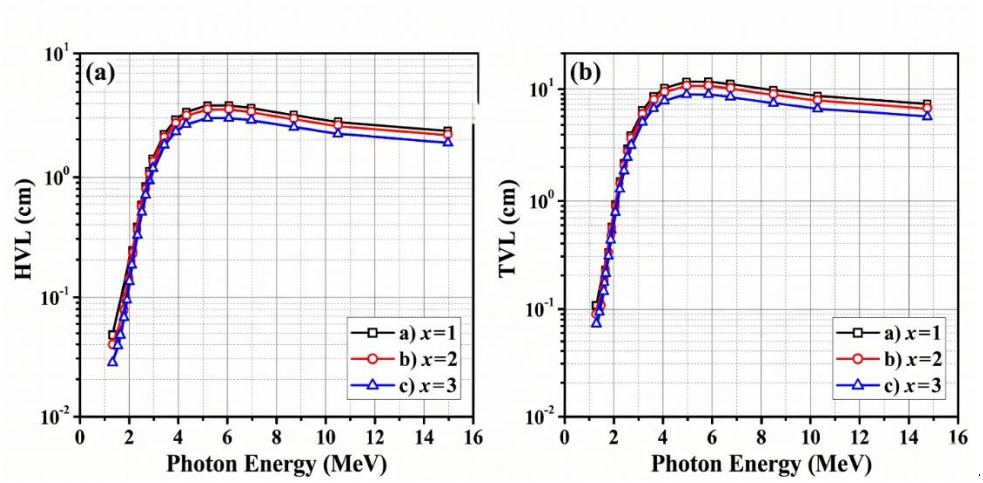


Figure 2. Variation of parameter HVL& TVL with respect to photon energy in Er_2O_3-doped bismuthate glasses.

3.1.3 Mean Free Path (MFP)

Another crucial parameter is mean free path (MFP) and can be derived using a common relation with LAC, as given in equation (5) [11].

$$\mathrm{MFP} = \mathrm{LAC}^{-1}\ (\mathrm{cm}) \qquad (5)$$

MFP is the mean distance covered by any moving atom, or photon between two successive collisions. MFP plays an important role in changing the energy and direction of particles. It also indicates the ability of any material to attenuate the gamma radiations. It has been found that the materials having lower MFP values provide better shielding against gamma radiations [18]. An increase in MFP values with increasing energies has been observed in Figure 3 of studied glass system. This increase has been assigned to the absorption of a large number of photons in high-energy regions. Additionally, the effect of concentration is clearly visible in Figure 3, depicting a decrease in MFP values upon increasing the content of Er_2O_3 in glasses. These decreased values of MFP are an outcome of higher density of glass samples [14]. Therefore, it has been concluded that glass sample with highest Er_2O_3 content (x=3%) demonstrates the superior radiation attenuation characteristics among all the studied glasses [18]. A highly erbium-doped glass sample found to be a better performer than many commercially available glasses and ordinary concretes [21].

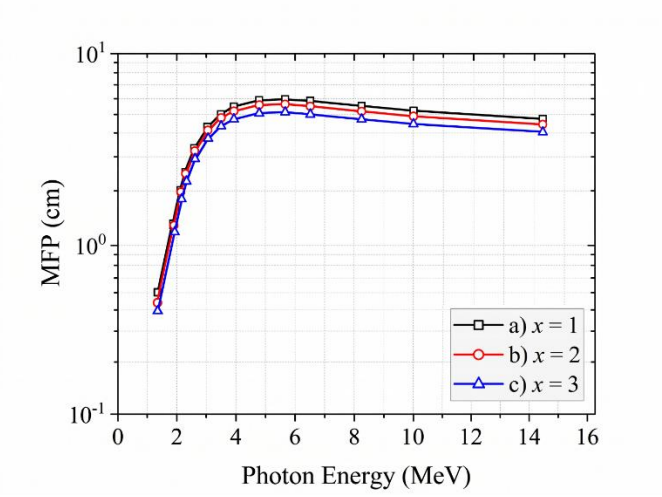


Figure 3. Variation of parameter MFP with respect to photon energy in Er_2O_3-doped bismuthate glasses.

4. Conclusions

This work studies the gamma radiation shielding, and mechanical properties of glass system having composition (80-x)Bi_2O_3-20($BaTiO_3$)-x(Er_2O_3) where x = 1, 2, and 3 (*wt.* %) required to fulfill demanding needs for robots and optical sensing systems operating in harsh nuclear radiation and cosmic zones. Gamma radiation attenuation effectiveness of the studied glass system was evaluated theoretically via simulation method using Phy-X/PSD software. A glass sample containing highest Er_2O_3 content (x=3%) found to be a better performer in attenuating the gamma radiations when compared with conventional concretes. This glass sample exhibits highest value of mass and linear attenuation coefficients (μ_m,μ) and holds a lowest value of (HVL and TVL) parameters. The potential of radiation attenuation effectiveness makes these glasses a promising candidate for durable and optically transparent protective windows.

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Declarations:

Conflicts of Interest
Authors declare that they have no competing financial interests that influence the work reported in this paper.

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