Investigation of gamma-ray shielding parameters of bismuth phospho-tellurite glasses doped with varying Sm$_2$O$_3$

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ABSTRACT

The gamma ray shielding parameters such as mass attenuation coefficient, effective atomic number, equivalent atomic number, exposure buildup factor, and energy absorption buildup factor were determined for the 47.5P$_2$O$_5$+45ZnO+(5-x) Bi$_2$O$_3$+2.5TeO$_2$+xSm$_2$O$_3$ glass system using Phy-X/PSD software in the energy range from 0.015 to 15 MeV at penetration depths of 1–40 MFP. To understand the effect of Sm$_2$O$_3$ on gamma ray shielding parameters in selected glass system, the Sm$_2$O$_3$ was varied in the glass from 0.01 to 1 mol%. The calculated results show that the mass attenuation coefficient decreases with increasing photon energy but not influenced by the addition of Sm$_2$O$_3$. The Zeq values are lower in low (<100 keV) and high energy regions (1 MeV–15 MeV) and higher in the medium energy region, indicating that the Compton scattering is significant in the medium energy region. The values of exposure buildup factors and energy absorption buildup factors are smaller in the low and high energy regions than in the intermediate energy region, indicating that the photo absorption and pair creation processes are important in the low and high energy regions, respectively. The 1% mole concentration of Sm$_2$O$_3$ in the selected glass shows higher exposure buildup factor and energy absorption buildup factor values in the intermediate energy region. The high density, high effective atomic number, and transparency to visible light of these materials indicate that they can be used as shielding materials in nuclear reactors and nuclear technology.

1. Introduction

Nuclear technology is used to generate not only nuclear power but also in agriculture, medical, nuclear desalination, etc. In nuclear power generation, the energy residing in the nucleus is used to generate electricity. In agriculture, nuclear radiation is used to prevent harmful insects from reproducing. In medical imaging, radioactive sources are used to obtain an image of the body to treat the disease. In nuclear desalination, the heat and electricity generated by the nuclear plant are used to remove salt and minerals from sea water. Therefore, nuclear technology has become an essential tool in developing society. However, the nuclear radiation emitted from atomic nuclei is hazardous to human health as well as the environment. Therefore, they are to be shielded in such a way that the personnel and environment are not affected by the radiation. Hence, handling and storage of radioactive materials at radiological establishments has become an essential task with the growing nuclear technology and safety measurements. Therefore, there is an urgent need to investigate shielding materials to protect personnel as well as the environment from nuclear radiation [1, 2]. Evaluation of gamma ray shielding parameters (GSP) such as mass attenuation coefficient (MAC), effective atomic number (Z$_{eff}$), equivalent atomic number (Z$_{eq}$), exposure buildup factor (EBF) and energy absorption buildup factor (EABF) helps in the selection of a suitable radiation shielding material. Calculations of these shielding parameters have already been carried out by various investigators using different computational methods and software for concrete, alloys, rocks, polymers, biomaterials, and glasses [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Although lead and concrete are being used as nuclear radiation shielding materials, they have several drawbacks, such as being non-transparent, lack of mobility, toxicity, and a tendency to crack [21].

Glass materials are being considered as good shielding materials as they are not only transparent but also heavy metal oxides can be substituted in such a way that they can absorb nuclear radiation. In this direction, several investigators have studied the shielding properties of...
glassy materials. It is interesting to note that heavy metal oxide doped glasses play a significant role in the shielding of gamma radiation. As the phosphate glasses have high mechanical, good chemical and high thermal stability, they are potential materials for radiation shielding, radiation sensing, medicine, and industry [22]. Phosphate glass exhibits good chemical durability and good transparency in visible and infrared regions [23]. Phosphate and borate glasses doped with Bi₂O₃ are attracting attention in the world of optoelectronics due to their dual roles as a conditional glass former (when added in large amounts) in some of the host glass matrix and as a modifier role when the concentration of the same is low in the host glass matrix [24, 25]. These glasses are environmentally more reliable than lead-based glasses, proving to be the best substitute for architectural glass and device applications like sensors, sealing, automobiles and solar cells in the electronics field. Interestingly, bismuth (Bi) also has similar glass-forming properties as lead (Pb). Hence, Bi can act as the best alternative for replacing lead content in glass systems in many applications due to its environment-friendly nature and good chemical durability. Because of their high atomic number, these glasses emerge as potential materials in optics, nuclear technology, and in the field of superconductors [24, 25]. Reports show that many glasses are known to fulfill these requirements, based on the recent investigation of different glass compositions for their radiation shield competence [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52].

In order to study luminescence parameters such as stimulated emission cross section and branching ratios, five glass samples having the composition 47.5P₂O₅+45ZnO+(5-x)Bi₂O₃+2.5TeO₂+xSm₂O₃ (where x = 0, 0.01, 0.1, 0.3, 0.5 and 1 mol%) were prepared and found that color vanishes with a minimal amount of Sm₂O₃ [23]. These prepared glasses are coded as 0PZBTS, 1PZBTS, 2PZBTS, 3PZBTS, 4PZBTS, and 5PZBTS. Among these glasses, 0PZBTS was found to be pinkish, and the other glasses were transparent. The molar densities of the prepared glasses were determined by the Archimedes principle and they are given in Table 1. In the present investigations, the motivation is to understand effect of Sm₂O₃ on gamma ray shielding parameters (GSPs) of PZBTS glasses. The Sm₂O₃ doped glasses have high quantum efficiency, high corrosion resistance, low phonon energy and wide transmittance window in UV and near IR region and hence these glasses can be used as shielding materials in nuclear reactors and nuclear technology. The chosen glass system in the present investigations is made up of 47.5P₂O₅+45ZnO+(5-x)Bi₂O₃+2.5TeO₂+xSm₂O₃, where x = 0, 0.01, 0.1, 0.3, 0.5, and 1 mol%. The gamma-ray shielding parameters (GSPs) were determined by using Phy-X/PSD [53] software for the 0PZBTS to 5PZBTS glass samples, which have densities ranging from 3.02 g/cm³ to 3.7 g/cm³. The gamma ray shielding parameters for this type of glass have been calculated for the first time with the best knowledge of the author.

2. Theoretical background

The gamma radiation incident on the shielding material, it may be scattered and absorbed. Photoelectric (PE) and pair production (PP) processes are responsible for absorption, while Compton scattering is responsible for the scattering of gamma radiation. The mass attenuation coefficient measures the strength of interaction of gamma photons with the material medium and hence it depends on the energy of the gamma photon, the atomic number of the target material and the type of geometry involved in the measurements. In narrow beam geometry and for thin targets, only the transmitted gamma photons passing through the target are measured, and they follow the Beer-Lamberts’ law. But in practice, because of the broad beam geometry and involvement of thick targets used in the experiment, the scattered gamma photons as well as secondary radiation from the target would also contribute to the measured transmitted photons. Therefore, the Beer-Lamberts’ law must be modified with the inclusion of the Compton scattered gamma photons and secondary radiation from the target. The buildup factor is a correction factor that accounts for the contribution of Compton scattered gamma photons plus secondary particles in the medium. The buildup factor depends on the atomic number and thickness of the shielding material, the energy of the gamma photon and the geometry of the experimental configuration. The buildup factors are determined experimentally by using different gamma sources. However, due to the non-availability of gamma sources of various energies, the buildup factor is calculated theoretically by solving the photon transport equation using attenuation coefficients and cross section data of elements, compounds, and mixtures. The buildup factors are classified as exposure buildup factor (EBF) and energy absorption buildup factor (EABF). In the EBF, the quantity of interest is the exposure, and the detector response function is that of absorption in air. However, the EABF deposits energy in the target material and the detector function is that of absorption in the interacting material.

2.1. Mass attenuation coefficient

The mass attenuation coefficient is the probability of interaction of gamma photons through photoelectric effects, Compton scattering, and pair production processes per unit density thickness. Therefore, it depends on the type of shielding materials, energy of gamma photons and the geometry adopted in investigations. When a beam of gamma photons is attenuated on the shielding material, it follows Beer-Lamberts’ law and calculated using Eq. (1) [3].

\[ I = I_0 e^{-\mu t} \]  

where I and I₀ are the transmitted and incident intensities, respectively, \( \mu \) (cm⁻¹) represents the linear attenuation coefficient, and t (cm) is the thickness of the target material. The linear attenuation coefficient (LAC) is calculated using Eq. (2).

\[ \mu = \frac{1}{t} \ln \frac{I}{I_0} \]  

The mass attenuation coefficient (MAC) measures the interaction of incident photons with the target material and calculated using Eq. (3) [54, 55].

\[ MAC = \frac{LAC}{\rho} = \frac{\mu}{\rho} \]  

Table 1. Lists of the sample code, chemical composition, density, and thickness of PZBTS glass samples.

| Sample Code | Chemical Composition | Density (g/cm³) | Thickness (mm) |
|-------------|----------------------|----------------|---------------|
|             | P₂O₅ | ZnO | Bi₂O₃ | TeO₂ | Sm₂O₃ |             |               |
| 0PZBTS      | 47.50 | 45.00 | 5.00 | 2.50 | 0.00 | 3.02   | 2.07 |
| 1PZBTS      | 47.50 | 45.00 | 4.99 | 2.50 | 0.01 | 3.08   | 2.08 |
| 2PZBTS      | 47.50 | 45.00 | 4.90 | 2.50 | 0.10 | 3.20   | 1.84 |
| 3PZBTS      | 47.50 | 45.00 | 4.7  | 2.50 | 0.30 | 3.30   | 2.07 |
| 4PZBTS      | 47.50 | 45.00 | 4.5  | 2.50 | 0.50 | 3.40   | 2.06 |
| 5PZBTS      | 47.50 | 45.00 | 4.0  | 2.50 | 1.00 | 3.70   | 1.95 |
\[
\frac{\mu}{\rho} = \sum_i w_i \left( \frac{\mu_i}{\rho_i} \right)
\]  \hspace{1cm} (4)

where \(w_i\) is the weight fraction and \((\mu/\rho)_i\) is the mass attenuation coefficient of the \(i\)th constituent element from Eq. (4). The weight fraction \(w_i\) is shown in Eq. (5)

\[
w_i = \frac{n_i A_i}{\sum_i n_i A_i}
\]  \hspace{1cm} (5)

where \(n_i\) is the number of the atoms in the \(i\)th constitutional element in the compound, and \(A_i\) is the atomic weight of the \(i\)th element. The mass attenuation coefficient of compounds was obtained from Phy-X/PSD [53]. The software calculates 18 different shielding parameters for materials using information on density and weight fractions of the compounds present in the target material. It provides the mass attenuation coefficient of elements and compounds for gamma photon energies of 0.015 MeV–15 MeV at penetration depths of 1–40 mean free path (MFP). Users can save the evaluated shielding parameters in an MS excel file. For the calculation of gamma radiation shielding parameters such as mass attenuation coefficient (MAC), effective atomic number (Z\(\text{eff}\)), equivalent atomic number (Z\(\text{eq}\)), exposure buildup factor (EBF), and energy absorption buildup factor (EABF) for the bismuth phospho-tellurite glasses containing P\(_2\)O\(_5\), ZnO, Bi\(_2\)O\(_3\), TeO\(_2\), and Sm\(_2\)O\(_3\) compounds, the Phy-X/PSD software is used [53].

2.2. Half value layer, tenth value layer and mean free path

The half value layer (HVL) and tenth value layer (TVL) parameters explain both the penetrating ability of the radiation and the probability of penetration through specific objects or targets. The concept of HVL and TVL is helpful in shielding design. HVL refers to the thickness of the material needed to weaken the incident radiation to half of its initial value. In other words, it attenuates the photon intensity by 50% of its initial value at different photon energies. Further, the TVL refers to the thickness of an absorber or a shield that attenuates the radiation level by one-tenth of the initial level [56]. Mean free path (MFP) is a parameter for distinguishing a material’s ability to transmit photons. HVL, TVL, and MFP were calculated based on the value of LAC using Eqs. 6, 7, and 8.

\[
\text{HVL} = \frac{\ln(2)}{\mu}
\]  \hspace{1cm} (6)

\[
\text{TVL} = \frac{\ln(10)}{\mu}
\]  \hspace{1cm} (7)

\[
\text{MFP} = \frac{1}{\mu}
\]  \hspace{1cm} (8)

where \(\mu\) is linear attenuation coefficient (LAC).

2.3. Effective atomic number

The effective atomic number is defined as the ratio of the effective atomic cross section \(\sigma_e\) (cm\(^2\)/atom) to the effective electronic cross section \(\sigma_a\) (cm\(^2\)/atom) and it is shown in Eq. (9) [57]

\[
Z_{\text{eff}} = \frac{\sigma_e}{\sigma_a}
\]  \hspace{1cm} (9)

The \(\sigma_a\) and \(\sigma_e\) are shown in Eqs. (10) and (11)

\[
\sigma_a = \frac{1}{N_A} \sum_i f_i A_i \left( \frac{\mu}{\rho_i} \right)
\]  \hspace{1cm} (10)

\[
\sigma_e = \frac{1}{N_A} \sum_i f_i A_i \left( \frac{\mu}{\rho_i} \right)
\]  \hspace{1cm} (11)

where \(f_i\) refers to the fraction abundance of the \(i\)th element with respect to the number of atoms, \(N_A\) is the Avogadro number and \(Z_i\) is the atomic number of the \(i\)th constituent element.

2.4. Equivalent atomic number

\(Z_{\text{eq}}\) is one of the GSPs, which describes the glass properties of equivalent elements similar to the atomic number of a single element. \(Z_{\text{eq}}\) is one of the GSPs to understand buildup phenomena via Compton scattering. The \(Z_{\text{eq}}\) shown in Eq. (12),

\[
Z_{\text{eq}} = \frac{Z_1 (\log R_2 - \log R_1) + Z_2 (\log R - \log R_1)}{\log R_2 - \log R_1}
\]  \hspace{1cm} (12)

where \(Z_1\) and \(Z_2\) are the atomic numbers corresponding to the ratios \(R_1\) and \(R_2\) respectively [3, 58] and the ratio \(R = (\mu/\rho)_{\text{Computed}} / (\mu/\rho)_{\text{Total}}\) at a particular energy.

The GP fitting parameters (b, c, a, X\(_0\), d) are calculated in the similar way as interpolation procedure used for the \(Z_{\text{eq}}\) and it is shown in Eq. (13),

\[
C = C_1 (\log Z_2 - \log Z_{\text{eq}}) + C_2 (\log Z_{\text{eq}} - \log Z_1)
\]  \hspace{1cm} (13)

where \(C_1\) and \(C_2\) are the values of the GP fitting parameters analogous to the atomic numbers \(Z_1\) and \(Z_2\) respectively at a given energy.

2.5. Buildup factors

The exposure buildup factor, energy absorption buildup factor, and geometric progression (GP) fitting parameters of the selected glass samples were determined by using the GP fitting formula (ANSI/ANS-6.4.3–1991) [59]. Buildup factor calculations are done by applying the GP fitting formula to an infinite homogeneous medium with an optical thickness range of 0.5–40 MFP (source to detector distance) and an energy range of 0.015–15 MeV [60]. The buildup factor is important for calculating absorbed dose, radiation shielding, and protection. For broad beam geometry, the intensity of transmitted photons is given in Eq. (14)

\[
I = B I_0 e^{-\mu x}
\]  \hspace{1cm} (14)

where \(B\) is the buildup factor and buildup factors are estimated by using the GP fitting formula at a particular energy.

\[
B(E, x) = 1 + \frac{b}{K - 1} (K - 1) \text{ for } K \neq 1
\]  \hspace{1cm} (15)

\[
B(E, x) = 1 + (b - 1) x \text{ for } K = 1
\]  \hspace{1cm} (16)

The GP fitting parameters were determined using Eq. (13) to evaluate EBF and EABF for a shielding target at penetration depths up to 40 MFP. The function \(K(E, x)\) represents the photon dose multiplication factor, which can be calculated by using the following Eq. (17).

\[
K(E, x) = C_1 x^d + d \frac{\tanh \left( \frac{x}{2} - 2 \right) - \tanh(-2)}{1 - \tanh(-2)} \text{ for } x \leq 40 \text{ MFP}
\]  \hspace{1cm} (17)
3. Results and discussion

3.1. Mass attenuation coefficient

A mass attenuation coefficient (MAC) versus photon energy has been plotted for the above glass system in which \( x \) was varied from 0, 0.01, 0.1, 0.3, 0.5, and 1, and they are shown in Figure 1 (a)-(b) along with the 3D plot. The figure shows that the MAC decreases as photon energy increases; at low photon energy regions (100 keV), the photo absorption process dominates. In the same energy region, a jump is observed, which is essentially due to the absorption of gamma photons by K shell electrons of the Bi element (90.5 keV). As photon energy increases, Compton scattering becomes more dominant. At energies above 1 MeV, the pair production process is dominant, and in this process, pair of electrons and positrons are produced. The figure also shows that the addition of \( \text{Sm}_2\text{O}_3 \) to the glass materials does not have much effect on MAC.

3.2. Half value layer and tenth value layer

The HVL and TVL values for all PZBTS glasses were calculated using Phy-X/PSD software, and they are given in Figure 2 (a)-(b) along with 3D plots. From the figures, it is noticed that HVL and TVL are almost constant in the low energy region and then increase with an increase in the energy of gamma photons up to 10 MeV. Above 10 MeV, it decreases slowly. The figures also indicate that the HVL and TVL values decrease with an increase in the concentration of \( \text{Sm}_2\text{O}_3 \) at a higher energy of gamma photons (see Figure 3 (a)-(b)).

![Figure 1](image1.png)  
Figure 1. (a)-(b) 2D and 3D plots of the PZBTS glass system's mass attenuation coefficient (MAC) as a function of photon energy and mole percent \( \text{Sm}_2\text{O}_3 \).

![Figure 2](image2.png)  
Figure 2. (a)-(b) Plots of the half value layer (HVL) of PZBTS glasses in 2D and 3D as a function of gammaphoton energy and \( \text{Sm}_2\text{O}_3 \) concentration.
3.3. Mean free path

Figure 4 shows the variation of the mean free path as a function of photon energy for the PZBTS glass samples. The current PZBTS glasses are compared with recently studied materials, such as MASLN [61], PSS5 [62], Pb–Al [63], Ca/Pb-BBC1 [64] and LTM-A [65]. Among the PZBTS glasses, the lower values of mean free path are observed for 5PZBTS. From the figure, it is observed that PZBTS glass shows higher values of mean free path compared to Ca/Pb-BBC1, LTM-A, PSS5 and PbAl-4. And PZBTS glasses show lower values of mean free path compared to MASLN glasses.

3.4. Effective atomic number and equivalent atomic number

The 3D and 2D plots of $Z_{\text{eff}}$ as a function of energy and mole% of Sm$_2$O$_3$ for the selected glass materials are shown in Figure 5 (a)-(b).
Figure 5 (a)–(b) shows that $Z_{\text{eff}}$ is more for 0PZBTS than for 5PZBTS in the energy region of 0.02–0.05 MeV. In the higher energy region, the $Z_{\text{eff}}$ values decrease with an increase in the energy of photons up to 15 MeV and are independent of the concentration of Sm$_2$O$_3$. The peak or jump is observed due to the K edge energy of the Bi (90.5 keV) element present in all the samples.

The 3D and 2D plots of Zeq as a function of energy and concentration of Sm$_2$O$_3$ for the selected glass materials are shown in Figure 6 (a)-(b). The Zeq value for selected glass was found to be low in both the low energy (less than 0.1 MeV) and high energy (3 MeV) regions. Zeq values are found to be higher in the intermediate energy region of 0.1–1 MeV. This indicates that in the low energy region, the photo absorption effect and in the high energy region, the pair production process play significant role and the photoelectric effect is proportional to $Z^{4.5}$ and $1/E^{3.5}$ and the pair production is proportional to $Z^2$ and log E. The results show that the Compton scattering is significant in the medium energy region, $Z_{\text{eq}}$, which is mainly due to the Compton scattering process. Zeq is more significant for 0PZBTS due to the percentage of Bi in 0PZBTS being higher than in other PZBTS samples.

3.5. Exposure buildup factor and energy absorption buildup factor

The 3D and 2D plots of EBF and EABF for selected glass materials in the photon energy range of 0.015–15 MeV are shown in Figures 7i (a)-(b), 7ii (a)-(f), 8i (a)-(b) and 8ii (a)-(f). Figure 7i (a)-(b) and 8i (a)-(b) show that EBF and EABF values gradually increase with an increase in the energy of photons up to 1 MeV, then decrease slowly with an increase in the energy of photons. This shows that in the low energy region as well as the high energy region, the values of EBF and EABF are low enough to indicate that most of the low energy gamma photons and high energy gamma photons would undergo the photo absorption process and pair production process, respectively. However, in the medium energy region, the values of EBF and EABF are found to be higher, indicates that Compton scattering is the predominant process in this energy region.
Figure 7. i (a)–(b) Variation in the EBF values of PZBTS glasses (at 1MFP) as a function of photon energy and Sm$_2$O$_3$ concentration in 2D and 3D plots. ii (a)–(f) Plots show PZBTS glasses’ exposure building factor (EBF) values as a function of photon energy at various penetration depths (1, 5, 10, 25, 40 MFP).

Figure 8. i (a)–(b) Energy absorption buildup factor (EABF) of PZBTS glasses (at 1 MFP) as a function of photon energy and Sm$_2$O$_3$ concentration in 2D and 3D plots. ii (a)–(f) Plots of energy absorption buildup factor (EABF) of PZBTS glasses as a function of photon energy and concentration of Sm$_2$O$_3$ at selected penetration depths (1, 5, 10, 25, 40 MFP).
the medium energy region, the EBF and EABF depend on the concentration of Sm$_2$O$_3$. The 1 mol% concentration of Sm$_2$O$_3$ in the PZBTS glass shows higher EBF values in the intermediate energy region. The calculated EBF and EABF values have been plotted in figures 7ii (a)-(f) and 8ii (a)-(f) as functions of energy at various penetration depth for selected glass materials. The EBF and EABF increases with an increase in the penetration depth for all glass materials. This is essential due to the multiple Compton scattering photons produced for higher penetration depth.

4. Conclusions

The gamma ray shielding parameters for the 47.5P$_2$O$_5$+45ZnO+(5-x)Bi$_2$O$_3$+2.5TeO$_2$+xSm$_2$O$_3$ (where x = 0, 0.01, 0.1, 0.3, 0.5 and 1 mol %) glass system have been studied using Phy-X/PSD software. The gamma ray shielding parameters for this type of glass have been calculated for the first time with the best knowledge of the author. The mean free path for present PZBTS glasses are compared with recently studied materials. It is found that EBF and EABF are found to have lower values in the low energy region as well as the high energy region and higher values in the medium energy region. Hence, these materials are good for gamma ray shielding in low energy and high energy regions. However, in the medium energy region, because of multiple Compton scattering, the buildup factor is greater.

5. Impact statement

The gamma ray shielding parameters such as mass attenuation coefficient, effective atomic number, equivalent atomic number, exposure buildup factor and energy absorption buildup factor were determined for 47.5P$_2$O$_5$ + 45ZnO + (5-x)Bi$_2$O$_3$ + 2.5TeO$_2$ + xSm$_2$O$_3$ glass system using Phy-X/PSD software in the energy range from 0.015 to 15 MeV at penetration depth from 1 to 40 MFP. To understand the effect of Sm$_2$O$_3$ on gamma ray shielding parameters in selected glass system, the Sm$_2$O$_3$ was varied in the glass from 0.01 to 1 mol%. The high density, high effective atomic number and transparent to visible light of selected materials indicate that they can be used as shielding materials in nuclear reactors and nuclear technology.

Declarations

Author contribution statement

Dr Sangeet B Kolavekar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Dr G B Hiremath; Dr N M Badiger; Dr N H Ayachit: Analyzed and interpreted the data; Wrote the paper.
Dr P N Patil: Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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