

RESEARCH ARTICLE

Photon Attenuation Characteristics of BaTiO₃–Modified V₂O₅–Bi₂O₃ Glasses

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ABSTRACT: Four glass compositions within the V₂O₅–Bi₂O₃–BaTiO₃ system were investigated for their photon-shielding capabilities across an energy spectrum of 0.015 to 20 MeV. The Bi₂O₃ content was held at 20 mol% throughout the series, while BaTiO₃ was systematically increased from 2.5 to 10.0 mol%, accompanied by a corresponding reduction in V₂O₅. This compositional adjustment resulted in a density increase from 4.18 to 4.42 g·cm⁻³ and a molar volume decrease from 57.411 to 55.165 cm³·mol⁻¹. The MIKE computational program was employed to determine mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), effective atomic number (Z_{eff}), and effective electron density (N_{eff}). The S4 glass, which contained the highest BaTiO₃ concentration, demonstrated superior LAC values and correspondingly lower HVL, TVL, and MFP across the entire energy range examined. For S4, the LAC values were 248.510, 9.833, 0.285, and 0.170 cm⁻¹ at photon energies of 0.015, 0.10, 1.00, and 20.0 MeV, respectively. The enhanced attenuation performance of S4 arises from its greater density, which is further complemented by increased Z_{eff} and N_{eff} values that strengthen photon-interaction probability. Based on attenuation per unit thickness, S4 emerges as the most effective glass composition in this series for radiation-shielding applications.

Keywords: V₂O₅–Bi₂O₃–BaTiO₃ Glass; Photon Attenuation; Radiation Shielding; Mass Attenuation Coefficient; Half-Value Layer; Effective Atomic Number

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1. INTRODUCTION

Radiation shielding is a central concern in nuclear power, medical imaging, radiotherapy, and space technology. The search for materials that can reduce ionizing radiation while remaining chemically stable, easy to shape, and optically clear has led to growing interest in heavy-metal oxide glasses [1, 2]. These glasses offer advantages over traditional concrete and lead shields because their composition can be adjusted to achieve high attenuation without the opacity or toxicity associated with some conventional materials. The

shielding efficiency of a glass depends on its elemental makeup, density, thickness, and the energy of the incoming photons [3, 4]. At low photon energies, photoelectric absorption dominates, and glasses containing high-atomic-number elements show a strong probability of interaction [3, 4]. As energy increases, Compton scattering and pair production become more important, so both electron density and atomic number influence performance. Designing an effective shield therefore requires a careful balance between heavy elements and network formers that can accommodate them without disrupting the glass structure.

The V₂O₅–Bi₂O₃–BaTiO₃ system is attractive because it combines bismuth, a heavy element with strong low-energy absorption, with a vanadate network that can be modified by barium titanate [5–7]. Bismuth oxide is known for its high photon attenuation, especially where the photoelectric effect is dominant. Vanadium pentoxide acts as a glass former, while barium titanate introduces barium and titanium that

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alter density, molar volume, and network packing [5-7]. Earlier work on bismuth-containing glasses has shown that increasing heavy-metal oxide content often improves shielding, but the specific effect of replacing V₂O₅ with BaTiO₃ while holding Bi₂O₃ constant has not been systematically examined over a broad energy range. Related studies on Bi₂O₃-CaO-K₂O-Na₂O-P₂O₅ and PbO-TeO₂-Bi₂O₃-MgO-B₂O₃ glasses have provided useful comparisons, yet they do not isolate the role of BaTiO₃ in a bismuth-vanadate network [8, 9]. This gap motivates the present investigation.

Computational tools have become important for predicting radiation-shielding parameters without extensive experimental work. The MIKE program is one such tool and has been used to calculate mass attenuation coefficients, linear attenuation coefficients, half-value layers, tenth-value layers, mean free paths, effective atomic numbers, and effective electron densities for various glass compositions [10, 11]. The reliability of any computational code depends on validation against established databases and experimental data. The XCOM database from NIST provides benchmark mass attenuation coefficients, and comparisons with such databases help confirm the accuracy of calculated values [12, 13]. Studies that compare photon attenuation software have also stressed the need for validation, especially for multicomponent systems where interpolation and mixture rules can introduce uncertainties [13]. In this work, MIKE was selected because it accepts basic compositional and density inputs and returns a wide set of shielding parameters quickly. The thickness-related parameters, including half-value layer, tenth-value layer, and mean free path, are particularly useful because they translate attenuation coefficients into practical thickness requirements [4, 14]. These parameters are inversely related to the linear attenuation coefficient, so a composition with higher density and higher linear attenuation will require less material to achieve a given reduction in intensity.

The novelty of this study lies in the systematic design of the glass series. Bi₂O₃ is fixed at 20 mol% in all four compositions, while BaTiO₃ increases from 2.5 to 10.0 mol% and V₂O₅ decreases from 77.5 to 70.0 mol%. This approach isolates the influence of BaTiO₃ on density, molar volume, oxygen packing density, and photon-shielding behavior without changing the bismuth content. Although bismuth-vanadate glasses and barium titanate-modified glasses have been studied separately, the specific V₂O₅-Bi₂O₃-BaTiO₃

combination in this compositional range has not been reported for photon attenuation from 0.015 to 20 MeV. The work also connects physical parameters with shielding performance. Density and molar volume trends indicate how compact the glass network becomes as BaTiO₃ increases [15, 6]. Such structural information is important because mass attenuation coefficient alone can show small crossovers at intermediate energies, whereas linear attenuation coefficient includes density and gives a clearer picture of practical shielding. By combining physical characterization with computational shielding analysis, this study provides a more complete understanding of how BaTiO₃ enrichment affects the ability of these glasses to attenuate photons.

In this paper, we report the photon-shielding characteristics of four V₂O₅-Bi₂O₃-BaTiO₃ glasses with increasing BaTiO₃ content. The density and molar volume were determined, and the MIKE program was used to compute mass attenuation coefficient, linear attenuation coefficient, half-value layer, tenth-value layer, mean free path, effective atomic number, and effective electron density over the energy range 0.015-20 MeV. The results show that as BaTiO₃ increases, the glass network becomes more compact, density rises, and molar volume falls. The S4 composition, containing 10.0 mol% BaTiO₃, exhibits the highest linear attenuation coefficient and the lowest half-value layer, tenth-value layer, and mean free path across the entire energy range. This behavior is attributed to its higher density and enhanced effective atomic number and electron density. The findings indicate that S4 is the most effective glass in this series for applications requiring efficient photon attenuation with minimal thickness, and they highlight the importance of considering density-related parameters when evaluating shielding materials.

2. EXPERIMENTAL DETAILS

2.1. Glass compositions and physical parameters

Different combinations of V₂O₅, Bi₂O₃, and BaTiO₃ were the investigated system consists of four V₂O₅-Bi₂O₃-BaTiO₃ glass compositions, designated S1-S4. Bi₂O₃ was fixed at 20 mol% in all compositions to retain a constant concentration of the high-atomic-number bismuth component [7, 9, 10].

Table 1. The compositions and physical parameters of V₂O₅-Bi₂O₃-BaTiO₃.

Sample	V ₂ O ₅ (mol%)	Bi ₂ O ₃ (mol%)	BaTiO ₃ (mol%)	Density (g·cm ⁻³)	Molecular weight (g·mol ⁻¹)	Molar volume (cm ³ ·mol ⁻¹)	Oxygen packing density (mol·L ⁻¹)
S1	77.5	20.0	2.5	4.18	239.978	57.411	79.253
S2	75.0	20.0	5.0	4.26	241.261	56.634	79.458
S3	72.5	20.0	7.5	4.34	242.544	55.886	79.627
S4	70.0	20.0	10.0	4.42	243.827	55.165	79.761

BaTiO₃ was increased systematically from 2.5 mol% in S1 to 10.0 mol% in S4, while the V₂O₅ content was reduced from 77.5 to 70.0 mol%. This design permits the influence of BaTiO₃ enrichment on the physical and photon-shielding properties to be evaluated without changing the Bi₂O₃ concentration. The density values used for S1, S2, S3, and S4 were 4.18, 4.26, 4.34, and 4.42 g·cm⁻³, respectively. The corresponding molecular weights increased from 239.978 to 243.827 g·mol⁻¹. In contrast, molar volume decreased from 57.411 cm³·mol⁻¹ for S1 to 55.165 cm³·mol⁻¹ for S4. Oxygen packing density increased gradually from 79.253 to 79.761 mol·L⁻¹. These physical parameters are summarized in Table 1 and were used in the photon shielding.

2.2. Photon-shielding calculations

The photon-shielding parameters were calculated over the energy range 0.015–20 MeV with the MIKE program [1]. MIKE was used as the computational tool to obtain the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), effective atomic number (Z_{eff}), and effective electron density (N_{eff}). The calculations use the chemical composition and density of each glass as input parameters. For a multicomponent glass, the mass attenuation coefficient was calculated using the mixture rule [2, 3]:

$$\left(\frac{\mu}{\rho}\right)_m = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (1)$$

where w_i is the weight fraction of the i -th constituent and $(\mu/\rho)_i$ is its mass attenuation coefficient. The linear attenuation coefficient was then obtained by multiplying MAC by the glass density. This distinction is important because MAC represents attenuation per unit mass, whereas LAC represents attenuation per unit thickness and therefore reflects the effect of density directly. The thickness-related shielding parameters were calculated from LAC according to [4, 12]:

$$\mu = \rho \left(\frac{\mu}{\rho}\right) \quad (2)$$

$$MFP = \frac{1}{\mu} \quad (3)$$

$$HVL = \frac{\ln 2}{\mu} \quad (4)$$

$$TVL = \frac{\ln 10}{\mu} \quad (5)$$

HVL is the thickness required to reduce the intensity of a narrow photon beam to one-half of its initial value, whereas TVL is the thickness required to reduce it to one-tenth. MFP represents the average distance traveled by a photon between successive interactions. Lower HVL, TVL, and MFP values therefore indicate more effective attenuation per unit

thickness.

3. RESULTS AND DISCUSSION

3.1. Effect of composition on physical parameters

The gradual substitution of V₂O₅ with BaTiO₃ brought about notable changes in the physical properties of the glasses. As the BaTiO₃ content increased from 2.5 to 10.0 mol%, the density rose from 4.18 to 4.42 g·cm⁻³, which represents a 5.74% increase. At the same time, the molar volume decreased from 57.411 to 55.165 cm³·mol⁻¹, a drop of 3.91%, and the oxygen packing density increased from 79.253 to 79.761 mol·L⁻¹. These trends point to a more compact glass network as BaTiO₃ concentration increases [8,11,15]. The rise in density is especially relevant for photon shielding because the linear attenuation coefficient is directly proportional to density [1,4,10]. For a given mass attenuation coefficient, a denser glass contains more atoms per unit volume, which leads to greater attenuation over the same thickness. This gives S4 a clear advantage over the other compositions. The decrease in molar volume reinforces this interpretation, as a lower molar volume means that one mole of glass occupies less space, consistent with tighter structural packing. While techniques such as Raman or infrared spectroscopy would be needed to identify specific structural changes, the density, molar volume, and oxygen packing density data consistently show that S4 is the most compact glass in this series [8,11]. The steady increase in oxygen packing density also suggests that the network is becoming more efficiently arranged, not just heavier. This structural compaction provides the physical foundation for the improved attenuation per unit thickness that will be discussed in the following sections.

3.2. Mass and linear attenuation coefficients

The mass attenuation coefficient (MAC) values drop significantly as photon energy increases from 0.015 MeV to the MeV region. In the low-energy range, photoelectric absorption is the dominant interaction, and its probability depends strongly on the atomic number of the elements present [3,4]. Since all glasses contain 20 mol% Bi₂O₃, bismuth plays a major role in the high attenuation observed at low energies. A distinct feature appears near 0.10 MeV, close to the bismuth K absorption edge at roughly 90.5 keV. At this edge, the photon energy becomes sufficient to eject an electron from an inner shell, causing a rapid change in interaction probability. The feature near 0.10 MeV is therefore consistent with the expected behavior of these bismuth-containing glasses. At 0.015 MeV, the MAC increases from 55.1518 cm²·g⁻¹ for S1 to 56.2240 cm²·g⁻¹ for S4. At intermediate energies, small crossovers appear.

Table 2. Representative mass and linear attenuation coefficients for S1 and S4, along with the percentage improvement in LAC for S4 relative to S1.

Energy (MeV)	MAC, S1 (cm ² ·g ⁻¹)	MAC, S4 (cm ² ·g ⁻¹)	LAC, S1 (cm ⁻¹)	LAC, S4 (cm ⁻¹)	LAC improvement of S4 over S1 (%)
0.015	55.1518	56.2240	230.535	248.510	7.80
0.10	2.17284	2.22472	9.08246	9.83325	8.27
1.00	0.064646	0.064501	0.270219	0.285095	5.50
10.0	0.033564	0.034079	0.140296	0.150629	7.37
20.0	0.037540	0.038361	0.156916	0.169554	8.05

For instance, at 1.00 MeV the MAC of S1 is 0.064646 cm²·g⁻¹, which is slightly higher than the 0.064501 cm²·g⁻¹ value for S4. This reversal indicates that MAC alone does not fully capture shielding performance. The linear attenuation coefficient (LAC), however, follows the order S4 > S3 > S2 > S1 across the entire energy range. Because LAC includes density through the relation $\mu = \rho(\mu/\rho)$ [1,4,10], the density increase from S1 to S4 more than compensates for the small MAC crossovers. As a result, S4 provides the greatest attenuation per unit thickness at every energy examined [8, 16]. Table 2 shows that at 0.10 MeV, the LAC of S4 is 9.833 cm⁻¹ compared with 9.082 cm⁻¹ for S1, an improvement of 8.27%. At 1.00 MeV, S4 retains a 5.50% advantage in LAC. At 20.0 MeV, the advantage is 8.05%. These values confirm that BaTiO₃ enrichment improves thickness-dependent attenuation in both the low- and high-energy regions.

Figure 1 depicts the LAC as a function of photon energy. The curves show a consistent separation, with S4 lying above the other compositions across the entire energy range. This separation reflects the combined effect of density and composition on LAC. Even where the MAC values cross, the curve for S4 remains the highest, which reinforces the importance of density in practical shielding.

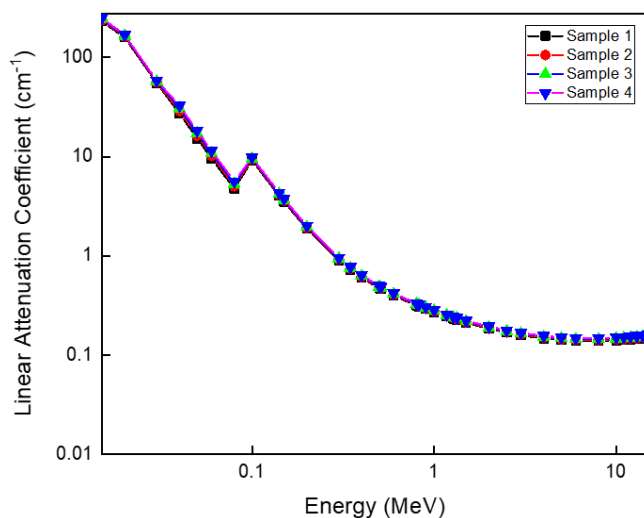
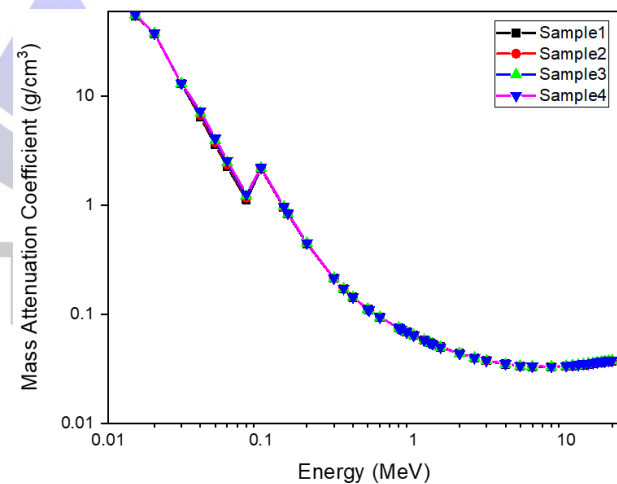
**Fig. 1.** Linear attenuation coefficient as a function of photon energy for the studied glasses.

Figure 2 depicts the MAC as a function of photon energy. The figure illustrates the steep decrease in MAC from low to intermediate energies, the influence of the Bi K edge near 0.10 MeV, and the small crossovers at intermediate energies. These crossovers explain why LAC, rather than MAC alone, is more suitable for comparing thickness-dependent shielding performance. The low-energy region is dominated by photoelectric absorption, while Compton scattering becomes more important at intermediate energies. At higher energies, the MAC values become relatively small and change more slowly with energy.

**Fig. 2.** Mass attenuation coefficient as a function of photon energy for the studied glasses.

3.3. Shielding thickness parameters

The half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP) are inversely related to LAC. Consequently, S4, which has the highest LAC, also has the lowest HVL, TVL, and MFP over the calculated energy range. These parameters are practical because they translate attenuation coefficients into the thickness needed to reduce photon intensity by a specified amount [4,12]. At 0.015 MeV, the required thickness is very small because LAC values are high.

Table 3. Representative half-value layer, tenth-value layer, and mean free path values for S1 and S4 at selected photon energies.

Energy (MeV)	HVL, S1 (cm ⁻¹)	HVL, S4 (cm ⁻¹)	TVL, S1 (cm)	TVL, S4 (cm)	MFP, S1 (cm ⁻¹)	MFP, S4 (cm ⁻¹)
0.015	0.00301	0.00279	0.00998	0.00926	0.00434	0.00402
0.10	0.07630	0.07048	0.25324	0.23390	0.11010	0.10170
1.00	2.56458	2.43077	8.51160	8.06749	3.70070	3.50760
10.0	4.93957	4.60070	16.39395	15.26928	7.12780	6.63882
20.0	4.41638	4.08718	14.65753	13.56497	6.37284	5.89781

The S4 has an HVL of 0.00279 cm and a TVL of 0.00926 cm, while S1 has values of 0.00301 cm and 0.00998 cm, respectively. As photon energy increases, attenuation weakens and the required thickness grows. At 0.10 MeV, the HVL decreases from 0.07630 cm for S1 to 0.07048 cm for S4, and the TVL falls from 0.25324 cm to 0.23390 cm. At 1.00 MeV, the HVL decreases from 2.565 cm for S1 to 2.431 cm for S4. The TVL falls from 8.512 cm for S1 to 8.067 cm for S4. The MFP drops from 3.701 to 3.508 cm. The lower values for S4 mean that the same attenuation can be achieved with less material. The advantage persists at high energy. At 20.0 MeV, the HVL values are 4.416 cm for S1 and 4.087 cm for S4, while the TVL values are 14.658 and 13.565 cm, respectively. This continued difference shows that the higher-density S4 glass remains the most effective composition across the studied energy interval [8,9,16].

Table 3 provides a direct comparison of thickness requirements and shows that S4 consistently requires less material than S1 to achieve the same reduction in photon intensity. The trend in Table 3 mirrors the LAC results, since every thickness parameter is inversely proportional to the linear attenuation coefficient.

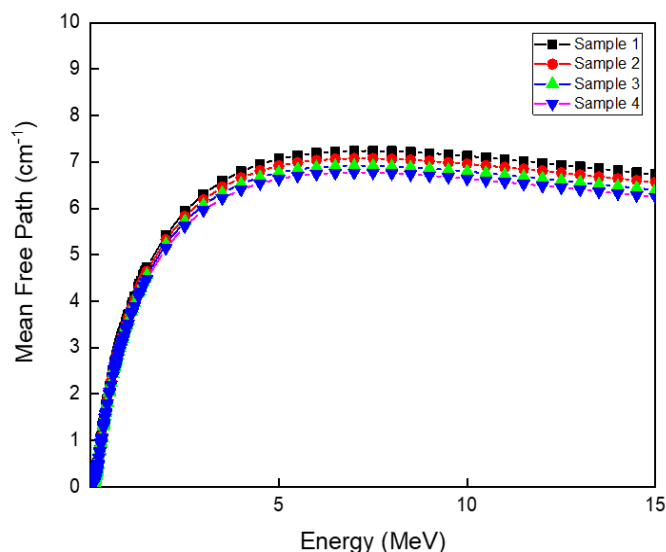
**Fig. 3.** Mean free path as a function of photon energy for the studied glasses.

Figure 3 depicts the MFP as a function of photon energy. The figure shows that S4 has the shortest mean free path at all energies, indicating that photons travel a shorter average distance between interactions in this glass. The MFP increases with energy up to about 10 MeV and then decreases slightly at 20 MeV, following the same shape as the inverse LAC.

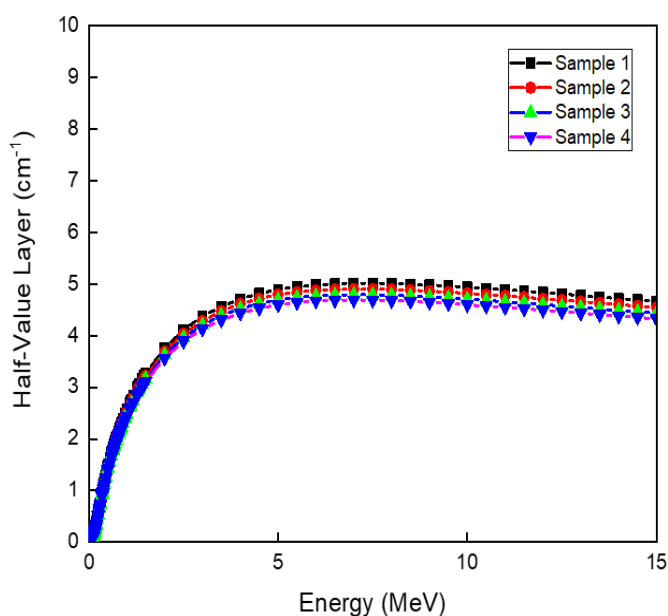
**Fig. 4.** Half-value layer as a function of photon energy for the studied glasses.

Figure 4 depicts the HVL as a function of photon energy. The figure demonstrates that S4 requires the smallest thickness to reduce the photon intensity to one-half of its initial value. The HVL rises sharply between 0.10 and 1.00 MeV and then changes more gradually at higher energies.

Figure 5 depicts the TVL as a function of photon energy. The figure confirms that the thickness needed to reduce intensity to one-tenth is also lowest for S4, consistent with its higher LAC. The TVL values are larger than the HVL values by a factor of about 3.32, as expected from the logarithmic definitions of the two parameters.

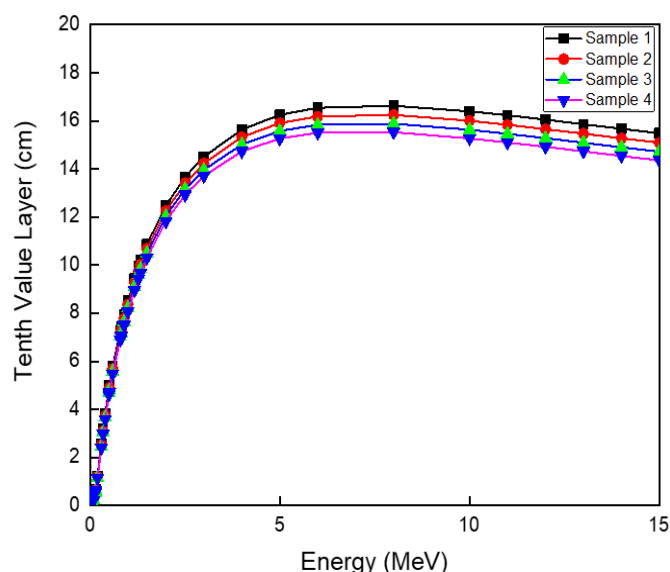


Fig. 5. Tenth-value layer as a function of photon energy for the studied glasses.

3.4 Effective atomic number and electron density

For both S1 and S4, the effective atomic number (Z_{eff}) reaches a peak near 0.10 MeV, with values of 62.625 for S1 and 62.839 for S4. This peak reflects the strong role of bismuth in low-energy photon interactions [3,5]. In the intermediate-energy region, Z_{eff} decreases because Compton scattering becomes more important and the dependence on atomic number weakens. At high energies, Z_{eff} rises again as pair production begins to contribute more strongly [4,5]. Over the computed energy range, S4 has the highest Z_{eff} and effective electron density (N_{eff}). At 0.015 MeV, N_{eff} is 2.420×10^{23} electrons·g⁻¹ for S1 and 2.515×10^{23} electrons·g⁻¹ for S4. The larger electron density of S4 increases the probability of photon interaction and is consistent with its higher LAC and lower thickness requirements [5,16]. The improvement in Z_{eff} is modest but systematic, and it works together with the density increase to enhance attenuation. This combination explains why S4 performs better than the other glasses even at energies where the MAC values are similar.

Figure 6 depicts the Z_{eff} and N_{eff} as functions of photon energy. The figure shows the peak near 0.10 MeV, the dip at intermediate energies, and the increase at high energies, as well as the higher values for S4 across the range. The shape of the Z_{eff} curve follows the competition between photoelectric absorption, Compton scattering, and pair production, while the N_{eff} curve tracks the same trends because electron density is closely linked to the effective atomic number and the glass composition.

The results show that increasing BaTiO₃ at the expense of V₂O₅, while keeping Bi₂O₃ constant, produces a more compact glass network with higher density and lower molar volume. These physical changes lead to higher LAC and

lower HVL, TVL, and MFP for S4. The simultaneous increases in Z_{eff} and N_{eff} further support the conclusion that S4 offers the best photon attenuation per unit thickness in this series. The findings are consistent with earlier work on heavy-metal oxide glasses, where density and effective atomic number were identified as key factors controlling shielding performance [1,4,8,16]. The present study extends those observations to the V₂O₅-Bi₂O₃-BaTiO₃ system and provides a clear compositional route for designing efficient, relatively thin glass shields.

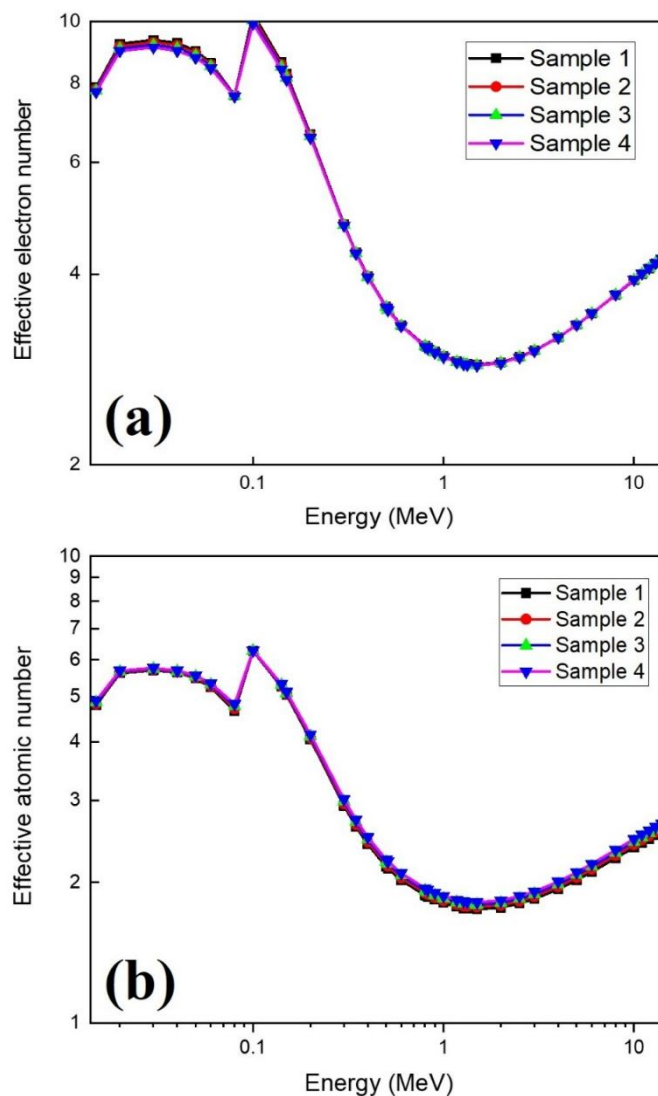


Fig. 6. Effective atomic number and effective electron density as functions of photon energy for the studied glasses.

4. CONCLUSION

The present study demonstrates that the concentration of BaTiO₃ has a pronounced effect on the photon-shielding performance of V₂O₅-Bi₂O₃ glasses. As the BaTiO₃ content increased from 2.5 to 10.0 mol%, the glass structure became

progressively more compact, as evidenced by the decrease in molar volume from 57.411 to 55.165 cm³·mol⁻¹ and the simultaneous increase in density from 4.18 to 4.42 g·cm⁻³. The oxygen packing density also rose from 79.253 to 79.761 mol·L⁻¹, indicating more efficient network arrangement. These physical changes directly influenced the radiation attenuation behavior of the glasses. The S4 composition, which contained the highest BaTiO₃ concentration, exhibited the highest linear attenuation coefficient and the lowest mean free path, half-value layer, and tenth-value layer across the entire energy range from 0.015 to 20 MeV. At 0.10 MeV, the LAC of S4 was 9.833 cm⁻¹ compared with 9.082 cm⁻¹ for S1, representing an 8.27% improvement. Even at 20.0 MeV, S4 maintained an 8.05% advantage in LAC over S1. The superior attenuation per unit thickness of S4 arises from the combined effects of its greater density and enhanced effective atomic number and effective electron density. The higher density means that more interacting atoms are present per unit volume, while the increased Z_{eff} and N_{eff} values reflect a greater probability of photon interaction. The improvement in Z_{eff} was modest but consistent, peaking near 0.10 MeV at 62.839 for S4 compared with 62.625 for S1. Similarly, the N_{eff} at 0.015 MeV increased from 2.420×10^{23} electrons·g⁻¹ for S1 to 2.515×10^{23} electrons·g⁻¹ for S4. These enhancements work together with the density increase to explain why S4 outperforms the other compositions. The mass attenuation coefficient alone showed small crossovers at intermediate energies, but the linear attenuation coefficient, which incorporates density, provided a clearer picture of practical shielding effectiveness. This highlights the importance of considering density-related parameters when evaluating shielding materials. Among all the compositions tested, S4 demonstrated the best photon-shielding performance, making it the most suitable choice for applications that require effective attenuation with minimal shielding thickness. The findings of this study are consistent with earlier work on heavy-metal oxide glasses, where density and effective atomic number were identified as key factors controlling radiation shielding behavior [1, 4, 8, 16]. The V₂O₅-Bi₂O₃-BaTiO₃ glass system therefore offers a promising compositional route for designing efficient, relatively thin shields for gamma-ray and X-ray applications.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

Fawaz Alqahtani: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; Abdulmalik Alahmari: Sample preparation, Experimental Work, Data collection, and interpretation of results. Saud Malawi: Data Curation, Write and Review. Abdullah Alzydan: Data Curation, Write and Review. Amel Omer Abd-alla: Data Curation, Write and Review.

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