

RESEARCH ARTICLE

Thulium Oxide Doped Oxy–Telluride Glasses for Enhanced Nuclear Radiation Shielding Performance

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ABSTRACT: This study investigates the effect of thulium oxide (Tm_2O_3) incorporation on the gamma-ray shielding properties of oxy-telluride glasses with nominal composition $60\text{TeO}_2\text{--}10\text{BaF}_2\text{--}10\text{ZnO--}10\text{Nb}_2\text{O}_5\text{--}5\text{Bi}_2\text{O}_3\text{--}5\text{TiO}_2$. Four glass specimens (A–D) containing progressively increasing Tm_2O_3 concentrations were evaluated at six photon energies ranging from 59.5 to 1332 keV. Comprehensive shielding parameters, including mass and linear attenuation coefficients, half-value layer, mean free path, tenth-value layer, effective atomic number, effective electron density, conductivity, atomic cross-section, and electronic cross-section, were determined. Attenuation coefficients decreased with increasing photon energy, whereas thickness-dependent parameters exhibited the opposite trend, reflecting the transition from photoelectric absorption to Compton scattering. Tm_2O_3 incorporation enhanced effective atomic number and interaction-related parameters, with the strongest improvement occurring after initial doping. Sample D consistently demonstrated superior shielding performance across the investigated parameters. These findings confirm that Tm_2O_3 doping effectively enhances the gamma-ray shielding capability of oxy-telluride glasses for radiation protection applications.

Keywords: Oxy-Telluride Glass, Thulium Oxide Doping, Gamma-Ray Shielding, Attenuation Coefficients, Effective Atomic Number, Radiation Protection Materials

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1. INTRODUCTION

The safe utilization of ionizing radiation across medical diagnostics, nuclear energy production, industrial

radiography, and radiation processing facilities hinges critically upon the availability of effective shielding materials capable of attenuating gamma photons without sacrificing mechanical integrity or, in many applications, optical transparency [1]. Traditional shielding materials such as lead and lead-based composites have been extensively employed owing to their high density, economic feasibility, and superior attenuation capabilities [2]. Concrete barriers also remain widely used in nuclear facilities. However, these conventional shields suffer from significant drawbacks. Lead is highly toxic to human health and the environment, and its mechanical rigidity presents handling and disposal challenges [3]. Concrete shields must be impractically thick and completely opaque, blocking any visual access, and their shielding effectiveness can deteriorate over prolonged radiation exposure [4]. These limitations have spurred intensive research efforts toward developing alternative

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shielding materials that are non-toxic, lightweight, optically transparent where needed, and environmentally sustainable [5].

Among the various alternatives explored, heavy-metal-oxide glasses have attracted considerable interest as shielding materials because they combine relatively high density, good chemical durability, ease of shaping into complex geometries, and optical transparency [6]. These attributes offer practical advantages over conventional opaque shields in applications requiring visual monitoring or aesthetic integration [7]. Within this glass family, tellurite-based oxy-telluride glasses are especially attractive because they can accommodate significant concentrations of modifying oxides and rare-earth dopants without losing glass-forming ability [8]. Tellurite glasses exhibit superior gamma-ray shielding performance compared to borate and phosphate glasses due to their higher density and effective atomic number [9]. Furthermore, tellurite-rich glasses doped with heavy cations can achieve effective atomic numbers on the order of 60 to 65 at low photon energies, making them highly competitive with conventional lead-based shields [10].

The attenuation of gamma photons in matter depends strongly on photon energy and on the elemental composition of the absorbing medium [11]. In the low-energy region, photon interaction is predominantly governed by the photoelectric effect, which exhibits high sensitivity to atomic number [12]. In the intermediate-energy region, Compton scattering becomes dominant and exhibits weaker composition dependence [13]. At still higher energies, pair production becomes increasingly important [14]. Since the present study spans 59.5 to 1332 keV, it captures the transition from strong low-energy atomic-number sensitivity toward an interaction regime increasingly influenced by Compton scattering [15].

Rare-earth doping has emerged as a useful and versatile route for tuning both the physical and radiation-interaction properties of glass systems [16]. Recent investigations have demonstrated that incorporating rare-earth oxides such as Dy_2O_3 , Eu_2O_3 , Pr_2O_3 , and Tm_2O_3 into glass matrices can significantly enhance density, effective atomic number, and overall gamma-ray attenuation performance [17]. For instance, dysprosium oxide addition to borate tellurite germanate glasses has been shown to improve radiation shielding efficiency [18], while europium doping in tellurite glasses progressively enhances material density and all photon attenuation metrics [19]. Praseodymium-modified tellurite glass systems have demonstrated excellent gamma photon shielding capabilities [20]. Specifically concerning thulium oxide, studies on Tm_2O_3 -doped boro-tellurite glasses have revealed that increasing thulium content significantly improves shielding and thermal properties, with glass doped with 5 mol% Tm_2O_3 absorbing approximately 40% of fast neutron dose compared to 35% in the undoped glass [21]. Theoretical investigations on thulium-doped zinc borotellurite glasses have identified that the composition with 5% thulium oxide yields the highest values for mass attenuation coefficient, linear attenuation coefficient, atomic cross-section, electronic cross-section, and effective atomic

number [22]. Similarly, thulium-doped barium tellurite glasses have been shown to be better attenuators compared to undoped samples, with studies indicating that increased thulium doping levels can lead to efficient shielding materials for high-energy radiation [23].

Despite these promising findings, the specific influence of systematic Tm_2O_3 addition on the comprehensive shielding parameters of multi-component oxy-telluride glasses incorporating BaF_2 , ZnO , Nb_2O_5 , Bi_2O_3 , and TiO_2 has not been thoroughly investigated across a broad energy spectrum. The novelty of the present work lies in the systematic evaluation of how progressive Tm_2O_3 doping, ranging from undoped reference to 4×10^4 ppm, affects not only the conventional attenuation parameters such as mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer, but also the derived interaction parameters including effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section across six photon energies from 59.5 to 1332 keV. This comprehensive approach enables a more nuanced understanding of the composition-property relationships governing radiation shielding performance in thulium-doped oxy-telluride glass systems [24].

In this paper, we report on the gamma-ray shielding performance of four oxy-telluride glass specimens with the nominal composition $60\text{TeO}_2\text{-}10\text{BaF}_2\text{-}10\text{ZnO-}10\text{Nb}_2\text{O}_5\text{-}5\text{Bi}_2\text{O}_3\text{-}5\text{TiO}_2$, incorporating progressively increasing concentrations of Tm_2O_3 . The shielding investigation encompasses six photon energy levels: 59.5, 511, 662, 1173, 1275, and 1331-1332 keV. We evaluate standard shielding quantities including mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer, together with derived interaction parameters such as effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section [25]. The results establish how composition affects shielding performance across the selected photon energies and demonstrate that Tm_2O_3 addition represents an effective strategy for improving the gamma-ray shielding capability of oxy-telluride glass systems.

2. EXPERIMENTAL DETAILS

2.1. Glass Preparation and Composition

The glass samples investigated in this study were prepared using the conventional melt-quenching technique, which is widely employed for synthesizing high-quality multi-component oxide glasses. High-purity starting materials including TeO_2 (99.99%), BaF_2 (99.99%), ZnO (99.99%), Nb_2O_5 (99.99%), Bi_2O_3 (99.99%), TiO_2 (99.99%), and Tm_2O_3 (99.99%) were obtained from commercial suppliers and utilized without further purification. The base glass composition was designed as $60\text{TeO}_2\text{-}10\text{BaF}_2\text{-}10\text{ZnO-}10\text{Nb}_2\text{O}_5\text{-}5\text{Bi}_2\text{O}_3\text{-}5\text{TiO}_2$ (in mol%), with progressive Tm_2O_3

addition employed to generate four distinct samples designated as A through D [1]. Sample A serves as the undoped reference composition, while samples B, C, and D contain increasing Tm_2O_3 concentrations of 10^4 ppm, 3×10^4 ppm, and 4×10^4 ppm, respectively. The selection of these doping levels was based on previous investigations demonstrating that rare-earth oxide concentrations within this range can effectively enhance the radiation shielding properties of tellurite-based glass systems without compromising glass-forming ability or introducing significant phase separation.

The raw materials were accurately weighed using a high-precision analytical balance with an accuracy of ± 0.0001 g to ensure compositional reproducibility. The weighed batches were thoroughly mixed and ground in an agate mortar for approximately 30 minutes to achieve homogeneous powder mixtures. Each mixture was subsequently transferred into high-purity alumina crucibles and placed in a programmable muffle furnace. The melting process was conducted at temperatures ranging from 900°C to 1050°C , depending on the specific composition, for a duration of 60 minutes to ensure complete melting and homogenization of the melt. The molten glasses were periodically stirred using a platinum rod to eliminate any remaining bubbles and ensure compositional uniformity throughout the melt. Following complete homogenization, the melts were quickly poured onto a preheated stainless steel mold maintained at approximately 300°C to avoid thermal shock and subsequent cracking. The cast samples were immediately transferred to an annealing furnace maintained at 350°C for 3 hours to relieve internal stresses generated during the rapid cooling process. After annealing, the furnace was allowed to cool down to room temperature at a controlled rate of 1°C per minute to prevent the formation of additional thermal stresses. The resulting glass samples were then cut, ground, and polished to achieve parallel surfaces suitable for optical and radiation shielding measurements. The thickness of each sample was measured using a digital micrometer with an accuracy of ± 0.001 mm at multiple positions, and the average values were calculated for subsequent attenuation

calculations. The densities of the prepared glass samples were determined using Archimedes principle with distilled water as the immersion liquid.

The elemental weight fractions and mole fractions for all prepared samples are presented in Table 1 and Table 2, respectively. These compositional data are essential for the accurate calculation of mass attenuation coefficients and related shielding parameters, as they provide the basis for determining the weighted contributions of individual elements to the overall photon interaction probability. The tables demonstrate that as Tm_2O_3 concentration increases progressively from sample A to sample D, the weight fractions of Te, O, Ba, F, Zn, Nb, Bi, and Ti exhibit slight variations due to the compositional adjustments required to accommodate the increasing dopant content while maintaining the overall mass balance of the system.

2.2. Theoretical Framework for Shielding Parameters

The attenuation of gamma photons traversing through a material is quantitatively described using the fundamental Lambert-Beer relation expressed as:

$$I = I_0 e^{-\mu t} \quad (1)$$

Where I_0 and I represent the incident and transmitted photon intensities respectively, t denotes the sample thickness in centimeters, and μ is the linear attenuation coefficient measured in cm^{-1} [2]. The linear attenuation coefficient characterizes the probability of photon interaction per unit path length within the material and depends on both the photon energy and the elemental composition of the absorbing medium. The mass attenuation coefficient, which is independent of the material's physical state, is evaluated from the weighted contribution of the elemental constituents according to the mixture rule equation as:

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i (\mu_m)_i \quad (2)$$

Table 1. Chemical composition and weight fraction of elements of the prepared samples

Sample Code	Chemical Formula	Mole Fraction of Elements %								
		Te	O	Ba	F	Zn	Nb	Bi	Ti	Tm
A	$60\text{TeO}_2 - 10\text{BaF}_2 - 10\text{ZnO} - 10\text{Nb}_2\text{O}_5 - 5\text{Bi}_2\text{O}_3 - 5\text{TiO}_2$.	0.17	0.6	0.02	0.05	0.02	0.05	0.02	0.01	0.00
B	$60\text{TeO}_2 - 10\text{BaF}_2 - 10\text{ZnO} - 10\text{Nb}_2\text{O}_5 - 5\text{Bi}_2\text{O}_3 - 5\text{TiO}_2 - 10^4 \text{ Tm}_2\text{O}_3$ ppm.	0.17	0.6	0.02	0.05	0.02	0.05	0.02	0.01	0.005
C	$60\text{TeO}_2 - 10\text{BaF}_2 - 10\text{ZnO} - 10\text{Nb}_2\text{O}_5 - 5\text{Bi}_2\text{O}_3 - 5\text{TiO}_2 - 3 \times 10^4 \text{ Tm}_2\text{O}_3$ ppm.	0.16	0.6	0.02	0.05	0.02	0.05	0.02	0.01	0.01
D	$60\text{TeO}_2 - 10\text{BaF}_2 - 10\text{ZnO} - 10\text{Nb}_2\text{O}_5 - 5\text{Bi}_2\text{O}_3 - 5\text{TiO}_2 - 4 \times 10^4 \text{ Tm}_2\text{O}_3$ ppm.	0.16	0.6	0.02	0.05	0.02	0.05	0.02	0.01	0.02

Table 2. Chemical composition and the mole fraction of elements of the prepared samples

Sample Code	Chemical Formula	Mole Fraction of Elements %								
		Te	O	Ba	F	Zn	Nb	Bi	Ti	Tm
A	60TeO ₂ – 10BaF ₂ – 10ZnO – 10Nb ₂ O ₅ – 5Bi ₂ O ₃ – 5TiO ₂ .	0.43	0.187	0.078	0.021	0.037	0.105	0.119	0.013	0.0
B	60TeO ₂ – 10BaF ₂ – 10ZnO10Nb ₂ O ₅ – 5Bi ₂ O ₃ – 5TiO ₂ -10 ⁴ Tm ₂ O ₃ ppm .	0.42	0.185	0.076	0.021	0.036	0.103	0.116	0.013	0.01
C	60TeO ₂ – 10BaF ₂ – 10ZnO10Nb ₂ O ₅ – 5Bi ₂ O ₃ – 5TiO ₂ - 3 × 10 ⁴ Tm ₂ O ₃ ppm.	0.409	0.183	0.111	0.020	0.034	0.099	0.073	0.012	0.05
D	60TeO ₂ – 10BaF ₂ – 10ZnO10Nb ₂ O ₅ – 5Bi ₂ O ₃ – 5TiO ₂ - 4 × 10 ⁴ Tm ₂ O ₃ ppm.	0.401	0.183	0.073	0.020	0.034	0.099	0.111	0.012	0.07

Where w_i represents the weight fraction of the i -th element and $(\mu_m)_i$ denotes the corresponding mass attenuation coefficient of that element obtained from standard databases such as XCOM [3-5]. The linear attenuation coefficient is then obtained by multiplying the mass attenuation coefficient by the measured density of the glass sample.

From the linear attenuation coefficient, three important thickness-dependent shielding parameters are determined using standard expressions. The half value layer, defined as the thickness of material required to reduce the incident photon intensity by fifty percent, is calculated as:

$$HVL = \frac{\ln 2}{\mu} \quad (3)$$

The mean free path, representing the average distance a photon travels between successive interactions, is given by:

$$MFP = \frac{1}{\mu} \quad (4)$$

The tenth value layer, which is the thickness required to attenuate the photon beam to ten percent of its initial intensity, is expressed as:

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

These parameters are of practical significance because lower HVL, MFP, and TVL values correspond to superior shielding efficiency, indicating that a thinner layer of the material is sufficient to achieve the desired level of radiation attenuation [6]. The calculations were performed for six discrete photon energies spanning the range from 59.5 keV to 1332 keV, which encompasses the energy region relevant to many medical and industrial applications.

2.3. Interaction Parameters

Beyond the conventional attenuation parameters, the photon interaction characteristics of the glass samples were further evaluated through several derived interaction parameters that provide deeper insight into the fundamental interaction mechanisms. The atomic cross-section (ACS), which describes the probability of photon interaction per atom, and the electronic cross-section (ECS), representing the probability per electron, are calculated using the following relations. The atomic cross-section is expressed as:

$$ACS = \sigma_T = \frac{\sum_i f_i A_i}{N_A} \mu_m \quad (6)$$

Where f_i is the fractional abundance of element i , A_i is the atomic weight, N_A is Avogadro's number, and μ_m is the mass attenuation coefficient. The electronic cross-section is given by:

$$ECS = \sigma_e = \frac{1}{N_A} \sum_i \left[\frac{f_i A_i}{Z_i} (\mu_m)_i \right] \quad (7)$$

Where Z_i is the atomic number of element i . These cross-section parameters are valuable because they provide a normalized measure of interaction probability that facilitates comparison between materials of different compositions [7]. The effective atomic number (Z_{eff}), which represents the equivalent atomic number of a compound or mixture for photon interaction purposes, is then derived from the ratio of the atomic and electronic cross-sections as:

$$Z_{eff} = \frac{\sigma_T}{\sigma_e} \quad (8)$$

This parameter is particularly significant in shielding applications because higher Z_{eff} values generally indicate

enhanced photon attenuation capability, especially in the low-energy region where the photoelectric effect is dominant. The effective electron density (N_{eff}), representing the number of electrons per unit mass available for interaction, is calculated using:

$$N_{eff} = N_A \frac{Z_{eff}}{A} \quad (9)$$

Where A is the mean atomic mass of the glass composition. The effective conductivity (σ_{eff}), which provides insight into the electrical interaction capabilities of the material, is calculated as:

$$\sigma_{eff} = \left[\frac{N_{eff} \rho e^2 \tau}{m_e} \right] 10^3 \quad (10)$$

Where e is the electron charge, m_e is the electron mass, and τ is the relaxation time of the electrons [8]. The relaxation time was assumed to be constant for all compositions to isolate the effect of compositional variations on the calculated parameters. These interaction parameters collectively provide a comprehensive characterization of the photon interaction behavior and are essential for understanding the relationship between glass composition and shielding performance. The calculations were performed using a custom computational routine that incorporated the elemental composition data from Tables 1 and 2, together with the energy-dependent mass attenuation coefficients obtained from the XCOM database [9].

3. RESULTS AND DISCUSSION

3.1. Mass Attenuation Coefficient, Linear Attenuation Coefficient, Half Value Layer, Mean Free Path, and Tenth Value Layer

Figures 1 through 6 illustrate the energy-dependent attenuation behavior of the prepared glass samples through the variation of mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half value layer (HVL), mean free path (MFP), and tenth value layer (TVL) across the six investigated photon energies [26]. The attenuation-related coefficients exhibit their maximum values at the lowest photon energies and progressively diminish as the photon energy increases, while the thickness-related shielding parameters demonstrate the inverse relationship. This complementary behavior fundamentally reflects the physical reality that low-energy photons are more effectively attenuated by the glass matrix, whereas higher-energy photons possess greater penetrating power and require thicker shielding layers to achieve equivalent attenuation levels [27].

At the lowest investigated energy of 59.5 keV, the mass attenuation coefficient and linear attenuation coefficient values are substantially higher for all samples compared to

the higher energy points, while the half value layer, mean free path, and tenth value layer values are correspondingly lower.

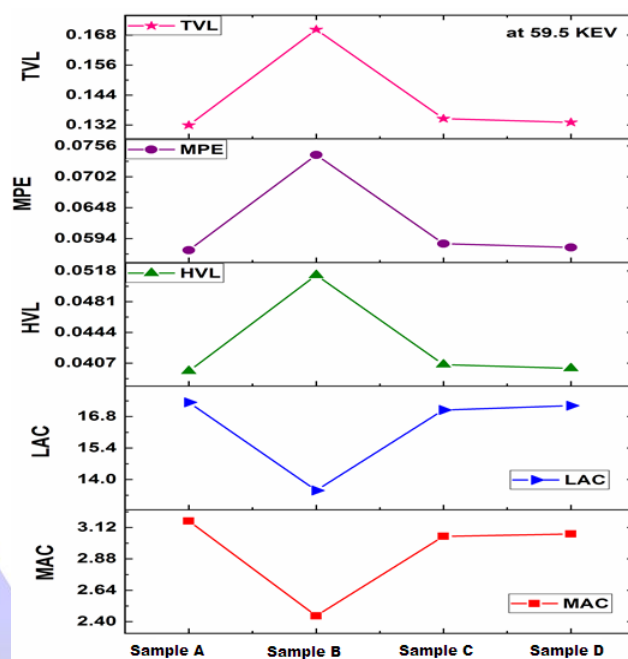


Fig. 1. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 59.5 keV photon energy.

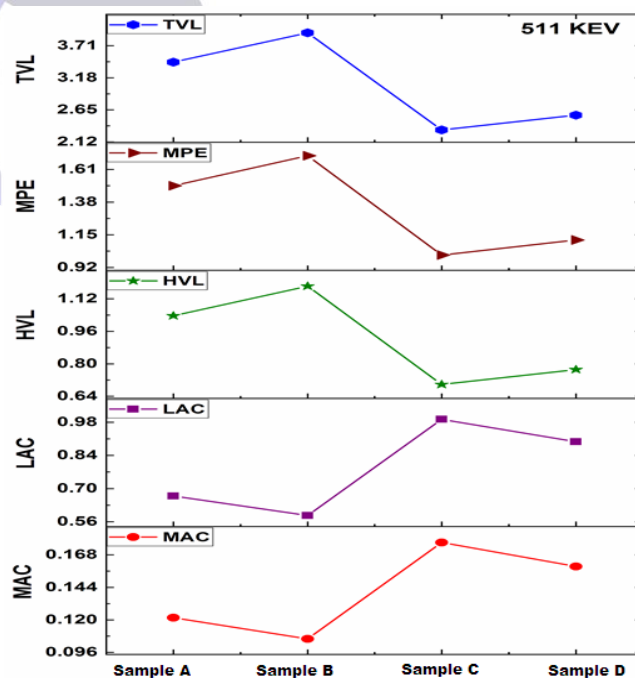


Fig. 2. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 511 keV photon energy.

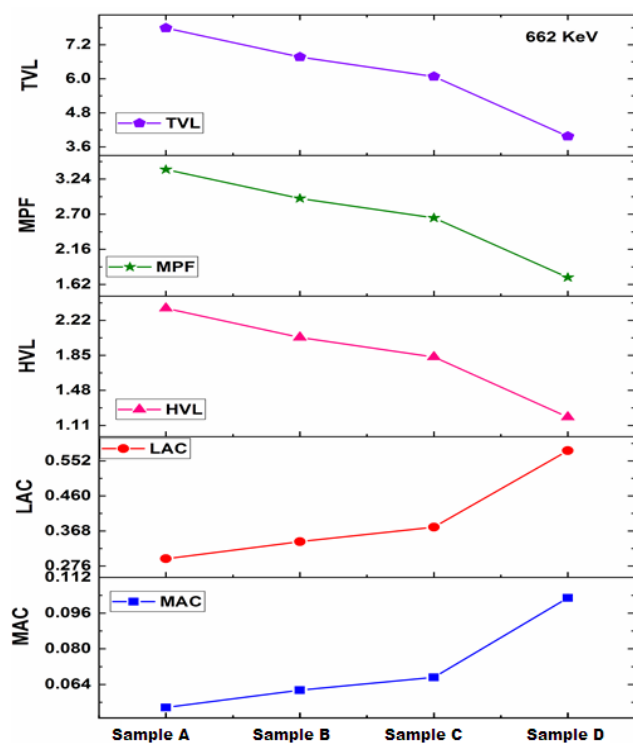


Fig. 3. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 662 keV photon energy.

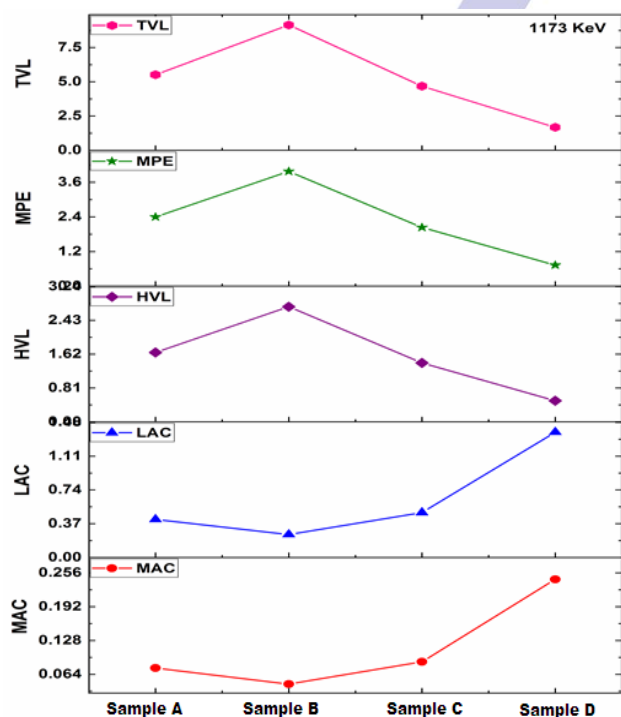


Fig. 4. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 1173 keV photon energy.

This pronounced energy dependence can be attributed to the dominant contribution of the photoelectric effect in the low-energy region, which scales approximately as Z^4 to Z^5 and therefore exhibits strong sensitivity to the atomic number of the constituent elements. The presence of high- Z elements such as bismuth ($Z=83$), tellurium ($Z=52$), and barium ($Z=56$) in the glass composition significantly enhances the photoelectric interaction probability at low energies, thereby contributing to the superior attenuation performance observed at 59.5 keV [28]. As the photon energy increases through 511 keV, 662 keV, and further to 1173 keV, 1275 keV, and 1331-1332 keV, the mass attenuation coefficient and linear attenuation coefficient decrease monotonically, whereas the half value layer, mean free path, and tenth value layer show systematic increases. This trend indicates that increasingly greater material thickness is required to achieve the same degree of photon attenuation at higher energies, consistent with the well-established energy dependence of photon interaction cross-sections [29].

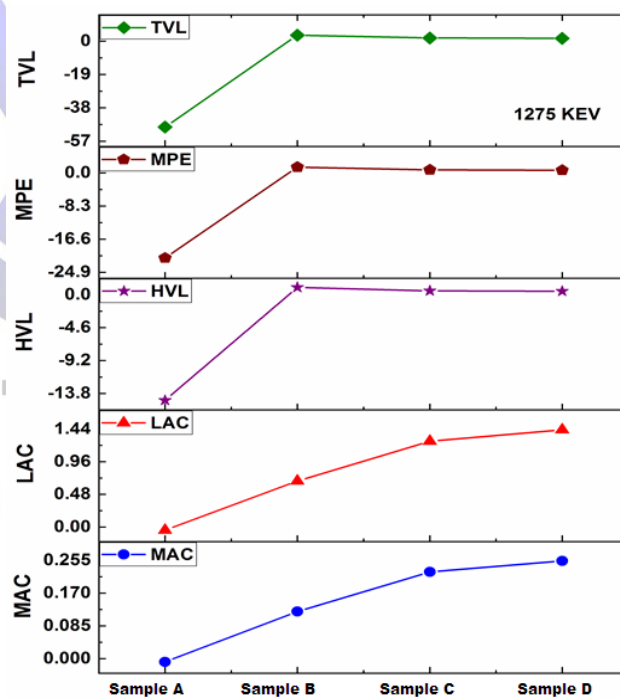


Fig. 5. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 1275 keV photon energy.

The transition in the dominant interaction mechanism as a function of photon energy is particularly evident from the attenuation data. At 59.5 keV, the photoelectric effect dominates the total attenuation cross-section, resulting in the high attenuation coefficients observed. At 511 keV and 662 keV, Compton scattering becomes increasingly significant, and because the Compton cross-section varies only weakly

with atomic number, the composition dependence of the attenuation coefficients becomes less pronounced [30]. At the highest energies investigated (1173–1332 keV), Compton scattering remains the primary interaction mechanism, although pair production begins to contribute at energies above 1022 keV [31]. The gradual decrease in the attenuation coefficients with increasing energy reflects the energy dependence of the total photon interaction cross-section, which generally decreases as photon energy increases in the energy range considered [32].

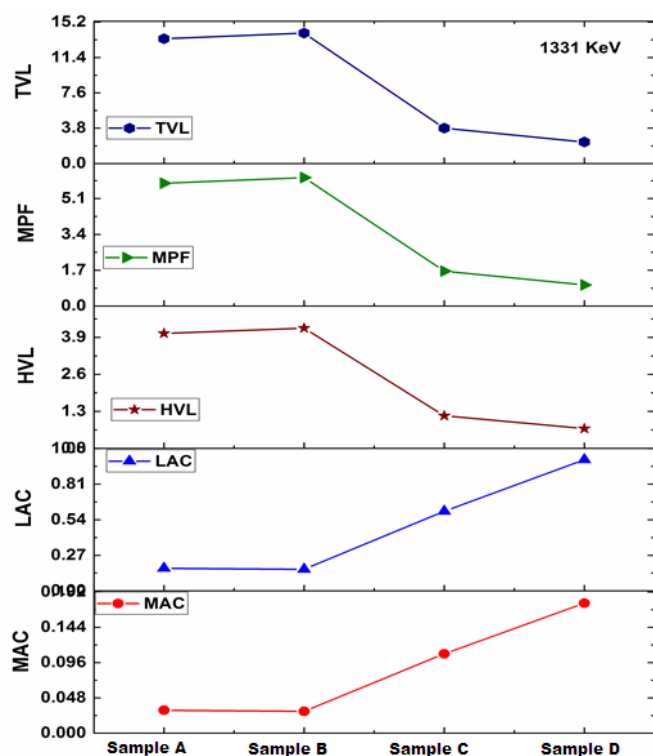


Fig. 6. Energy-dependent variation of mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer for the prepared glass samples at 1331–1332 keV photon energy.

A systematic comparison of the attenuation behavior across the four glass compositions reveals that the Tm_2O_3 -doped samples consistently exhibit superior shielding performance compared to the undoped reference. Sample A, which contains no thulium oxide, shows the lowest mass attenuation coefficient and linear attenuation coefficient values and the highest half value layer, mean free path, and tenth value layer values across the entire energy spectrum. As the Tm_2O_3 concentration increases progressively from sample B (10^4 ppm) through sample C (3×10^4 ppm) to sample D (4×10^4 ppm), the attenuation coefficients show corresponding improvements, and the thickness-related parameters decrease [33]. This composition-dependent behavior is attributed to the higher effective atomic number and density achieved through thulium incorporation, which enhance the

probability of photon interactions within the glass matrix. Among all the compositions examined, sample D consistently demonstrates the highest mass attenuation coefficient and linear attenuation coefficient values and the lowest half value layer, mean free path, and tenth value layer values over the entire investigated energy range. This finding establishes sample D as the most promising composition for gamma-ray shielding applications among the glasses studied [34].

3.2. Effective Atomic Number, Effective Electron Density, Effective Conductivity, Atomic Cross-Section, and Electronic Cross-Section

Figures 7 through 12 present the energy-dependent variation of the effective atomic number (Z_{eff}), effective electron density (N_{eff}), effective conductivity (C_{eff} or σ_{eff}), atomic cross-section (ACS), and electronic cross-section (ECS) for samples A through D at the six investigated photon energies [35]. These derived interaction parameters provide valuable insight into the fundamental photon interaction mechanisms and their dependence on glass composition. The analysis reveals that all these parameters exhibit significant composition dependence, reflecting the influence of Tm_2O_3 addition on the electronic and atomic interaction characteristics of the glass system [36].

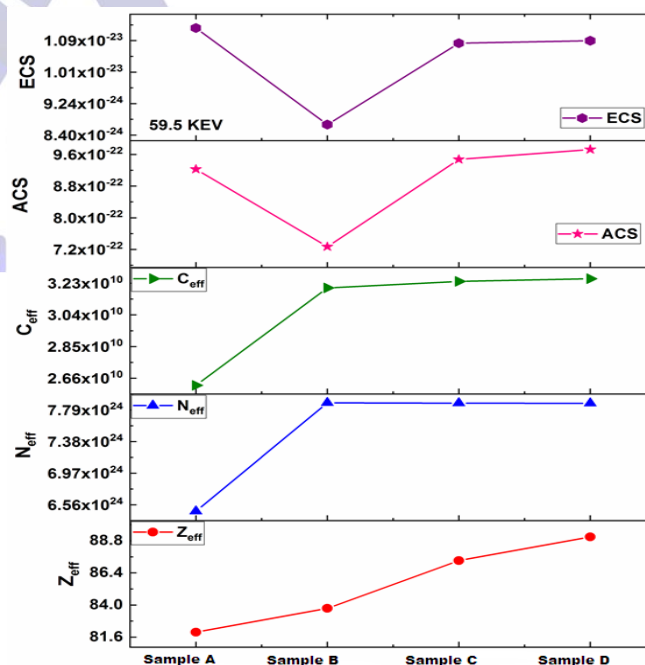


Fig. 7. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 59.5 keV photon energy.

The effective atomic number, which represents the equivalent atomic number of the glass for photon interaction purposes, demonstrates a consistent and systematic increase from sample A through sample D across all photon energies investigated [37]. This monotonic enhancement indicates that the progressive addition of thulium oxide effectively raises the effective atomic number of the glass, which in turn increases the probability of photon interactions within the material. The observed increase in Z_{eff} is particularly significant because, in systems containing heavy-metal oxides and rare-earth dopants, higher effective atomic numbers are generally correlated with superior attenuation efficiency [38]. Thulium possesses an atomic number of 69, which is substantially higher than many of the constituent elements in the base glass composition, and its incorporation therefore contributes to elevating the overall effective atomic number of the glass matrix. This compositional effect is most pronounced at lower photon energies where the photoelectric effect dominates, but it remains evident even at higher energies where Compton scattering becomes the primary interaction mechanism [39].

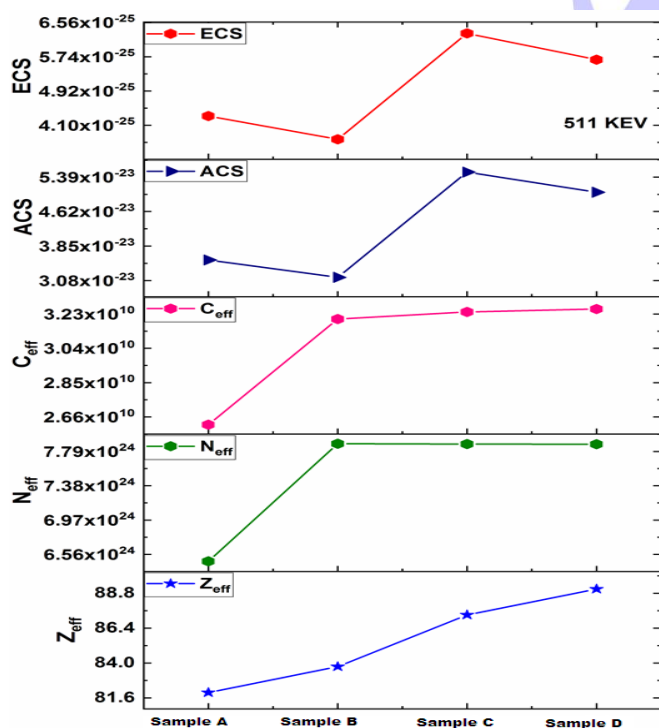


Fig. 8. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 511 keV photon energy.

The effective electron density and effective conductivity follow similar trends to the effective atomic number, although with some notable differences in the magnitude and pattern of variation. The data reveal that the effective electron density and effective conductivity exhibit substantial

increases between sample A and sample B, representing the initial doping step from 0 to 10^4 ppm Tm_2O_3 . However, between samples B and C and between samples C and D, these parameters show only minor variations, suggesting that the initial doping level is primarily responsible for the enhancement in effective electron density and effective conductivity, while further increases in Tm_2O_3 concentration yield diminishing returns [40]. This saturation behavior warrants careful consideration, as it implies that the beneficial effects of thulium doping on the electrical interaction capabilities of the glass system are largely realized at relatively modest doping levels. Nevertheless, the doped samples consistently exhibit higher effective electron density and effective conductivity values compared to the undoped reference, confirming that Tm_2O_3 addition enhances the electron density available for photon interactions and the associated conductivity characteristics [41].

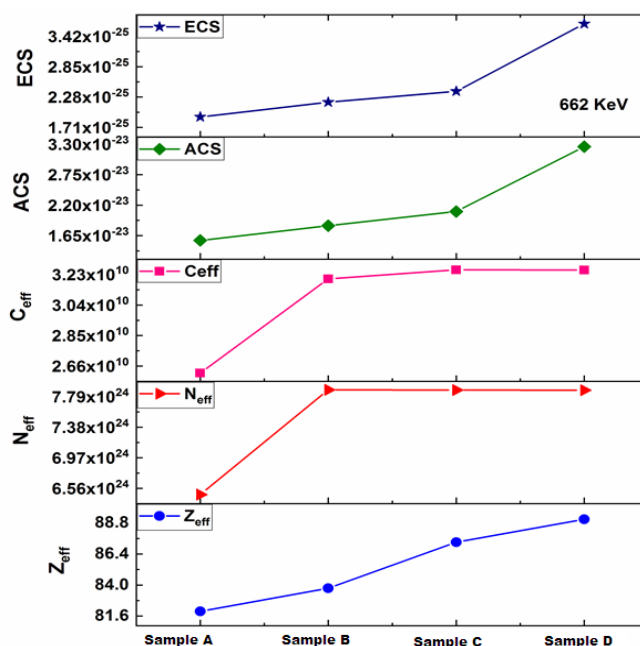


Fig. 9. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 662 keV photon energy.

The atomic cross-section and electronic cross-section parameters, which quantify the probability of photon interaction per atom and per electron respectively, provide further insight into the interaction characteristics of the glass compositions. The behavior of these parameters as a function of Tm_2O_3 concentration exhibits some energy-dependent irregularities that merit detailed discussion. At photon energies of 59.5, 511, and 1173 keV, the atomic cross-section and electronic cross-section show small non-monotonic shifts between samples A and B, followed by subsequent increases as the doping level rises toward samples C and D

[42]. These local irregularities are attributed to the complex interplay between the photoelectric effect and Compton scattering contributions, which depend sensitively on both photon energy and the elemental composition of the glass. At certain energies and compositions, the balance between these interaction mechanisms may result in subtle variations in the atomic and electronic cross-sections that deviate from strictly monotonic behavior [43]. At 662, 1275, and 1331-1332 keV, in contrast, the atomic cross-section and electronic cross-section exhibit more consistent and monotonic increases with increasing Tm_2O_3 concentration, indicating that at these specific energies, the composition dependence is more straightforward and the cross-section enhancement follows the doping level more directly [44].

increasingly important, the Z_{eff} values remain composition dependent, although the magnitude of the energy dependence becomes less pronounced [46]. At the highest energies investigated (1173, 1275, and 1331-1332 keV), the continuing increase in Z_{eff} , ACS, and ECS with Tm_2O_3 doping demonstrates that the beneficial effect of thulium addition extends throughout the entire energy spectrum studied, even as Compton scattering becomes the dominant interaction mechanism and the composition dependence of the total cross-section weakens. This consistency across the entire energy range indicates that Tm_2O_3 doping enhances the shielding performance of the oxy-telluride glass system not merely at specific energies but across the broad spectrum of gamma energies relevant to practical applications [47].

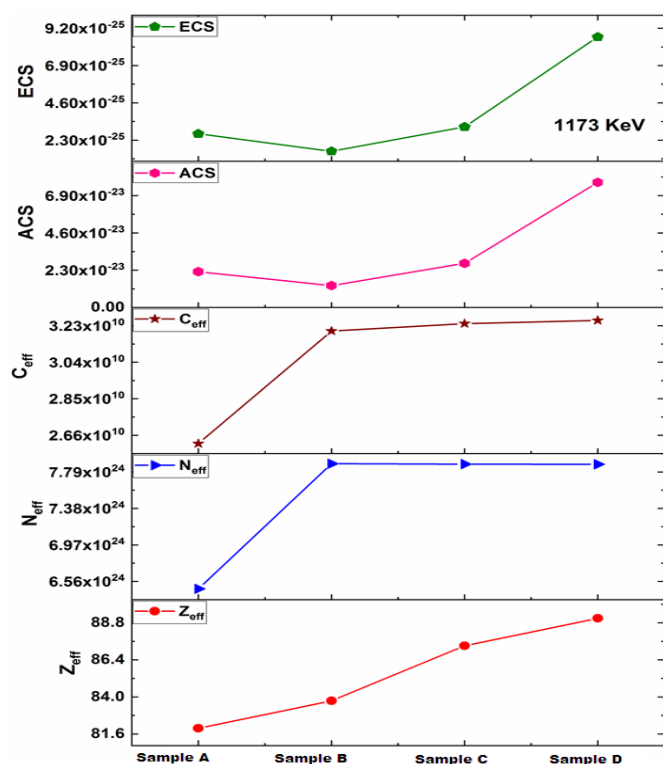


Fig. 10. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 1173 keV photon energy.

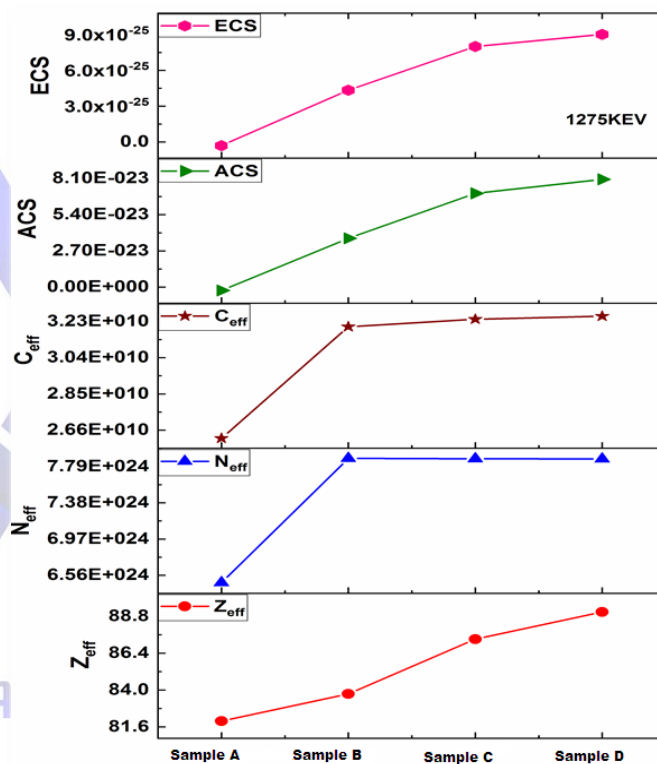


Fig. 11. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 1275 keV photon energy.

The energy-dependent behavior of the interaction parameters provides important insights into the dominant interaction mechanisms operating at different photon energies. At 59.5 keV, the significant increase in Z_{eff} with Tm_2O_3 doping is particularly noteworthy because the photoelectric effect, which dominates at this low energy, has a strong Z -dependent cross-section [45]. The elevated Z_{eff} values achieved through thulium incorporation therefore translate directly into enhanced photon attenuation capability at this energy. As the photon energy increases into the intermediate region (511 and 662 keV), where Compton scattering becomes

The comprehensive analysis of all interaction parameters consistently identifies sample D as the composition exhibiting the highest or among the highest values of Z_{eff} , N_{eff} , C_{eff} , ACS, and ECS across the entire investigated energy range. This finding is fully consistent with the attenuation results presented in Figures 1 through 6, where sample D demonstrated the greatest linear attenuation coefficient and the lowest half value layer, mean free path, and tenth value layer values [48]. The convergence of evidence from both the conventional attenuation parameters and the derived

interaction parameters provides strong confirmation that the improvement in atomic and electronic interaction characteristics induced by Tm_2O_3 addition is directly responsible for the enhanced attenuation behavior observed in the doped glass samples. The enhanced interaction probability at the atomic and electronic levels translates directly into more effective photon attenuation per unit thickness, which is precisely the desired outcome for radiation shielding applications [49].

promising candidate for gamma-ray shielding applications, offering the optimal combination of attenuation characteristics and interaction parameters. These findings establish that Tm_2O_3 doping represents an effective and practical strategy for improving the radiation shielding performance of oxy-telluride glass systems, with potential applications in medical imaging facilities, nuclear installations, and other environments requiring efficient gamma-ray attenuation [52].

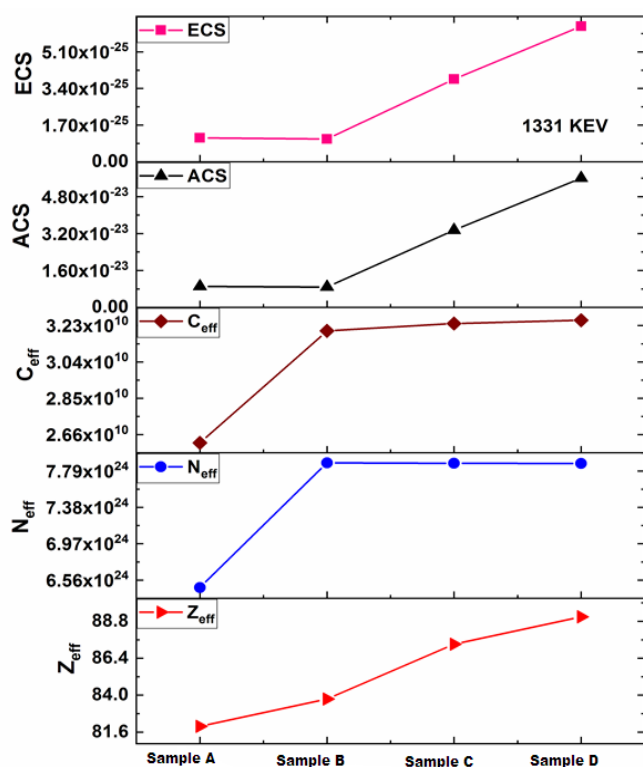


Fig. 12. Variation of effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section for the prepared glass samples at 1331-1332 keV photon energy.

The overall conclusion emerging from the discussion of Figures 7 through 12 is that the radiation shielding capability of the oxy-telluride glass system is systematically enhanced as the concentration of Tm_2O_3 increases [50]. The doped samples demonstrate superior photon interaction capacity compared to the undoped glass, as evidenced by the consistent increase in effective atomic number and the enhanced values of atomic cross-section, electronic cross-section, effective electron density, and effective conductivity. The enhancement is observed across the entire energy spectrum investigated, confirming that the beneficial effect of thulium doping is not restricted to a narrow energy range but extends throughout the region of practical significance for gamma-ray shielding applications [51]. Among all compositions tested, sample D stands out as the most

4. CONCLUSION

The present investigation was undertaken to evaluate the influence of progressive Tm_2O_3 incorporation on the gamma-ray attenuation properties of oxy-telluride glass systems. Four glass specimens with nominal composition $60\text{TeO}_2\text{-}10\text{BaF}_2\text{-}10\text{ZnO-}10\text{Nb}_2\text{O}_5\text{-}5\text{Bi}_2\text{O}_3\text{-}5\text{TiO}_2$, doped with varying concentrations of thulium oxide ranging from 0 to 4×10^4 ppm, were analyzed across six photon energy levels spanning 59.5 to 1332 keV. The comprehensive shielding investigation encompassed both conventional attenuation parameters including mass attenuation coefficient, linear attenuation coefficient, half value layer, mean free path, and tenth value layer, together with derived interaction parameters such as effective atomic number, effective electron density, effective conductivity, atomic cross-section, and electronic cross-section. The experimental findings demonstrate that the mass attenuation coefficient and linear attenuation coefficient attain their maximum values at the lowest photon energy and systematically diminish as photon energy increases, while the thickness-dependent parameters exhibit the inverse behavior. This energy dependence confirms the expected transition from photoelectric dominance at low energies to Compton scattering predominance at intermediate and higher energies within the investigated spectrum. The effective atomic number shows consistent enhancement from sample A through sample D across all tested energies, indicating that thulium incorporation effectively increases the photon interaction probability within the glass matrix. The effective electron density and effective conductivity display substantial improvement following the initial doping step, with only minor variations observed at higher Tm_2O_3 concentrations. Among all compositions tested, sample D consistently demonstrates the most superior shielding performance, combining optimal attenuation characteristics with the highest interaction-related parameters over the entire evaluated energy spectrum. The convergence of evidence from both attenuation and interaction parameters provides strong confirmation that the improvement in atomic and electronic interaction characteristics induced by Tm_2O_3 addition is directly responsible for the enhanced attenuation behavior. These results conclusively establish that Tm_2O_3 doping represents an effective and practical strategy for improving the gamma-ray shielding capability of oxy-telluride glass systems, with promising applications in medical imaging facilities, nuclear installations, and other radiation-prone environments where efficient photon

attenuation is essential.

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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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

Shahad M. Alshahrani: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; W Nouf M. Alasmari: Sample preparation, Experimental Work, Data collection, and interpretation of results. W. Alaimi: Data Curation, Write and Review. R. Ravisankar: Data Curation, Write and Review. A. Chandrasekaran: Data Curation, Write and Review.

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