

RESEARCH ARTICLE

Depth Analysis of Protection Shielding Properties of TNZP Host Glasses

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ABSTRACT: This research investigates the influence of increasing Er_2O_3 mol% concentration on the radiation shielding characteristics of a tellurite glass system with the composition $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}10\text{ZnO-}5\text{PbO}$ (TNZP) using the Phy-X/PSD computational software across an energy range spanning from 15 keV to 15 MeV. The experimental findings demonstrate exceptionally high attenuation factors at 15 keV, with mass attenuation coefficients ranging between 42.91338 and 43.9844 cm^2/g for the prepared samples. At 10 MeV, the mass attenuation coefficients vary minimally from 0.03509 to 0.03523 cm^2/g , while linear attenuation coefficients at 15 keV extend from 239.01035 to 248.56466 cm^{-1} . The addition of Er_2O_3 significantly enhances the effective atomic number, with the sample containing the highest Er_2O_3 concentration (coded as S7) exhibiting superior shielding performance compared to the Er-free sample (S1). Maximum effective atomic number values approaching 49.5 were observed at 0.1 MeV for all compositions. The half-value layer and tenth-value layer thicknesses decrease substantially with increasing Er_2O_3 content, with S7 demonstrating the lowest values and consequently the best radiation attenuation capability. Furthermore, the effective removal cross-sections for fast neutrons show progressive enhancement with increasing Er_2O_3 concentration, confirming the multifunctional shielding potential of these glasses for both photon and neutron radiation protection applications.

Keywords: Tellurite Glasses; Radiation Shielding; Er_2O_3 Doping; Mass Attenuation Coefficient; Effective Atomic Number; Neutron Removal Cross-Section.

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1. INTRODUCTION

Glasses have emerged as remarkably versatile materials in modern technological applications, primarily owing to their exceptional combination of structural and physical characteristics. These include optical transparency, relatively low melting temperatures, excellent transmission capabilities, electrical conductivity, resistance to corrosion, high dielectric constants, environmental compatibility, and elevated refractive indices [1-5]. The unique convergence of these properties has enabled widespread utilization across diverse technological domains, encompassing

thermoluminescent dosimeters, microelectronic components, electro-optic switching devices, solid oxide fuel cells, laser systems, photovoltaic cells, telecommunications infrastructure, and various medical applications [3-10]. The fundamental advantages offered by glass materials stem from their amorphous nature, which provides isotropic properties and compositional flexibility that crystalline materials cannot readily achieve. This compositional versatility allows researchers to tailor glass properties for specific applications through careful selection of constituent oxides and dopants.

The relationship between radiation sources and living organisms presents a complex duality. While ionizing radiation undeniably poses significant health risks through mechanisms including DNA damage, cellular disruption, and increased cancer susceptibility, these same radiation sources serve indispensable functions across numerous beneficial applications. In medicine, radiation enables diagnostic imaging techniques such as X-ray radiography, computed

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tomography, and positron emission tomography, along with therapeutic interventions including radiation oncology for cancer treatment. Industrial applications encompass non-destructive testing, sterilization processes, materials modification, and quality control procedures. Nuclear reactors utilize radiation for energy generation, while research activities across physics, chemistry, biology, and materials science depend heavily on various radiation sources. This dichotomy necessitates the development and implementation of effective shielding materials that can provide adequate protection for personnel, patients, and the general public while allowing beneficial applications to proceed safely [11].

The search for optimal radiation shielding materials has increasingly focused on glass systems due to their inherent advantages over conventional shielding materials such as lead and concrete. Tellurite-based glasses have garnered particular attention in this context, finding applications in thermoelectric devices, optical amplifiers, gas sensors, and radiation shielding protective glasses [12-15]. Recent investigations have extensively explored the chemical, optical, physical, and structural characteristics of TeO_2 -based glasses incorporating rare earth oxides or transition metal oxides [16-19]. The exceptional radiation shielding capabilities of TeO_2 -based glasses derive primarily from the intrinsically high density of tellurium dioxide ($\rho=5.67 \text{ g/cm}^3$), which enhances photon interaction probabilities through increased electron density per unit volume [20, 21]. Furthermore, the relatively low melting temperatures of tellurite glasses facilitate fabrication while maintaining excellent glass-forming ability across a wide compositional range.

Rare earth doped glasses occupy a strategically important position in the development of novel luminescent and optical materials, with emissions spanning both visible and near-infrared regions proving particularly valuable for laser applications [22]. The erbium ion (Er^{3+}), in particular, has attracted substantial research interest owing to its prominent green emission in the visible region and characteristic infrared emission at approximately $1.5 \mu\text{m}$, which coincides with the telecommunications window for optical fiber amplifiers [23-26]. Different glass matrices including borates, phosphates, and silicates containing bismuth have been evaluated for their broadband emission characteristics covering 1100-1600 nm. Borate glasses exhibit high rare earth solubility, facile bulk fabrication, low production costs, excellent moisture resistance, and suitable amorphous matrices for optical devices, although their high vibrational phonon energies can be detrimental to visible upconversion processes [27, 22].

The scientific literature contains numerous comparative studies on shielding properties of various glass systems. El-Mallawany and colleagues conducted a comprehensive investigation of 21 tellurite glasses, evaluating mass attenuation coefficients, effective atomic numbers, half-value layers, and neutron removal cross-sections within the 10 keV to 10 MeV photon energy range using the XCOM program, establishing that $\text{TeO}_2\text{-V}_2\text{O}_5\text{-CeO}_2$ glasses

exhibited the highest photon radiation performance [28]. Shielding properties of borotellurite glasses have also been extensively characterized [29]. Comprehensive investigations of physical, elastic, and shielding properties of lead zinc phosphate glasses, along with tellurite and bismuth modified zinc boro-tellurite glasses, have been reported in the literature [30-32]. These studies consistently demonstrate that acceptable shielding materials must satisfy several critical criteria including ease of fabrication, high density, environmental friendliness, and superior radiation shielding capacity characterized by low mean free paths and high effective atomic numbers [33, 34].

Heavy metal oxide glasses have recently received intensified attention for radiation protection applications because they simultaneously fulfill all radiation shielding requirements while offering cost advantages and optical transparency that provide unique benefits across various radiation applications [35-37]. The increasing emphasis on environmentally sustainable materials has further accelerated interest in heavy metal oxide glasses as alternatives to lead-based shielding materials. However, despite extensive research on various glass systems, there remains a significant gap in understanding the specific effects of systematic Er_2O_3 incorporation on the comprehensive radiation shielding parameters of tellurite-niobium-zinc-lead glass systems across a broad energy range.

The novelty of the present study lies in its systematic investigation of the progressive influence of Er_2O_3 concentration on both photon and neutron attenuation properties of the $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}10\text{ZnO-}5\text{PbO}$ glass system, utilizing the advanced Phy-X/PSD computational platform to provide a comprehensive analysis of shielding parameters including mass attenuation coefficients, linear attenuation coefficients, half-value and tenth-value layers, mean free paths, effective atomic numbers, effective electron densities, and neutron removal cross-sections. This approach enables direct correlation between Er_2O_3 content and shielding performance, providing valuable insights for optimizing glass compositions for radiation protection applications.

In this paper, we report a comprehensive investigation of the radiation shielding properties of Er^{3+} ion doped tellurite glasses with composition $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}5\text{PbO-}10\text{ZnO-}x\text{Er}_2\text{O}_3$, where x ranges from 0.00 to 0.875 mol%. The glasses were prepared using the conventional melt-quenching technique and characterized using the Phy-X/PSD online software platform to evaluate all relevant shielding parameters across the 15 keV to 15 MeV photon energy range. The systematic variation of Er_2O_3 content allows us to establish quantitative relationships between dopant concentration and shielding performance, while comparison with conventional concretes and commercial shielding glasses provides practical context for potential applications. The results of this investigation contribute to the fundamental understanding of structure-property relationships in rare earth doped tellurite glasses and provide guidance for the design of advanced radiation shielding materials.

2. EXPERIMENTAL DETAILS

2.1. Experimental Procedure

The Er^{3+} ions doped glass systems with a composition of $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}5\text{PbO}\text{-}10\text{ZnO}\text{-}x\text{Er}_2\text{O}_3$ (where $x = 0.00, 0.25, 0.375, 0.5, 0.625, 0.75$ and 0.875 % mol) by using the conventional quench-melting method. The raw materials were powdered and put in the platinum crucible and heated in a melting furnace to a temperature of 920°C kept for 45 min; the melt was stirred from time to time. The highly viscous melt was cast in a graphite mold. The quenched samples were annealed at 340°C for 2 h and then cooled inside the furnace down to room temperature [38-40]. The samples codes are listed among Table 1. Chemical composition and density of the $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}10\text{ZnO}\text{-}5\text{PbO}$ (TNZP) glasses.

2.2. The Phy-X/PSD Online Software

Phy-X/PSD, the remote server which possesses Intel(R) Core(TM) i7- 2600 CPU @ 3.40 GHz CPU with 1GB installed memory, is a recent software developed by Sakar et al. [41] and can compute several shielding factors at any energies. It is written in NodeJS v8.4.0 serving with Nginx 1.15.8. Security among server and client browsers is being established through 256 Bit Positive SSL. The most important parameter used to assess the ability of the glass to block or attenuate the photons is the mass attenuation coefficient (μ/ρ). It gives an indication about the interaction of the photons with the atoms of the glass. Furthermore, μ/ρ is used to compute some other quantities such as electron density (N_{eff}), linear attenuation coefficient (μ), etc.

2.3. Theoretical Basis

Assuming a mono-energetic photon beam with an I_0 initial intensity passes through an x cm thick barrier, its intensity is reduced depending on Beer-Lambert law as mathematically written in Eq. (1) [42]:

$$\mu = - \frac{\ln \frac{I}{I_0}}{x}, \quad (1)$$

Where μ represents the linear attenuation coefficient (cm^{-1}), I_0 and I show the un-attenuated and attenuated photon intensities, respectively. On the other hand, the interaction probabilities of photons with barrier is identified as the mass attenuation coefficient (μ/ρ) and indicated for a mixture of elements or any chemical compound as follows [43]:

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i (\mu/\rho)_i, \quad (2)$$

Where ρ shows the density of material, $(\mu/\rho)_i$ (cm^2/g) is the mass attenuation coefficient of individual elements in each

component and w_i is the fractional weight. Besides, the μ/ρ parameter is generally utilized to evaluate some related attenuation factors namely; the total electron density, the effective atomic number, the atomic and the electronic cross-section, etc. The atomic (σ_a) and the electronic cross-sections are firstly estimated for obtaining the effective atomic number (Z_{eff}) for a material. Dividing the molecular cross-section (σ_m) by the total number of formula units, σ_a can be obtained in Eq. (3) [44]:

$$\sigma_a = \sigma_m \frac{1}{\sum_i n_i} = (\mu/\rho)_{\text{target}} / N_A \sum_i \frac{w_i}{A_i} \quad (3)$$

Where N_A is the Avogadro constant and A_i denotes the atomic weight for the individual element in the target. Besides, σ_e can be estimated as below [45]:

$$\sigma_e = \frac{1}{N} \sum_i \left(\frac{\mu}{\rho}\right)_i \frac{f_i w_i A_i}{Z_i} \quad (4)$$

Where f_i defines the fractional abundance and Z_i is the atomic number of the individual element in the target. Therefore, Z_{eff} can be easily obtained by the above parameters as follows [46]:

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_e} \quad (5)$$

Another quantity, the electron density (N_{eff}) represents the electron numbers per unit mass of the interacting target. The chances of photon interaction are directly proportional to the value of N_{eff} . It is expressed by the next relation [47]:

$$N_{\text{eff}} = N \frac{Z_{\text{eff}}}{\sum_i f_i A_i}, \quad (6)$$

The mean free path (MFP) identifies the average distance where a photon can move in the barrier before being interacting and is determined by μ which is obtained by multiplying the corresponding μ/ρ value and density [48]:

$$MFP = \frac{1}{\mu}, \quad (7)$$

The tenth (TVL) and half value layer (HVL) define the thickness of interacting target at which the attenuated intensities are 90% and 50% of the narrow photon beam intensity, respectively. The shielding material of the required thickness is inversely proportional to the TVL and HVL values. It can be determined as follows [49]:

$$TVL = \frac{\ln 10}{\mu}, \quad (8)$$

$$HVL = \frac{\ln 2}{\mu}, \quad (9)$$

Effective removal cross-section (Σ_R), shows the probability of the neutrons to pass through the material without any interaction. Σ_R of any absorber can be estimated as following [50]:

$$\frac{\Sigma_R}{\rho} = \sum_i w_i \left(\frac{\Sigma_R}{\rho} \right)_i, \quad (10)$$

And

$$R = \sum_i \rho_i \left(\frac{R}{\rho} \right)_i \quad (11)$$

Where $(R/\rho)_i$ is the removal cross-section of the i^{th} component W_i denotes the weight percentages of the component. Calculation of equivalent atomic number (Z_{eq}). The (Z_{eq}) can be calculated by determining the ratio (Y) between the mass attenuation coefficient related to Compton interaction and the total mass attenuation coefficient. Thereafter, the interpolation method was employed to obtain (Z_{eq}) through the equation below [51]:

$$Z_{eq} = \frac{Z_1 (\log Y_2 - \log Y) - Z_2 (\log Y - \log Y_1)}{\log Y_2 - \log Y_1} \quad (12)$$

Where, Z_1 , and Z_2 are the atomic numbers related to the ratios Y_1 , and Y_2 , respectively.

3. RESULTS AND DISCUSSION

Figure 1 Demonstrates the variation of μ/ρ values with photon energy for the glasses 75TeO₂-10Nb₂O₅-10ZnO-5PbO-xEr₂O₃ (TNZP-x) with (x= 0.0, 0.25, 0.375, 0.5, 0.625, 0.75 and 0.875 wt %). These values vary with photon energy of 0.015–15 MeV using Phy-X/PSD online software as diagrammatically demonstrated in **Figure 1**.

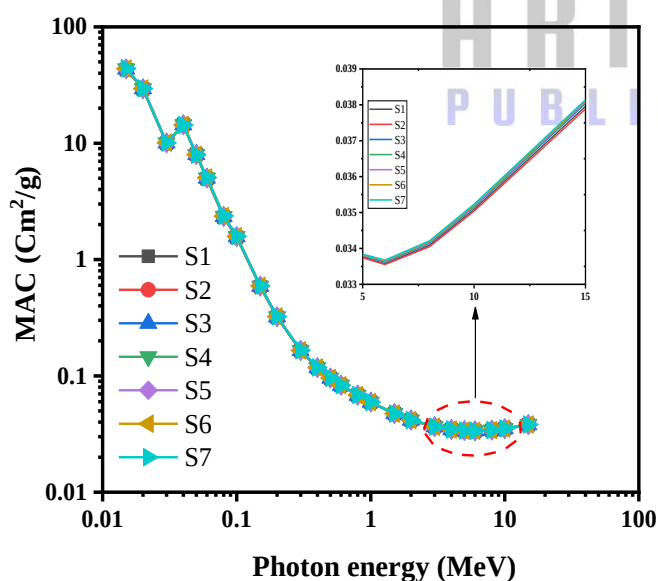


Fig. 1. Mass attenuation coefficients of the glasses in the energy range 0.015–15 MeV.

As well as with the chemical composition of the glass. (MAC)

of all the glasses has the same photon energy dependence, and it significantly increases as Er₂O₃ content increases in the glass sample. Maximum (MAC) values for the present glasses were observed in the low photon energy zone at 0.015 MeV. Such that (MAC) = 42.913 cm²/g, 42.957 cm²/g, 43.378 cm²/g, 43.531 cm²/g, 43.683 cm²/g, 43.834 cm²/g and 43.984 cm²/g for S1, S2, S3, S4, S5, S6 and S7 respectively. Then, the (MAC) values decrease rapidly with increasing the photon energy. The comparatively high values in the attenuation factor at 15 keV can be attributed to photoelectric phenomenon as discussed early by Waly et al. [52].

In this phenomenon, the (MAC) has a high dependence on the atomic number (i.e. Z^α , where $\alpha = 4-5$), and the glasses in the present system contain heavy elements (Te) which increase the chances of this phenomenon to happen. After that above 5MeV, the (MAC) values have a very weak dependence of the photon energy. This relation of (MAC) with the photon energy is attributed by the partial photon interaction. In the low photon energy zone (0.015–0.04 MeV), the photoelectric absorption is the main interaction and it varies with $1/E^3$. Moreover, one can see a sudden change in the curve of (MAC) at 0.0374 MeV due to the K-absorption edge of Er element. In the intermediate photon energy zone (0.04–5 MeV), the Compton scattering is the main interaction and it is proportional inversely to E . Then, in the high photon energy zone (5–15 MeV), the pair production is the main interaction and varies with $\log E$. However, there is almost no impact or rather low impact compared to intermediate or higher energies. The reason of this change in the basic parameter depending on the energy is explained considering several interaction modes which are dominant at different energy regions. These modes, called photoelectric absorption (PE), Compton scattering (CS) and pair production (PP), are effective in the lower, intermediate and higher energy regions, respectively.

Together with photon-material interaction, the entire energy of photon is absorbed in the PE mode. Thence, the (MAC) values are aggressively reduced with increasing the energy in **Figure 1**. Moreover, since the original photons are partially scattered in CS as well as PP modes, the attenuation become linear and gradually constant. From the obtained results, it is found that the (MAC) vary from 4.94485 to 5.08332 cm²/g for Er₂O₃ concentrations with 0 (Er = 0.0) and 0.875 mol% (Er = 0.875) at 0.06 MeV, while varying only from 2.30839 to 2.37534 at 0.08 MeV and 0.04168 to 0.04172 cm²/g at 2 MeV. This case can be resulted from the dependence of the cross-sections for PE, CS and PP modes on Z^4 , Z and Z^2 , respectively. In additionally, this change of (MAC) values against the energy is agreement to those of the determined by El-Mallawany et al. [28] and Agar et al. [53]. On the other hand, it is found the fluctuations in μ/ρ at 0.04 MeV is for all the glasses. The present aggressive rise in the PE mode is related to photoelectric absorption around the K-absorption edge of Er element which happens at 50 keV. The fraction of attenuated gamma photons per unit thickness of the glass sample is represented by the parameter known as the linear attenuation coefficient (LAC). The LAC is measured as a unit inverse of the length. If the LAC value of

certain attenuator is high, then the number of transmitted photons through the attenuator is small, indicating this attenuator's good shielding characteristics [54]. For the $75\text{TeO}_2\text{-}10\text{Nb}_2\text{O}_5\text{-}10\text{ZnO}\text{-}5\text{PbO}$, (TNZP) glass system, we also evaluated the linear attenuation coefficient (μ) at the energy range under examination and we plotted the results in Figure 2.

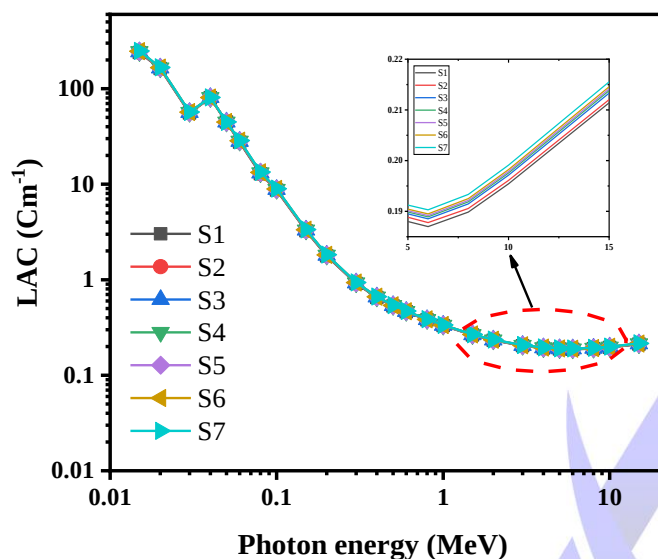


Fig. 2. Linear attenuation coefficients of the glasses in the energy range 0.015–15 MeV.

The μ curves for the S1– S7 samples presented in this figure have the same behavior to the findings of Sharma et al. [55] and Sayyed et al. [54] who evaluated the shielding factors for $\text{CaO-B}_2\text{O}_3\text{-SrO}$ glasses by two methods. Clearly, as we found in the previous curve, μ attains maximum values for all S1– S7 glasses at 15 keV and equal to 239.010, 240.422, 243.266, 244.512, 245.593, 246.768 and 248.565 cm^{-1} . for the samples with 0.0, 0.25, 0.375, 0.5, 0.625, 0.75 and 0.875 mol% of Er_2O_3 . The μ depends mainly on the density of the glass and this demonstrates the increment in the μ value with the addition of Er_2O_3 . In brief, we can observe from the μ curve that S1 ($\rho=5.5696\text{ g/cm}^3$) has the lowest μ and S7 ($\rho=5.6512\text{ g/cm}^3$) has the highest μ . For example, at 1 MeV, the μ values corresponding to the samples with density of 5.5696, 5.5968, 5.6081, 5.6170, 5.6222, 5.6295 and 5.6512 g/cm^3 are 0.331, 0.333, 0.333, 0.334, 0.334, 0.335 and 0.336 cm^{-1} respectively. This result implies that the glass specimen with high density can efficaciously absorb the gamma photons and it is suitable to be utilized as alternative protective glasses during different medical and industrial applications. Another important notice can be observed from the μ curve, the attenuation ability depends highly on the energy for the low energy zone, and this dependence diminishes with increasing the energy especially for $E > 1$ MeV. Let's explain this observation in one example and takes two energy ranges: 0.02–0.04 MeV and 2–4 MeV for the sample with 0.25 mol% of Er_2O_3 . In the first range; μ changes

from 163.122 to 80.248 cm^{-1} , while in the second range it changes only from 0.233 to 0.193 cm^{-1} . For the S1– S7 glass system, we also evaluated the Electronic Cross Section, (ECS) and Atomic Cross Section, (ACS) at the energy range under examination (between 15 keV and 15 MeV) and we displayed the results in Figure 3 and 4.

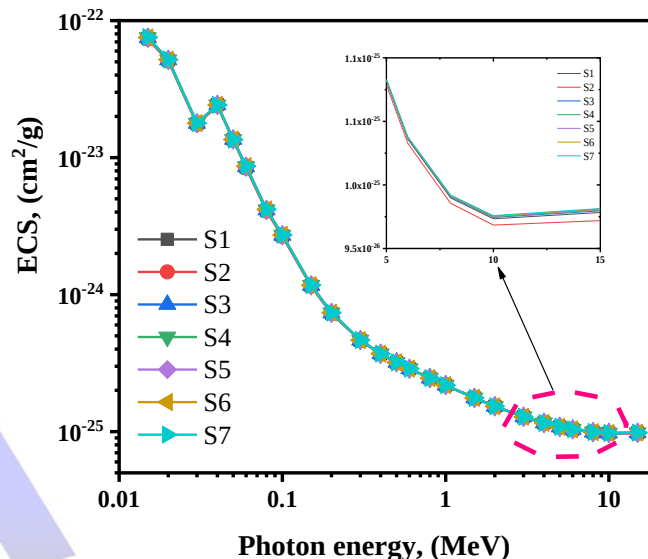


Fig. 3. Electronic Cross Section of the glasses in the energy range 0.015–15 MeV.

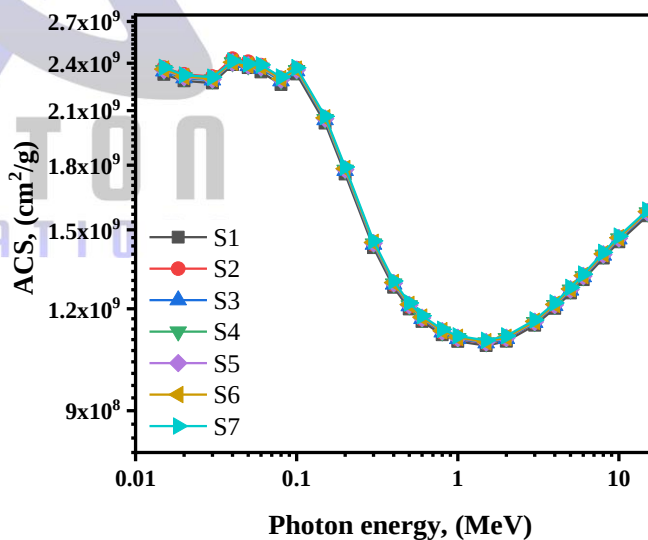


Fig. 4. Atomic Cross Section of the glasses in the energy range 0.015–15 MeV.

It is fundamental to note that the samples which possess high (ECS) and (ACS) values are more able to block or attenuate the incident photons respectively. The respective zoom-in photon energy regions of 5–15 MeV are shown as inset plots for Figure 3 and 4. Generally, for inorganic and organic materials, electronic, atomic and molecular cross-sections

can be measured in barn units ($1\text{ barn} = 10^{-24}\text{ cm}^2$). For all selected samples, one can notice that (ECS) and (ACS) values increase with high Z element (Er) increment at lower photon energies, while the changes in these values are minimal at higher energies. Moreover, at 0.04 MeV energy, all S1–S7 samples show a slight increase in (ECS) and (ACS) values (Figure 3 and 4) for S1–S7 glasses. At low photon energies about $\sim 40\text{ keV}$, mainly PE effect dominates due to electrons' presence in the samples, where the effects from nuclei are disordered only with various binding energies (BE) of electrons, as high Z materials impart higher BE for inner electrons [56]. The Z_{eff} behaviors for the Er_2O_3 doped glass samples depending on various energies (between 0.015–15 MeV) are displayed in Figure 5.

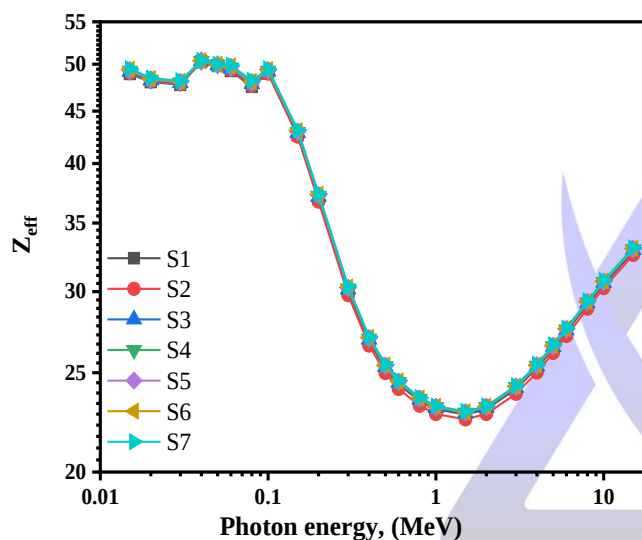


Fig. 5. The effective atomic numbers of 75TeO_2 - $10\text{Nb}_2\text{O}_5$ - 10ZnO - 5PbO glasses.

As can be seen in these results, there is decreasing order of Z_{eff} : $\text{Er}_2\text{O}_3 = (0.875, 0.75, 0.625, 0.5, 0.375, 0.25 \text{ and } 0.0 \text{ \% mol})$. The sample coded as $\text{Er}_2\text{O}_3 = 0.875$ possess the highest Z_{eff} at all the studied energies and could be understood from having a maximum amount of Er_2O_3 . This high Z_{eff} values mean that the gamma photon interacts more with $\text{Er}_2\text{O}_3 = 0.875$ sample. For this reason, the energy of the photons begins to rapidly minimize and so, penetrating of the photons reduces through $\text{Er}_2\text{O}_3 = 0.875$, while gamma photons have the highest penetrating value when interacting with $\text{Er}_2\text{O}_3 = 0.0$ sample (has no doping of Er_2O_3). Also, it is clear from Figure 5 that the Z_{eff} decreased with the increasing of the energy for tellurite glasses. This variation in Z_{eff} values versus the energy is in line with the results obtained by Agar et al. [57], Al-Hadeethi and Sayyed [58, 59]. S7 has superior photon attenuation competence, and high amount of Er_2O_3 is required to enhance this attenuation competence for the selected glass system. It is worth mentioning that the lowest Z_{eff} occurs at 1.5 MeV and equals to 32.82, 32.58, 32.94, 32.98, 33.02, 33.06 and 33.10 for S1– S7 glasses

respectively according to Al-Hadeethi and Sayyed [59]. Moreover, the trends of N_{eff} dependence on photon energy in all glasses are almost similar to those of Z_{eff} due to being inversely proportional to the average atomic weight of the material as seen in Figure 6.

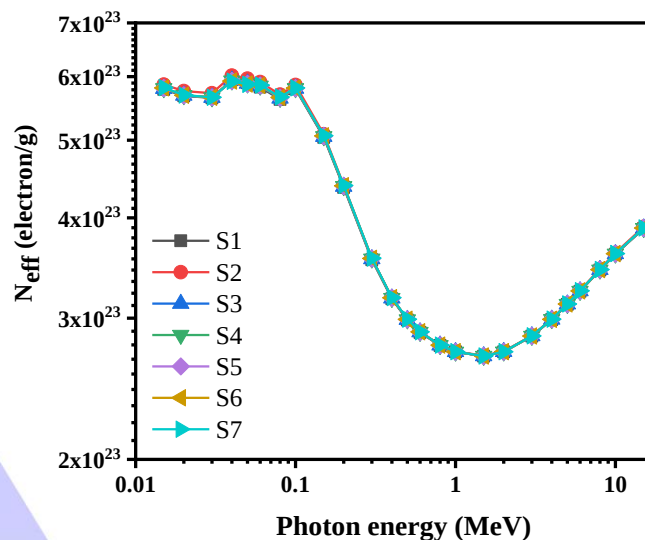


Fig. 6. The electron densities (N_{eff}) of the chosen glass systems.

Therefore, $\text{Er} = 0.0$ and $\text{Er} = 0.875$ glasses with Er-free and larger atomic weights have highest and lowest N_{eff} values. It is clear from Figure 6 that N_{eff} depends on the photon energy and chemical composition of the glass samples under investigation. At low energies ($E < 0.1\text{ MeV}$), N_{eff} has high values and it reduces with the increase in the energy, indicating the presence of more electrons per unit mass at lower energies. While, the minimum N_{eff} has been observed in the moderate energies and this is attributed to the domination of Compton scattering.

Moreover, for the TeO_2 - Nb_2O_5 - ZnO - PbO system, we determined the thickness of the specimen needed to minimize the intensity of the photons by 50% namely; the half value layer (HVL). The HVL for the S1– S7 specimens are plotted in Figure 7. From these curves, we can state that the HVL depends mainly on the energy and the amount of Er_2O_3 (or in other words the density of the glass). Let's explain the two factors in the next paragraphs. Firstly, Figure 6 revealed an increase of the HVL values when the energy changes from 15 keV to 15 MeV. The lowest HVL occurs at 15 keV for S7 and equals to 0.0028 cm, while the HVL at this energy for S1 equals 0.0029 cm. This demonstrates that the prepared samples had good attenuation at lower energies. Similar findings were also obtained for MoO_3 - WO_3 - TeO_2 glass [60]. The HVL increases to 3.547 cm (for S1) and 3.481 cm (for S7). This result implies that the likelihood of photon-glass interaction is very high if the energy of the photon is low, while this likelihood is small for high energy photons. Accordingly, large thickness of the glass is wanted to block

the high energy photons. Secondly, from Figure 7 one can observe that the addition of bismuth oxide affects the HVL, namely HVL decreases with the insertion of Er_2O_3 on the expense of TeO_2 . This is related directly to the relation between the density of the sample and the shielding potentiality of the sample. In brief, as we can see from Table 1, when the Er_2O_3 content increases from 0.0 to 0.875 mol%, the density increases from 5.5696 to 5.6512 g/cm^3 , and the chances of the photons to interact and absorb with the higher density sample may be higher than the lower density glass.

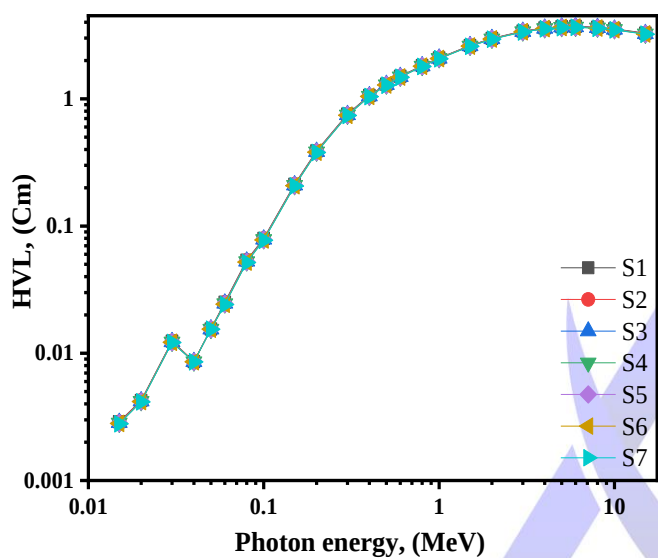


Fig. 7. The half value layer of (HVL) values of the glasses.

Table 1. Chemical composition of metal oxides in nanosize (mol%) and density (ρ) of the prepared glass samples.

Sample Code	Glass Composition in mol %	Density ρ (g/cm^3)
S1	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO	5.5696
S2	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.250 Er_2O_3	5.5968
S3	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.375 Er_2O_3	5.6081
S4	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.500 Er_2O_3	5.6170
S5	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.625 Er_2O_3	5.6222
S6	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.750 Er_2O_3	5.6296
S7	75 TeO_2 -10 Nb_2O_5 -5 PbO -10 ZnO -0.875 Er_2O_3	5.6512

For the two samples from S1 to S7 with the lowest and highest density, the HVL at 0.06 MeV is 0.025 and 0.024 cm, while the HVL corresponding to these two samples at 6 MeV are 3.707 and 3.642 cm. It is worth mentioning that for

estimating the possibilities of the tellurite glasses as a gamma attenuation absorber, it would be quite important to compare the photon shielding performances of the current glasses in terms of half value layer (HVL) with previously studied concrete types [61] and various commercially-available shielding glasses [62]. Figure 8 represents the comparison of HVLs of TeO_2 - ZnO - Nb_2O_5 - Gd_2O_3 glassy samples with other conventional concretes (barite, chromite, ferrite, magnetite) and commercial glasses (RS-253-G18, RS 360 and RS 520).

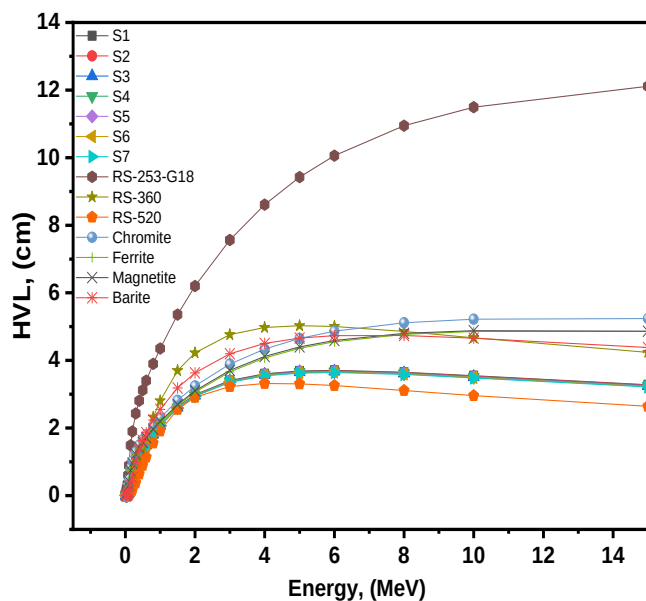


Fig. 8. Comparison of the half layer values (HVLs) (cm) of the investigated glass systems with other materials.

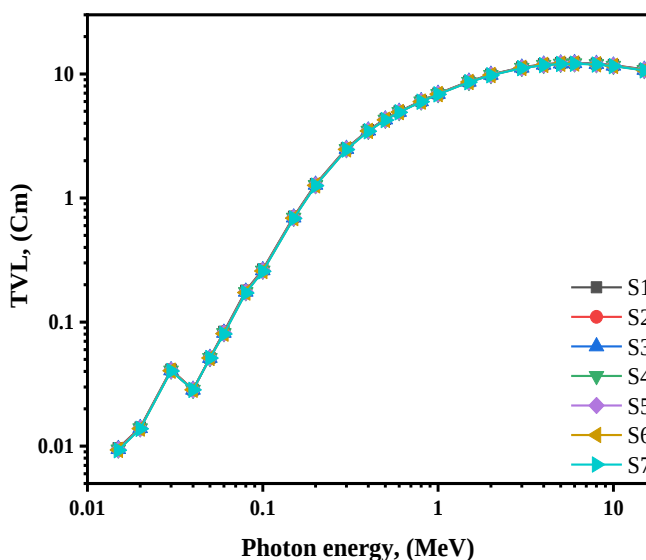


Fig. 9. Tenth value layer (TVL) values of the glasses.

It can be viewed that all the studied glasses possess lower

HVL than barite, ferrite, magnetite and chromite-based concretes and RS- 253-G18 and RS 360 glass types in the energy region of 0.015–15 MeV whereas higher than that of RS 520 which contains 71% PbO. The TVL values of the studied glasses are estimated using Eq. (8). Figure 9 represents the variation in TVL data against photon energy between 0.015–15 MeV.

Similar to MFP, HVL, TVLs of these glasses are quite low for lower photon energy up to $E < 0.1$ MeV while the values of TVL aggressively increase depending on energy after 0.1 MeV. The HVLs of the Er = 0.0, 0.25, 0.375, 0.5, 0.625, 0.75 and 0.875 glasses are found to be 10.892, 10.859, 10.794, 10.770, 10.752, 10.731 and 10.683 cm at 15 MeV, respectively. Therefore, the increase in the density as a result of adding Er enhances more than about 10% TVL reduction.

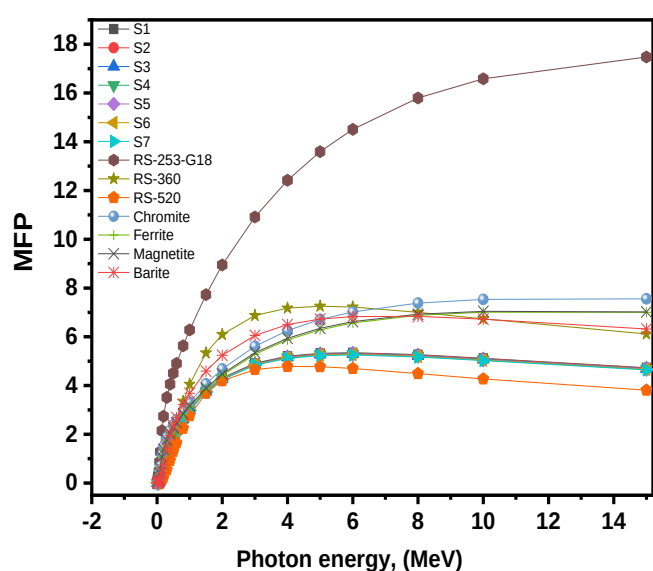


Fig. 10. Comparison of the mean free paths (MFP) (cm) of the glass systems investigated with other materials.

Figure 10 represents the comparison of MFP of $\text{TeO}_2\text{-ZnO-Nb}_2\text{O}_5\text{-Gd}_2\text{O}_3$ glassy samples with other conventional concretes (barite, chromite, ferrite, magnetite) and commercial glasses (RS-253-G18, RS 360 and RS 520).

It can be viewed that all the studied glasses possess lower MFP than barite, ferrite, magnetite and chromite-based concretes and RS- 253-G18 and RS 360 glass types in the energy region of 0.015–15 MeV whereas higher than that of RS 520 which contains 71% PbO. Figure 10, the $\text{TeO}_2\text{-Nb}_2\text{O}_5\text{-ZnO-PbO}$ glass system has better efficiency in terms of photons shielding when compared to some reference concretes and glasses used for several shielding applications.

Another parameter that can be calculated by photon transmission experiments is σ_{eff} (C_{eff}) relating to the number of free electrons in the materials formed by the photons coming into the material. This parameter is directly proportional to the densities and effective electron densities of the materials. The three major dominant events that occur during the photon-matter interaction can lead to changes in

the number of un-bonded (free) electrons of the material. This change can affect the effective electron density and hence the effective conductivity degree of the material. Therefore, the σ_{eff} values can be affected by the changes of photon energy. Thus, the change in the σ_{eff} value of a material can cause some of its properties such as conductance to change. For this reason, in this study, the σ_{eff} values of present alloys were determined both theoretically and experimentally, and the results obtained are exhibited in Figure 11.

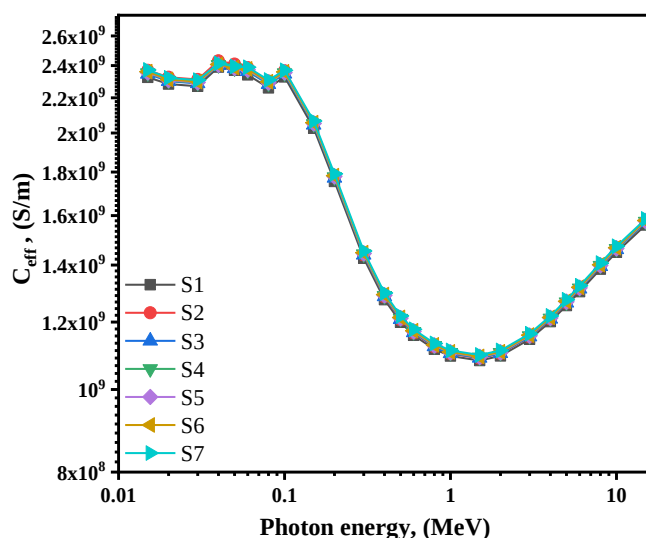


Fig. 11. The changes of σ_{eff} (C_{eff}) values against incident photon energy for present glasses.

According to results obtained, in Z_{eff} and N_{eff} values. Variations of the $R_{\text{inc}}/\text{total}$ values in the energy range of 0.015–15 MeV are shown in Figure 12.

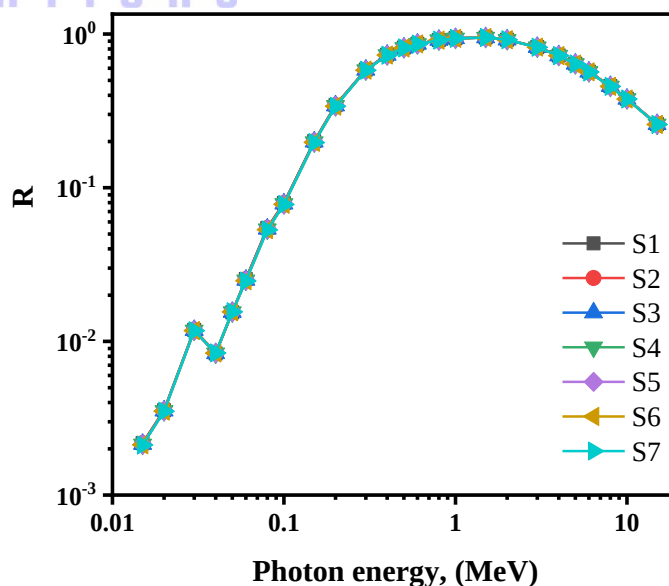


Fig. 12. Ratios $(\mu/\rho)_{\text{com}} / (\mu/\rho)_{\text{total}}$ for present glasses.

As it is known, Compton scattering is inelastic scattering and is dominant in the middle energy region. Given that the total cross-section is constant, the inelastic scattering cross-section reaches the maximum level within the specified range and is almost become independent of the material composition. In addition, as the energy increases the dominance of the pair-production increase and the probability of Compton scattering begins decreasing. Accordingly, $R_{inc}/total$ values tend to decrease after a certain maximum. When photons are absorbed in materials, the virtual atomic number that identifies the complex material is Z_{eff} , while this value is called Z_{eq} in the case of scattering. Figure 13 presents the changes in the Z_{eq} values of the seven different glasses examined.

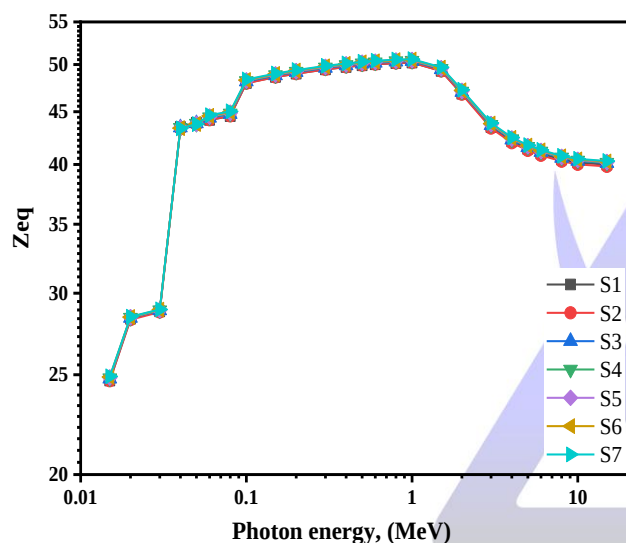


Fig. 13. Equivalent atomic number (Z_{eq}) values of the glasses.

Since $75TeO_2-10Nb_2O_5-10ZnO-5PbO$ (TNZP) glasses are composed of almost neighboring atoms in themselves, Z_{eq} values of these glasses do not show large energy-dependent fluctuations as in Z_{eff} , N_{eff} and σ_{eff} parameters. Effective removal cross-sections of fast neutrons (Σ_R) is an important parameter in designing any neutron shielding since it presents the probability that a fast neutron undergoes a first collision, which removes it from the group of penetrating uncollided neutrons [63]. The removal cross sections of fast neutrons (Σ_R), we used Phy-X/PSD software to evaluate Σ_R for the $75TeO_2-10Nb_2O_5-5PbO-10ZnO-xEr_2O_3$ (where $x = 0.00, 0.25, 0.375, 0.5, 0.625, 0.75$ and 0.875 % mol) glass system and we plotted the results in Figure 14.

The values of Σ_R , partial density, and composition for all glasses are given in Figure 14. It is clear that the obtained results of Σ_R are varied between 0.10721, 0.10837, 0.10775, 0.10786, 0.10789, 0.10797 and 0.10832 cm^{-1} from S1 to S7. It is obvious that the Σ_R values of the investigated glasses increase with increase the concentration of Er_2O_3 . Figure 14 shows a comparison of Σ_R of the glasses under study with some commonly used neutron shielding materials. It is seen

clearly that our prepared glasses are promising candidates for neutron shielding applications as compared with frequently used neutron shielding materials such as conventional concretes (barite, chromite, ferrite, magnetite) and commercial glasses (RS-253-G18, RS 360 and RS 520). Further, the neutron shielding features of our glasses are better than those commercial glasses (RS-253-G18, RS 360, RS 520 and barite). Σ_R values rely upon the physical and chemical properties of the glasses. These Σ_R results confirm that they change in accordance with transmission factor (TF).

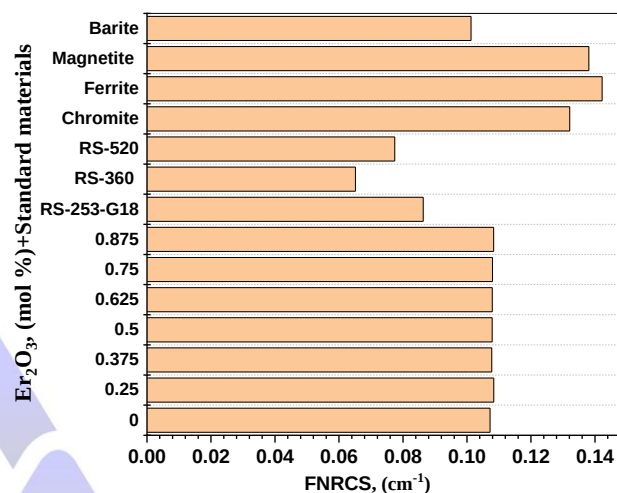


Fig. 14. Comparison fast neutron removal cross-section of (Σ_R) the investigated glasses systems with other materials.

4. CONCLUSION

In this study, the Er^{3+} ions doped glass systems with a composition of $75TeO_2-10Nb_2O_5-5PbO-10ZnO-xEr_2O_3$ (where $x = 0.00, 0.25, 0.375, 0.5, 0.625, 0.75$ and 0.875 % mol) by using the conventional quench-melting method. Radiation shielding parameters of Er^{3+} ions doped tellurite glasses used in optical applications for gamma and neutron rays were interpreted using many nuclear structure analyses such as; MAC, LAC, HVL, TVL, MFP, Z_{eff} , N_{eff} , C_{eff} , ACS, ECS, R, Z_{eq} , Σ_R , MSP, and PR. These analyses have been conducted for (S1 to S7) glasses in the energy region between 0.015–15 MeV. The mass attenuation coefficient (MAC) at 15 keV lies within the range of 42.91338–43.9844 cm^2/g for the selected samples. The μ/ρ for the investigated samples at 10 MeV is in the range of 0.03509–0.03523 cm^2/g and the linear attenuation coefficient (LAC) at 15 keV lies within the range of 239.01035 – 248.56466 cm^{-1} for the selected samples. The (LAC) for the investigated samples at 10 MeV is in the range of 0.19543 – 0.19911 cm^{-1} . The results also revealed that the addition of Er_2O_3 enhances the effective atomic number (Z_{eff}) and the sample corresponding to the lowest and highest amount of Er_2O_3 (coded as S1 and S7) has the lowest and highest Z_{eff} . Moreover, Z_{eff} has high values between 15 keV and 0.1 MeV and the maximum Z_{eff} occurs at 0.1 MeV (equal to 48.983, 48.963, 49.195, 49.264, 49.333,

49.401 and 49.469 for S1– S7 samples respectively). The half value layer (HVL) increased when the energy changes from 15 keV to 10 MeV and the lowest HVL occurs at 15 keV for the sample coded as S7 and equal to 0.00279 cm, while the HVL at this energy for S1 is 0.0029 cm. Also, we calculated the tenth value layer (TVL) for the present system and we found that TVL reduces with the increment of Er_2O_3 content, and the sample corresponding to 0.875 and 75 mol% of Er_2O_3 and TiO_2 respectively namely S7 possesses the lowest value of TVL, thus has the best radiation attenuation performance in comparison to other selected glasses. Also, we evaluated the effective removal cross-sections of fast neutrons (Σ_R) for the investigated glass system, and we found that the Σ_R values increase with increase the concentration of Er_2O_3 . The estimated MFP results for S1 to S7 glasses have been compared with some commercial shielding glasses and previously studied concretes. The shielding capacity for the investigated glasses has been observed to be comparable to those of the glasses and concretes (barite, chromite, ferrite, magnetite) and commercial glasses (RS-253-G18, RS 360 and RS 520).

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

A. Y. M. AbouDeif: Formal Analysis, Data Curation, interpretation of results and Original draft preparation,

Sample preparation, Experimental Work, Data collection, and interpretation of results.

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