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Investigation on Gamma Radiation Shielding Behaviour of $CdO–WO_3–TeO_2$ Glasses from 0.015 to 10 MeV

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Abstract. In the present study, the gamma radiation shielding properties of glasses in $CdO–WO_3–TeO_2$ ternary systems have been calculated using WinXCom program. The mass attenuation coefficient (μ_m), half value layer (HVL), effective atomic number (Z_{eff}) and electron density (N_{eff}) values for total photon interaction for a wide range of photon energies from 0.015 to 10 MeV have been estimated. The obtained results for the investigated glass systems have been compared in terms of HVL with some standard concrete and different glass samples in order to validate these glasses in point of the radiation shielding. Among the present glasses, G6 glass sample has the best shielding capability against gamma radiation.

Keywords: Glass, $CdO–WO_3–TeO_2$, attenuation coefficients, WinXCom.

$CdO–WO_3–TeO_2$ Camlarının 0.015–10 MeV için Gama Radyasyonu Zırhlama Davranışlarının Araştırılması

Özet. Bu çalışmada, $CdO–WO_3–TeO_2$ üç sistemli camların gama radyasyonu zırhlama özellikleri WinXCom program kullanılarak hesaplanmıştır. 0.015–10 MeV'lik geniş bir foton enerji aralığı için kütle zayıflatma katsayısı (μ_m), yarı-kalınlık değeri (HVL), etkin atom numarası (Z_{eff}) ve elektron yoğunluğu (N_{eff}) değerleri tahmin edilmiştir. İncelenen cam sistemlerini radyasyon zırhlaması açısından onaylamak için araştırmada elde edilen sonuçlar, bazı standart beton ve farklı cam örneklerinin HVL değerleri karşılaştırılmıştır. Mevcut camların içinde G6 örneği gama radyasyonuna karşı en iyi zırhlama yeteneğine sahiptir.

Anahtar Kelimeler: Cam, $CdO–WO_3–TeO_2$, zayıflatma katsayıları, WinXCom.

1. INTRODUCTION

Radiation shielding is required for protection from penetrative gamma-rays since radioactive sources are detrimental both to human health and to sensitive laboratory instruments. There are three parameters to attenuate intensity of gamma-rays: exposure time, distance from the source and shielding. Among these parameters, the most relevant technique on protection from nuclear radiation has been provided by shielding with a material of convenient thickness [1–3]. Therefore, the option of improvement and production of different content materials as preventive shielding for ionizing radiation has been of great interest. Utilization of traditional shielding materials such as concrete, lead (Pb) has some disadvantages such as: (i) difficulty of transportation from one place to another, (ii) opaque and unsuitable materials as transparent materials that can be used in various technological applications such as radiotherapy room, iodine injection and hot cell [4–7].

Glasses are particularly alternative matrices to the other standard materials because of their excellent

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transparency to visible light and absorbing high-energy gamma rays as well as being modifiable with different chemical compositions and preparation methods [8–10]. Recently, some glass systems have been experimentally [11–15], theoretically [16–20] and computationally [20–25] reported by a number of researchers in order to investigate their ability to different types of nuclear radiation attenuations.

Among various glass matrices, tellurite glasses are well-known to be the most attractive owing to easy of fabrication and some superior physical properties [16, 17, 26–30] such as high thermal and chemical stability, low-phonon energy, good infrared transmission, high refractive index and dielectric constant, etc. Tellurium oxide (TeO_2), however, does not possess glass shaping capability under normal quenching conditions. For this reason, the doping with network modifiers is necessary to compose the glasses based on tellurite. Addition of both WO_3 and CdO as a network modifier to tellurite glasses enhances many advantages such as the increasing devitrification resistance and chemical stability, change the composition by a third, fourth, and even fifth component, higher phonon energy and glass transition temperature, stabilizing the glass structure and improving the electrical properties [31–32]. The thermal and structural features of CdO–WO_3–TeO_2 glass system have previously investigated by Ersundu et al. [32] and the chemical compositions (mol %) of the glass system in their paper have considered.

The main objective of this study was to estimate the shielding parameters of glasses consisted of CdO–WO_3–TeO_2 ternary system by using WinXCom software in photon energy range from 0.015 to 10 MeV and compare the shielding ability for this glass system in terms of half value layer with those of different concretes and some glass systems reported in the literature.

2. THEORETICAL BASIS

The linear attenuation coefficient (μ) of any glass system is defined from the well-known exponential attenuation rule:

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

where I and I_0 are the transmitted and initial intensities, respectively, x is the penetration thickness (cm).

The mass attenuation coefficient (μ_m) is described for a compound and mixture by the relation [33]:

$$\mu_m = \frac{\mu}{\rho} = \sum w_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

where $(\mu/\rho)_i$ and w_i represent the mass attenuation coefficient value and the weight fraction of the ith element in the material, respectively. It is expressed in cm^2/g. The μ_m value of glass systems can be calculated for a specific energy range using WinXCom software based on the mixture rule [34].

Using the above basic parameter, it can be derived many absorption quantities such as total atomic and electronic cross sections, the effective atomic number and electron density, etc. The total atomic cross section (σ_a) can be determined as follow [35]:

$$\sigma_a = \frac{(\mu_m)_{glass}}{N_A \sum_i \frac{w_i}{A_i}} \quad (3)$$

where N_A shows the Avogadro number, w_i and A_i represent the fractional and the atomic weight of the ith element in any glass, respectively. It is expressed in cm^2/atom.

The total electronic cross section (σ_e) can be given as follows [36]:

$$\sigma_e = \frac{1}{N} \sum_i w_i \frac{f_i A_i}{Z_i} \quad (4)$$

where Z_i and f_i are the atomic number and the fractional abundance of the ith element. It is expressed in cm^2/electron.

The Z_{eff}, dimensionless quantity, can be obtained from σ_a and σ_e [37]:

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

The electron density (N_{eff}) is the electron numbers per unit mass of the interacting matter and given by [38]:

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

It is expressed in electron/g.

The half value layer (HVL) is the thickness at which the transmitted intensity is one-half the incident intensity for the gamma radiation and depends only on μ value [39]:

$$HVL = \frac{ln2}{\mu} \quad (7)$$

The mean free path (MFP) indicates the mean distance a photon can travel before interacting with the material. It has been estimated from μ as below [11]:

$$MFP = \frac{1}{\mu} \quad (8)$$

3. RESULTS AND DISCUSSIONS

The glasses on which gamma radiation shielding effectiveness is researched are consisted of different ratios of $CdO–WO_3–TeO_2$ ternary system [32]. The chemical compositions (mol %) and densities (g/cm^3) of the investigated ternary systems are given in Table 1.

Table 1. The coding, chemical compositions (mol %) and densities of the $CdO–WO_3–TeO_2$ glass system.

Sample Code	CdO	WO_3	TeO_2	Density (g/cm^3)
G1	5	5	90	5.82
G2	10	5	85	5.85
G3	5	10	85	5.90
G4	10	10	80	5.88
G5	15	15	70	6.13
G6	20	20	60	6.22

In this study, the fundamental gamma radiation shielding quantities of $CdO–WO_3–TeO_2$ glass systems were investigated using WinXCom package software [34] in the photon energy region of 0.1–10 MeV. The theoretically calculated quantities are: mass attenuation coefficients (μ/ρ), the effective atomic number (Z_{eff}), the electron density (N_{eff}), the half value layer (HVL) and the mean free path (MFP).

Fig. 1 represents the variations of total μ/ρ values for $CdO–WO_3–TeO_2$ glass samples depending on the photon energies. Apparently, in the low energy region (E <0.5 MeV), μ/ρ has large values and reduce rapidly with increments of photon energy. Additionally, it decreases more slowly in the intermediate energy region (0.5 MeV<E<5 MeV) whereas it became nearly constant for higher energies (E>6 MeV). These trends in μ/ρ values for glasses systems are arisen from different dominant interaction mechanisms at different energies such as photoelectric absorption mechanism in low energy region, Compton scattering in intermediate energy region and pair production in high energy region [40].

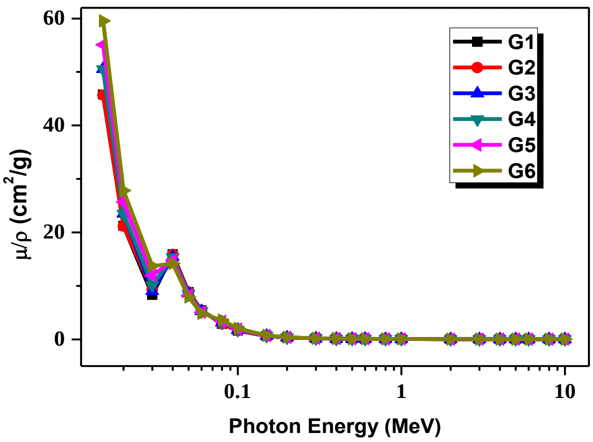

Figure 1. The mass attenuation coefficients (cm^2/g) of the studied glass systems.

The Z_{eff} and N_{eff} values of $CdO–WO_3–TeO_2$ glasses are estimated by using μ/ρ parameter. The variations of Z_{eff} and N_{eff} as a function of the photon energy for total interaction mechanisms in all ternary glass systems under investigation has been represented in Fig. 2 and Fig. 3, respectively. As seen in these two figures, the dependence of both parameters for the glasses on photon energy is almost similar to each other. The trend in N_{eff} is provided by Z_{eff} for mixtures and compounds since atomic number expresses information on number of protons (or electrons) for elements. From the other side, the present behavior of variations is described on the basis of dominance of different interaction mechanisms and can be easily clarified into well-known types of photon scattering with material. Below 0.1 MeV, the variations have discontinuities due to photoelectric absorption around the K-, L- and M-absorption edge of Cd, Te and W. Between 0.1 and 10 MeV, the Z_{eff} values show nearly energy independent behavior and this may be owing to dominance of the Compton scattering. Therefore, these quantities help in visualizing the interaction possibility of photons with various glasses.

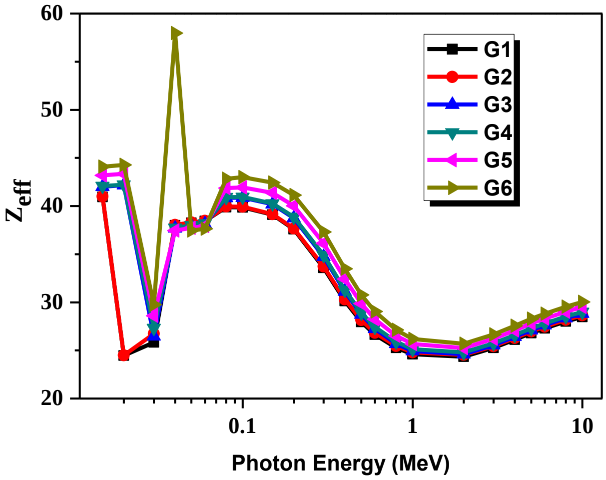

Figure 2. The effective atomic numbers (Z_{eff}) of the studied glass systems.

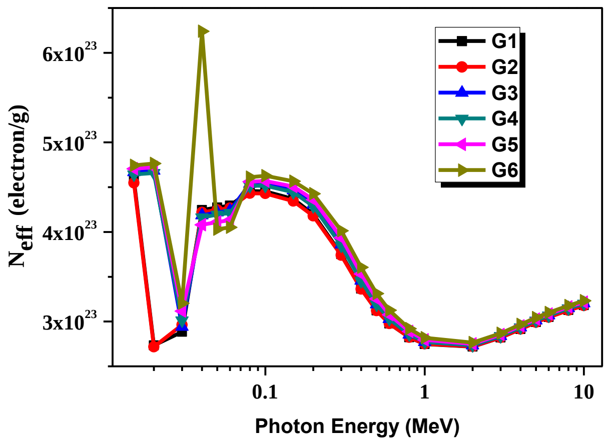

Figure 3. The electron densities (N_{eff}) of the selected glass systems.

Fig. 4 shows that the values of HVL for the present G1–G6 glasses increased with the increments in the incident photon energy. It is found that the HVL thickness is the lowest for G6 glass system with ρ=6.22 g/cm^3 and the highest for G1 glass system with ρ=5.82 g/cm^3. It can be easily expressed that the HVL values reduces with the increase of density; hence the shielding superiority increases with the density of the material.

In order to determine the characteristic of the selected glass systems and the possibility of development as a promising shielding material, it is required to compare the radiation shielding performance with previously published various materials (such as concretes, glasses). Therefore, the HVL thicknesses of $CdO–WO_3–TeO_2$ glass systems have been compared to some standard radiation shielding concretes and glass samples. The concrete types are ordinary, hematite–serpentine, ilmenite–limonite, basalt–magnetite, ilmenite, steel–scrap and steel–magnetite concretes [41]. Glass samples are different oxides (PbO, Bi_2O_3, CdO, Al_2O_3, SiO_2, B_2O_3) [39] and xBaO–5ZnO–5MgO–14Na_2O– 1Li_2O–(75-x)B_2O_3, where x=0, 10, 20, 30, 40 and 50 mol % [42]. The obtained HVLs have lower than all concretes (C1–C7) and glasses (S1–S7) while they are higher than those of Gl4, Gl5 and Gl6 glass samples having densities of 7.726, 7.801 and 8.284 g/cm^3, respectively [39]. Furthermore, the present results are a rather similar as those of Gl2 and Gl3 glass types.

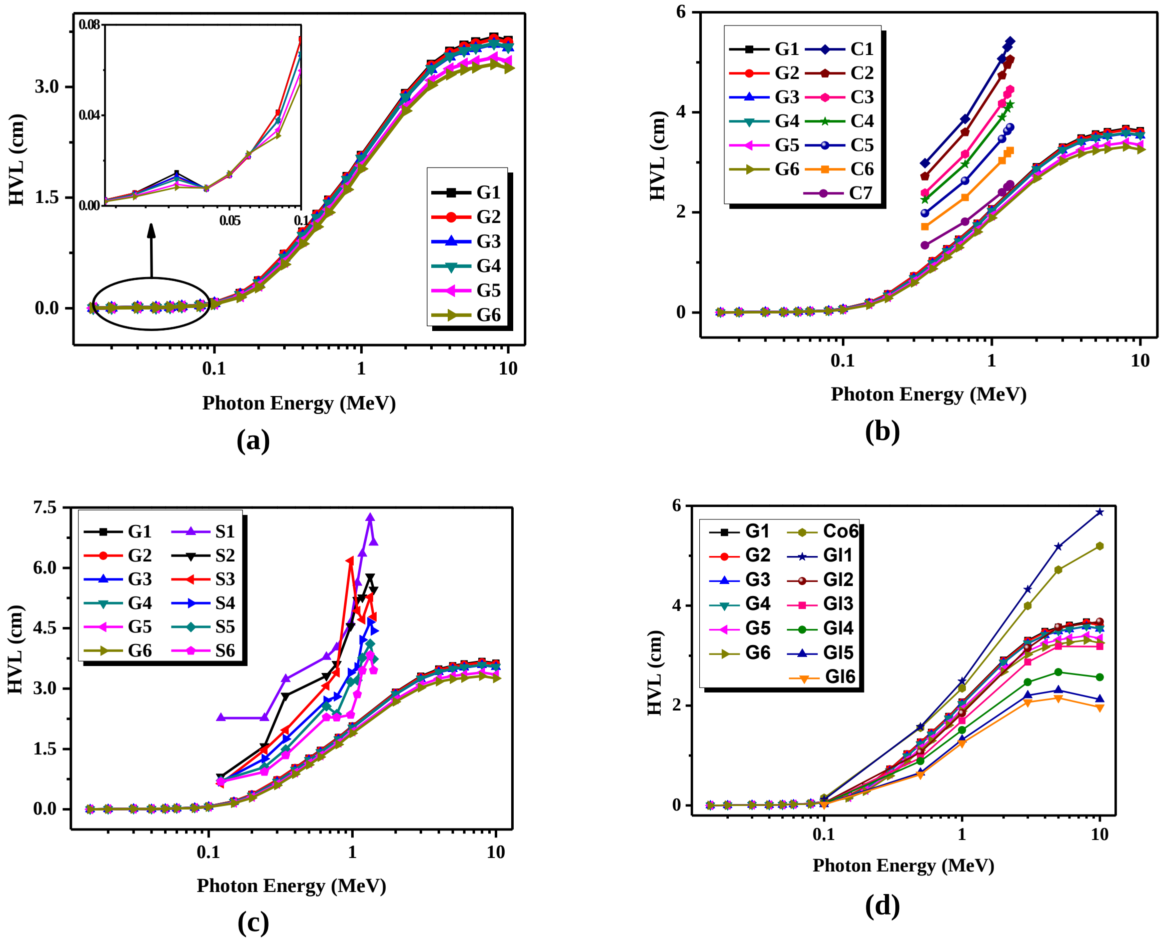

Figure 4. Comparison of half value layers (HVLs) of (a) the studied glass systems with (b) concrete [41] and (c-d) glass samples [39,42].

The variation of MFP for the present glass samples against photon energies is shown in Fig. 5. It can be separated three regions. Up to E<0.1 MeV energy region, the interaction of photons with the selected glasses is gradually reduced with increments of MFP. In 0.1<E<7 MeV region, it shows an increment in lesser rates. And finally, the MFP displays almost constant in value with increase of photon energy in higher energies (E>7 MeV). Smaller values of MFP among the glass systems indicate more performance of glass sample to attenuate the gamma rays photon of a specific energy and thus, better are the shielding capabilities.

4. CONCLUSIONS

The following conclusions have been drawn according the results from the present study:

- G6 glass system has the best shielding capability against gamma radiation among glass systems because of higher values of μ/ρ, Z_{eff} and lower HVL values.
- The calculated HVL values as a function the photon energy are corresponded with previously worked various materials. It is found that most of $CdO–WO_3–TeO_2$ glass systems show lower values of HVL in comparison to the standard radiation shielding concretes and the different glasses. These results are good indications that the $CdO–WO_3–TeO_2$ trenary glasses can be used as radiation shielding materials.

- The obtained results can be useful in various applications of radiation shielding materials.

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