Chalcogenide Letters Vol. 14, No. 3, March 2017, p. 113 - 118

ENHANCEMENT OF GAMMA RAY SHIELDING PROPERTIES BY PbO PARTIAL REPLACEMENT OF WO_3 IN TERNARY $60TeO_2$–(40-x)WO_3–xPbO GLASS SYSTEM

M. DONG[a], B. O.ELBASHIR[b,c], M. I. SAYYED[b*]
[a]*Department of Resources and Environmental, Northeastern University, Shenyang 110004, China*
[b]*Department of Physics, Faculty of Science, University of Tabuk, Tabuk, KSA*
[c]*Institute of laser, Sudan8 university of science and technology (SUST)*

The main aim of this work is to investigate the gamma ray shielding properties of ternary TeO_2–WO_3–PbO glass system. WinXCom software was used to calculate; mass attenuation coefficients (μ/ρ), effective atomic numbers (Ze_{ff}) and mean free path (MFP) for total photon interaction in the energy range of 1 keV to 100 GeV. For the purpose of this study this energy range was divided into three sub ranges, low, medium and high. PbO percentage in the tellurite glass contents was found one of the main reasons behind the change of values of μ/ρ and Z_{eff}. The tellurite glass with 40mol % PbO is found superior gamma-ray shielding. The obtained results of the selected glass systems were compared, in terms of MFP with some common shielding concretes in order to test the validity of these glass systems with respect to the radiation shielding. The shielding efficiency of the selected glasses is found better properties wise to that of common ones. The investigation was carried out to clarify the possibility of tellurite glasses to be used in different radiation shielding applications.

(Received January 9, 2017; Accepted March 31, 2017)

*Keywords:*Tellurite glasses; Effective atomic number; Mean free path; Gamma ray; WinXCom.

1. Introduction

In today world, tellurite glasses becomes well known as an ideal materials for various scientific and technological applications because of their excellent chemical and physical characteristics like high refractive index, low melting point (800 °C), high dielectric constant, good chemical resistance and low photon energy [1-4].It is recognized that TeO_2 is not a typical glass former; consequently it requires the addition of other components to form a glass. The addition of WO_3 to tellurite glasses leads to an increase in the devitrification resistance and chemical stability, while the addition of PbO to tellurite glasses lowers the melting temperature [5, 6].A considerable number of investigations have been reported on elastic [7], structural [8],Optical, thermal and electrical [1] properties of ternary TeO_2–WO_3–PbO glasses. Radiation shielding properties play a significant and major role in the selection of the glass for certain application because it supplies convenient details on the capability of a material to shield the radiation of specific energy. When dealt with concrete as a shielding material in nuclear reactors, it is found the most commonly used because of its distinguishable properties in that field. Economically it is cheap and adaptable for any building design. Moreover, concrete has an acceptable strength and density for attenuation of gamma rays. However concrete has many drawbacks [9] such as: (1) crack formation due to prolonged exposure to nuclear radiations (2) variability in its water content as a result of evaporation of water at high gamma ray energies which leads to uncertainty in calculations for shield design and (3) non-transparency to visible light due to which it is not possible to see through concrete based shield design. According to this

[*]Corresponding author: mabualssayed@ut.edu.sa

situation, it is necessary to develop better gamma ray material which can act as an alternate to concrete. Glass can be a good alternate for the concrete as gamma ray shielding material [10].

Interaction of radiation with shielding materials can be described by some essential parameters like, the mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}), half value layer (HVL) and mean free bath (MFP). The mass attenuation coefficient measures the rate of energy loss by gamma ray as it penetrates a medium. It is the important tool utilized to obtain the effective atomic number and mean free path. Effective atomic number (Z_{eff}) is quantity that characterizes the properties of the mixtures and compounds in terms of equivalent elements, and it changes with photon energy. On the other hand, the gamma ray interaction with a medium can be describes by the mean free path which represents the average distance traveled by a photon in a medium before the interaction occurs [11]. Recently tellurite glasses are reported as materials that can be used in radiation shielding purposes. Some of shielding parameters for boro-tellurite glasses [2] and zinc boro-tellurite glasses were calculated [4]. This work comes as continuity in the line of research work on this type of glasses.

In this work, we report theoretical computation of the mass attenuation coefficients (μ/ρ), effective atomic numbers (Z_{eff})and mean free path (MFP)of ternary TeO_2–WO_3–PbO glass system using WinXCom program [12]. We discuss the influences of PbO content in $60TeO_2$–(40-x)WO_3–xPbOwhere x=0 to40mol %in the interval of 10 mol%) glass system. The chemical composition and density of the selected glasses selected for this work have been given in Table 1, the density was obtained from [1].

Table 1.Glass compositions and density of the $60TeO_2$–(40-x) WO_3-xPbO glass system

Glass sample	TeO_2	WO_3	PbO	Density (gcm^{-3})
TWP1	60	40	0	6.392
TWP2	60	30	10	6.508
TWP3	60	20	20	6.621
TWP4	60	10	30	6.724
TWP5	60	0	40	6.819

2. Calculation method

Photoelectric absorption, coherent scattering, incoherent scattering and pair production are the interactions the photon will undergo during its passage through a material medium. If $I_0$is an initial intensity of a photon beam penetrates the matter, it wills experiences attenuation and its intensity decreases exponentially according to the Beer–Lambert law [13]:

$$I = I_0 \exp[^{-(\mu/\rho)x}] \tag{1}$$

where I_0 is the incident intensity, I is the transmitted intensity, *x* is sample mass thickness and *μ/ρ* is the mass attenuation coefficient (cm^2/g).

For interactions occurs between the incident photon and matter, the mass attenuation coefficient can be defined as a measure of probability per unit mass per unit area. The *μ/ρ* values for gamma ray and X ray beams are valuable for verity of applications in the diverse fields such as radiation dose calculation, nuclear application in medicine, radiography, geophysical prospecting and radiation safety.

As in our case and for a chemical mixture composed of various elements and compounds, the mass attenuation coefficient of the mixture *μ/ρ* is given by

$$\mu/\rho = \sum_i w_i(\mu/\rho)_i \tag{2}$$

Where $(\mu/\rho)_i$ and w_i represents the mass attenuation coefficient respectively and the fractional weight of the i^{th} constituent in the mixture, $(\mu/\rho)_i$ was obtained from WinXCom [12].

The following relation is useful in the calculations of the mean free path

$$MFP = \frac{1}{\mu} \tag{3}$$

Where: μ represents the linear attenuation coefficient; which is equal to multiplication of mass attenuation coefficient value and density of the glass sample and measured in (cm^{-1}).

The effective atomic number, (Z_{eff}), is the ratio between the total atomic effective cross-section and the total electronic effective cross-section [14]:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{4}$$

The mass attenuation coefficient can be used to evaluate the total atomic cross-section (σ_a) using the following equation

$$\sigma_a = \frac{\mu/\rho}{N_A \sum_i \frac{w_i}{A_i}} \tag{5}$$

Where A_i is the atomic weight of element i, and N_A is the Avogadro constant.
In addition, the total electronic cross-section, (σ_e), is expressed by the following equation

$$\sigma_e = \frac{1}{N_A}\sum_i \left(\sum_j \frac{f_j A_j}{Z_j}\right) w_i \tag{6}$$

Where f_i and Z_i are respectively the fractional abundance and the atomic number of the element ith.

3. Results and discussion

The variations of the mass attenuation coefficient, within photon energy, of the selected glass systems in the energy region (E < 500 keV) and (E >500 keV) are shown in Fig.1 and Fig. 2 respectively. For the purpose of discussion of this work we will call the energy ranges (1 KeV to 500KeV, 500 KeV<E<10 MeV and E>10 MeV) low, intermediate and high ranges respectively. When tackling its relation with the incident photon energy in the low energy range for the studied glass shielding, mass attenuation coefficient (μ/ρ)found tending to decrease exponentially with the increase of the energy as illustrated in Fig.1. Values of μ/ρ of the selected glass specimen are very large in this energy region and decrease rapidly with the increase of energy; this can be seen easily in the same figure. Also, in this energy region, values of μ/ρ were observed not of a continuous mode at different energies due to K-, L- and M-absorption edge of Te, W and Pb as exhibited in Table 2.While μ/ρ values for E >150 MeV tend to become constant when energy values increased, it can be seen in the intermediate energy regionμ/ρ values decrease at a slower rate (Fig. 2).Variations in μ/ρ values are explainable according to the three well-known photon scattering in matter. While photoelectric effect and pair production processes appearing at lower and higher energy regions, Compton scattering process on the other hand is the dominate one within the intermediate energy region [4]. Additional amounts of PbO in tellurite glasses content results in an increase of μ/ρ values. As illustrated in Fig. 2 that the μ/ρ values for TWP5which contains40mol% PbO are the largest percentages in the tellurite glasses contents. This will lead to conclude that this sample can be considered as a promising gamma ray shielding glasses.

Table 2.Photon energies (in KeV) of absorption edges for elements.

Element	Z	M5	M4	M3	M2	M1	L3	L2	L1	K
Te	52	-	-	-	-	1.01	4.34	4.61	4.94	31.18
W	74	1.81	1.87	2.28	2.58	2.82	10.21	11.54	12.10	69.53
Pb	82	2.48	2.59	3.07	3.55	3.85	13.04	15.20	15.86	88.00

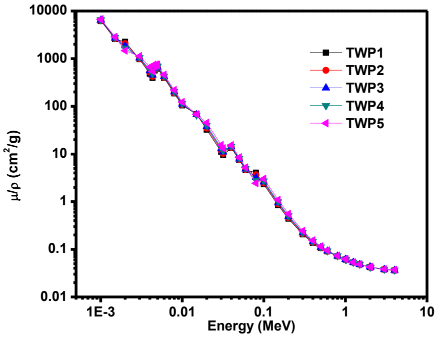

Fig.1. Mass attenuation coefficients for TeO2–WO3–PbO glass system in the energy region (E < 500 keV).

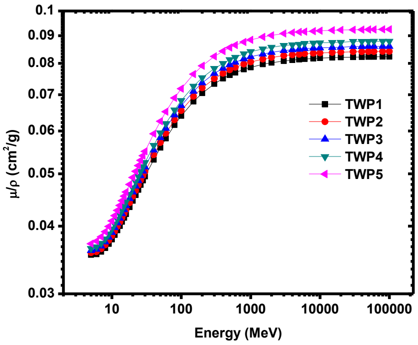

Fig.2 Mass attenuation coefficients for TeO2–WO3–PbO glass system in the energy region (E >500 keV).

For total interaction process inside the selected glass specimen (tellurite glasses), the variation of Z_{eff} is shown in Fig. 3taking into account that the values of atomic numbers and atomic masses of the elements were taken from IUPAC [15].It is noticeable that, Z_{eff} for all tellurite glass samples increases with the increment of the incident photon energy. Sudden jumps are seen at 31.18KeV, 69.53 KeV and 88.00KeV (Fig. 3). These jumps can be explained in the light of k edge absorption of Te, W and Pb respectively. Regarding the energy range 30 keV to 800keV, a noticeable decrease in the effective atomic number (Z_{eff}) happened with the increase of the incident photon energy for all the glass samples. An explanation for this can be done based on the dependence of cross-section of photoelectric process which varies inversely with the photon energy as $E^{-3.5}$. With further amounts of photon energy in the range 800 KeV-3 MeV, Zeff value wise becomes nearly independent of photon energy, for all the glass samples. Dominance of Compton scattering process may be one of the reasons behind that. As the photon energy increases above 3.0 MeV, the value of Zeff slowly increases and becomes nearly constant above 80 MeV. In the light of dominance of pair production in this higher energy region phenomenon is acceptable.

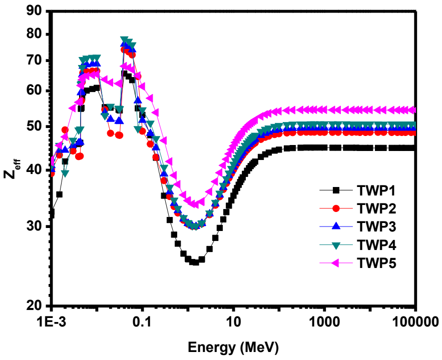

Fig. 3 Variation of effective atomic number with photon energy in range of 1 keV to 100 GeV for TeO2–WO3–PbO glass system.

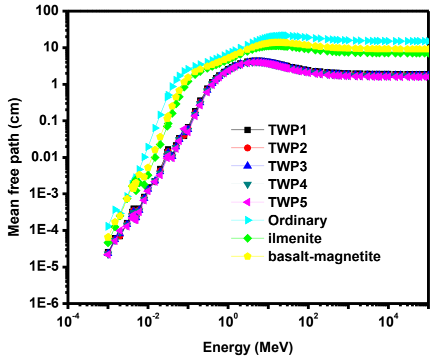

Fig. 4 Comparison of mean free path for TeO2–WO3–PbO glass system with those of shielding concretes.

The average traveled distance between two successive photon interactions can be represented by what called mean free path (MFP).Whenever we find the shorter MFP this will indicates more interaction of photons to material and consequently the better shielding properties are achieved.

For tellurite glasses, the collected results were compared in terms of MFP values with some standard radiation shielding concretes (ordinary, ilmenite and basalt magnetite) [16]. The results are graphically exhibited in Fig. 4. Fromthis figure, it has been noticed that our glass samples have got lower values of MFP when compared with the selected standard concretes. These results gave a good indication that the studied sample of glass in the present work can be considered as one of the promising radiation shielding materials

4. Conclusions

For different molar concentrations of PbO for photon energy 1 keV to 100 GeV and by using WinXCom program, the mass attenuation coefficient, the effective atomic number and mean free path of tellurite glasses were calculated.

According to the collected results, the values of μ/ρ and Z_{eff} were found tend to increase with increasing gamma energy and PbO concentration.

The μ/ρ and Z_{eff} of sample TWP5 (which is having maximum contribution of Pb) is maximum and the effective atomic number of other samples reduces with the reduced percentage of Pb. Hence, among the selected samples, TWP5 provides better shielding for gamma rays.

The glasses of all PbO studied compositions showed lower values of MFP than some of standard shielding concretes in the selected energy region.

This study provided sufficient information for these glasses for design and applications as shielding materials in various applications in nuclear engineering and technologies.

References

[1]G.Upender, V.Chandra Mouli J. Mol. Struct.**1006,** 159(2011).
[2] M. I. Sayyed,Elhouichet H. Radiat. Phys. Chem.**130,** 335(2017).
[3] M. I. Sayyed,J. Alloys Compd. **695,** 3191 (2017).
[4] M. I. Sayyed,J. Alloys Compd. **688,** 111 (2016).
[5]M.Çelikbilek, A. E.Ersundu, S.Aydin J. Am. Ceram. Soc. **96,** 1470 (2013).
[6] V.Dimitrov, S.Sakka J. Appl. Phys. **79,** 1741(1996).
[7] S.Azianty,A. K. Yahya J. Non-Cryst. Solids **378,** 234 (2013).
[8] D.Munoz-Martín, M. A.Villegas, J.Gonzalo,J. M.Fernández-Navarro,J. Eur. Ceram. Soc. **29,** 2903 (2009).
[9] C.-M.Lee, Y.H.Lee,K.J.Lee,Prog.Nucl.Energy **49,** 303 (2007).
[10] M. I. Sayyed, Can. J. Phys. **94,** 1133 (2016).
[11] M.I. Sayyed Chin J. Phys. **54,** 408 (2016).
[12] L.Gerward, N.Guilbert,K. B.Jensen,H.Levring,Radiat. Phys. Chem. **71,**653 (2004).
[13]Y.Elmahroug, B.Tellili,C.SougaAnn. Nucl. Energy **75,** 268 (2015).
[14]Y.Elmahroug, B.Tellili, C.Souga, K.ManaiAnn. Nucl. Energy**76,** 94 (2015).
[15] E. W.Michael, et al. Pure Appl. Chem. **85,** 1047 (2013).
[16]I. I.BashterAnn. Nucl. Energy **24,** 1389 (1997).