Eurasian Journal of Physics and Functional Materials

2021, 5(2), 126-132

Study of gamma radiation shielding efficiency by $0.5TeO_2$-(0.5-x)Bi_2O_3-xWO_3 glasses

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DOI: **10.32523/ejpfm.2021050205**
Received: 27.04.2021 - after revision

This article is devoted to the study of determination of gamma radiation shielding efficiency by new radiation-resistant glasses of the $0.5TeO_2$-(0.5-x)Bi_2O_3-xWO_3 type. As a method of obtaining glasses, the method of solid-phase synthesis combined with thermal annealing and subsequent hardening was used. The amorphous nature of the synthesized samples was confirmed by X-ray phase analysis. Determination of the shielding efficiency, as well as the effect of Bi_2O_3 and WO_3 content in the glass composition on the attenuation efficiency was carried out by evaluation of gamma radiation intensities from the ^{137}Cs source, with a gamma ray energy of 661 keV. The evaluation was performed on parameters such as radiation protection efficiency, linear and mass attenuation coefficients, half-value layer and mean free path. During the studies, it was found that glasses of the following composition $0.5TeO_2$-$0.1Bi_2O_3$-$0.4WO_3$ are most effective, which are 1.3-2 times higher than those of the composition $0.5TeO_2$-$0.4Bi_2O_3$-$0.1WO_3$.

Keywords: glasses, radiation protection efficiency, mean free path, half-value layer, TeO_2-Bi_2O_3-WO_3.

Introduction

Today, the widespread use of sources of ionizing radiation has led to an expanded search for new materials capable of high shielding efficiency [1, 2]. As a rule, conventional shielding materials are lead and concrete, which, despite their high absorption and attenuation efficiency, have a number of significant disadvantages. These disadvantages for lead include high toxicity, low melting point, limiting their use at elevated temperatures. Concrete products, in turn, are limited by crack resistance and mechanical resistance [3-5].

In turn, one of the alternative methods of protecting against the negative effects of ionizing radiation is telluride glasses, which contain oxides of rare-earth elements [6-10]. This type of glass has high performance of shielding and attenuation of ionizing radiation, especially gamma-quantum and neutron radiation, which have a high penetrating ability. Also, telluride glasses have good transparency indicators, which makes them promising materials for areas where direct visual observation of sources of ionizing radiation and their effects is necessary [11-15].

At the same time, despite quite a large number of scientific works in this area of research [16-27], there are still many unresolved issues related to the search for optimal compositions and structural compounds, which will combine high absorbing and weakening ability, as well as minimum thickness. One of the promising compositions for shielding materials is a composition containing TeO_2, Bi_2O_3, WO_3, a combination of which allows obtaining high values of density, stability and values of shielding efficiency [28-30]. The main purpose of this article is to study the effect of changing the stoichiometry of the selected TeO_2-Bi_2O_3-WO_3 composition on the shielding characteristics and attenuation of gamma radiation with an energy of 662 keV. The relevance of this work lies in the development of technologies for the production of radiation-resistant glasses and their potential use.

Experimental part

The objects of study were $0.5TeO_2$-$(0.5\text{-}x)Bi_2O_3$-xWO_3 glasses with different contents x=0.1-0.4. The synthesis of glasses with different stoichiometric compositions was carried out using the method of solid-phase synthesis followed by thermal annealing at a temperature of $1100\,^{\circ}$C. Annealing was carried out for 5 hours, followed by taking out the samples and hardening in air. As a result of the performed procedures, a series of glass samples with good transparency and crack resistance were obtained.

The study of the phase composition and crystalline nature of the glasses under study was carried out using the X-ray diffraction method, performed on a D8 Advance ECO X-ray diffractometer (Bruker). The survey was carried out with the Bregg-Brentano geometry.

The shielding efficiency was determined according to the standard scheme for measuring the intensity of gamma radiation and its reduction as a result of the use of protective shields. Intensity measurement was carried out using a NaI detector located at a distance of 10 cm from a gamma radiation source located in a lead box with an opening at the end with a diameter of 1 cm. The source of gamma radiation was ^{137}Cs, with a gamma ray energy of 661 keV.

The exposure time of the dose acquisition in order to determine the shielding efficiency was carried out for 2 hours and 5 consecutive measurements in order to obtain statistical data and determine the measurement errors.

The change in Radiation protection efficiency (RFE) value, which reflects the efficiency of reducing the transmitted gamma radiation intensity by a protective shield, was carried out according to the standard method of comparative analysis of gamma radiation intensity before and after transmission and was calculated using the equation (1) [29]:

$$RFE = (1 - \frac{I}{I_0}) \times 100\%, \tag{1}$$

where I and I_0 are the spectral intensities before and after shielding.

The values of the linear attenuation coefficient (μ) and the mass absorption coefficient of gamma radiation (μ_m) by the protective shield were estimated using equations (2) and (3):

$$\mu = \frac{\log I_0/I}{d}, \tag{2}$$

$$\mu_m = \frac{\mu}{\rho}, \tag{3}$$

where I_0 is initial intensity value, I is the intensity value after shielding; d is thickness, ρ is the glass density.

The half-value layer (HVL) and mean free path (MFP) coefficients, which make it possible to determine the required thicknesses of protective shields in order to attenuate the radiation intensity by 50% and the average distance between two successive interactions of gamma quanta with the crystal structure, were determined using equations (4) and (5) [29, 30]:

$$HVL = \frac{0.693}{\mu}, \tag{4}$$

$$MFP = \frac{1}{\mu}, \tag{5}$$

Results and discussion

Figure 1 shows the results of studies of the phase composition of the synthesized glasses depending on the concentration of Bi_2O_3 and WO_3. The general view of the presented diffraction patterns testifies to the amorphous nature of the synthesized glasses, which is confirmed by the absence of obvious diffraction reflections in the obtained diffraction patterns. At the same time, a change in the concentration of Bi_2O_3 and WO_3 leads to the formation of a halo peak in the area of 2θ=23-30°, however, full reflexes characterizing the presence of an ordered structure are not observed for all samples.

Due to the amorphous nature of the synthesized glasses, density determination was carried out using a standard procedure for immersing the test samples

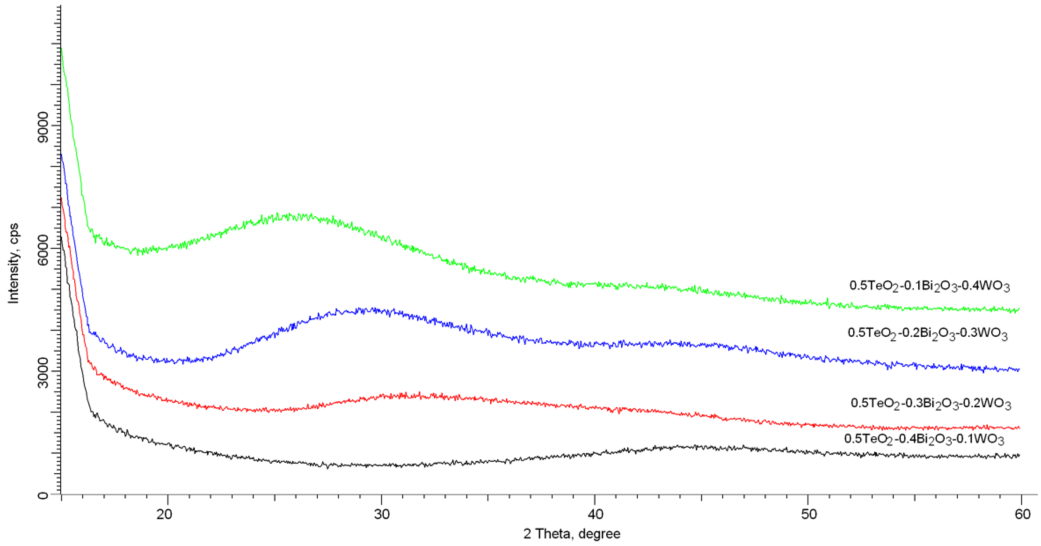

Figure 1. Dynamics of X-ray diffraction patterns of the studied samples of $0.5TeO_2$-$(0.5$-$x)Bi_2O_3$-xWO_3 glasses.

in a liquid and subsequent calculation according to the Archimedes method. According to the data obtained, a change in the concentration of Bi_2O_3 and WO_3 in the composition of glasses leads to an increase in the density of the synthesized glasses from 7.09 g/cm^3 for the $0.5TeO_2$-$0.4Bi_2O_3$-$0.1WO_3$ sample, to 7.24 g/cm^3, 7.29 g/cm^3, and 7.54 g/cm^3 for samples $0.5TeO_2$-$0.3Bi_2O_3$-$0.2WO_3$, $0.5TeO_2$-$0.2Bi_2O_3$-$0.3WO_3$ and $0.5TeO_2$-$0.1Bi_2O_3$-$0.4WO_3$, respectively. The increase in glass density depending on the change in concentration of the components is due to the difference in density of the initial components, as well as their weight. The change in density is known to lead to a decrease in oxygen packing density and a decrease in the porosity of the glasses, which has a significant effect on both strength characteristics and shielding ability.

Figure 2 shows the results of the change in radiation protection efficiency depending on the concentration of WO_3 in the composition of TeO_2-Bi_2O_3-WO_3 glasses. The data obtained indicate that in the case where the concentration of WO_3 in the glass composition is 0.1-0.2, the value of the decrease in the intensity of gamma radiation passing through the shield was less than 50%, which indicates a rather low shielding efficiency. However, an increase in the concentration of WO_3 in the glass composition leads to an increase in shielding efficiency by 5-15%, which is associated with an increase in the density of the glass, as well as a change in its electronic structure as a result of a change in the stoichiometric ratio of the components.

Two important parameters for estimating the shielding efficiency are linear and mass attenuation coefficients of the intensity of gamma radiation transmitted through the material. These parameters make it possible not only to evaluate the required thicknesses for effective radiation protection, but also to carry out a comparative analysis with other various protective materials. Figure 3 shows a graph of changes in these values depending on the concentration of WO_3. As is known, for gamma quanta with energies above 0.5 MeV, the main processes of interaction with matter, leading to energy loss and beam weakening, are the formation of electron-positron pairs and subsequent cascade effects leading to

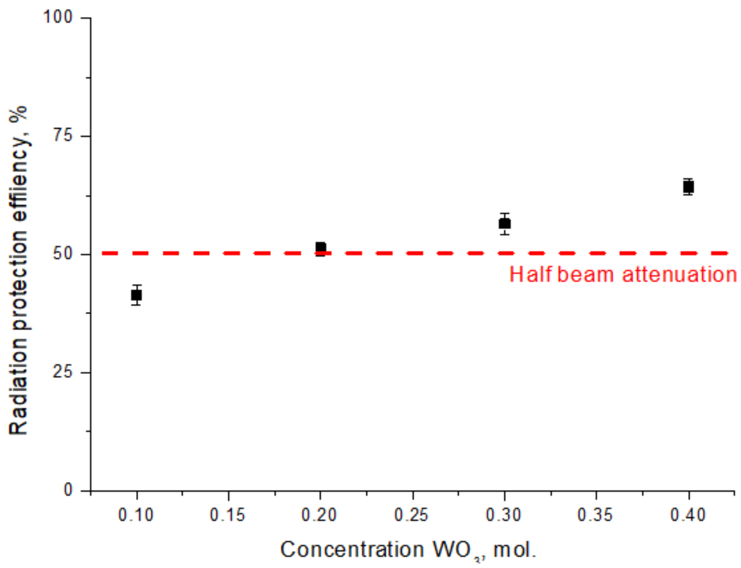

Figure 2. Graph of the dependence of the change in the radiation protection efficiency on the WO_3 concentration in TeO_2-Bi_2O_3-WO_3 glasses.

a change in the electron density in the matter. At the same time, an increase in glass density, and therefore a change in electronic states, leads to an increase in intensity reduction due to large energy losses of gamma quanta in the glass structure. At the same time, an increase in the concentration of WO_3 in the composition of glasses leads to an increase in attenuation coefficients by more than 1-1.5 times.

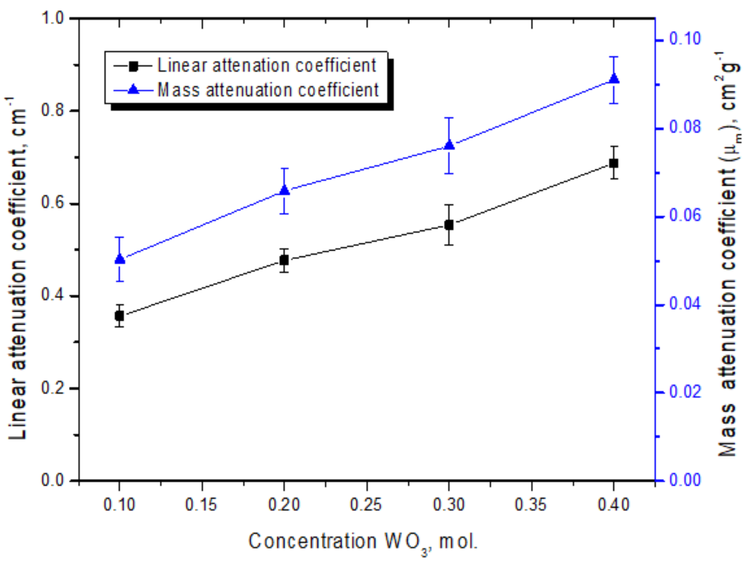

Figure 3. Graph of the dependence of the change in the linear and mass attenuation coefficient of gamma radiation on the concentration of WO_3 in the composition of TeO_2-Bi_2O_3-WO_3 glasses.

Figure 4 shows the results of changes in half value layer and mean free path values for synthesized glasses depending on the concentration of WO_3, which characterize the required glass thicknesses to attenuate 50% of radiation, which is a standard value in the development of safety standards for the use of protective shielding materials.

It can be seen from the presented data that in the case of $0.5TeO_2$-$0.4Bi_2O_3$-$0.1WO_3$

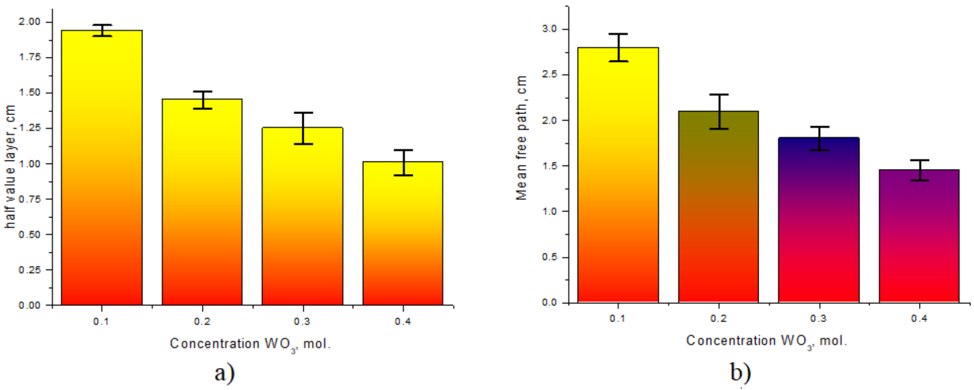

Figure 4. Graphs of half value layer (a) and mean free path (b).

composition, the glass thickness should be at least 1.9 cm in order to halve the gamma-ray flux. At the same time, an increase in WO_3 concentration leads to a significant decrease in the half value layer and mean free path, which indicates an increase in gamma radiation shielding efficiency.

Conclusion

By analyzing the data obtained, we can come to the following conclusion. Changing the stoichiometry of the glasses, in particular increasing the concentration WO_3 leads not only to an increase in density, and therefore a decrease in porosity, but also to an increase in the shielding efficiency and gamma radiation attenuation. At the same time, glasses of the following composition $0.5TeO_2$-$0.1Bi_2O_3$-$0.4WO_3$ are most effective. Such high efficiency indicators, which are 1.3-2 times higher than the same for the composition $0.5TeO_2$-$0.4Bi_2O_3$-$0.1WO_3$ are due not only to the change in glass density, but also to the electronic configuration and vacancy density, and therefore to the value of Z_{eff}, which directly depends on the glass composition. The data obtained are also in good agreement with the literature data [18-20] devoted to the study of the efficiency of WO_3 doping in various types of glasses and radiation-resistant ceramics. The prospect of the obtained data on the shielding efficiency opens up wide opportunities not only for the development of technology for creating such glasses, but also for further research in this direction in order to increase the shielding efficiency.

Acknowledgements

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (No. AP09562301).

References

[1] E. Schmid et al., Journal of Radiological Protection **32**(3) (2012) N129.
[2] Yue Kun et al., Radiation protection dosimetry **133**(4) (2009) 256-260.

[3] N.J. AbuAlRoos et al., Radiation Physics and Chemistry **165** (2019) 108439.
[4] H.M. Soylu et al., Journal of Radioanalytical and Nuclear Chemistry **305**(2) (2015) 529-534.
[5] M. Alwaeli, Journal of Cleaner Production **166** (2017) 157-162.
[6] H. Algarni et al., Science of Advanced Materials **10**(6) (2018) 818-826.
[7] M.E. Camilo et al., Thin solid films **571** (2014) 225-229.
[8] M.Y. Hassaan et al., Journal of Materials and Applications **9**(1) (2020) 46-54.
[9] Al-Buriahi et al., Radiation Physics and Chemistry **166** (2020) 108507.
[10] Tonguc Baris T. et al., Radiation Physics and Chemistry **153** (2018) 86-91.
[11] Al-Buriahi et al., Indian Journal of Pure & Applied Physics (IJPAP) **57**(6) (2019) 433-437.
[12] Al-Buriahi et al., Journal of the Australian Ceramic Society **56**(3) (2020) 1127-1133.
[13] G. Lakshminarayana et al., Applied Physics A **126**(3) (2020) 1-18.
[14] M.S. Al-Buriahi et al., Ceramics International **46**(10) (2020) 15464-15472.
[15] M.S. Al-Buriahi et al., Materials Research Express **7**(2) (2020) 025202.
[16] M.S. Al-Buriahi and Y.S. Rammah, Radiation Physics and Chemistry **170** (2020) 108632.
[17] A. Temir et al., Solid State Sciences (2021) 106604.
[18] A.L. Kozlovskiy and M.V. Zdorovets, Materials Chemistry and Physics **263** (2021) 124444.
[19] S. Stalin et al., Ceramics International **47**(4) (2021) 5286-5299.
[20] T.N. Nurakhmetov et al., Eurasian Journal of Physics and Functional Materials **5**(1) (2021) 24-30.
[21] L. Aleksandrov et al., Journal of Chemical Technology and Metallurgy **50**(4) (2015) 429-434.
[22] D.N. Kakimzhanov et al., Eurasian Journal of Physics and Functional Materials **5**(1) (2021) 45-51.
[23] M. Celikbilek et al., Journal of non-crystalline solids **378** (2013) 247-253.
[24] A.S. Rysbaev et al., Eurasian Journal of Physics and Functional Materials **4**(1) (2020) 50-60.
[25] A. Temir et al., Optical Materials **115** (2021) 111037.
[26] M.I. Sayyed, Canadian journal of physics **94**(11) (2016) 1133-1137.
[27] H.O. Tekin et al., Radiation Physics and Chemistry **150** (2018) 95-100.
[28] G. Pal Singh and D.P. Singh, Canadian Journal of Physics **89**(12) (2011) 1281-1285.
[29] A. Temir et al., Optical Materials **113** (2021) 110846.
[30] D.K. Gaikwad et al., Materials Chemistry and Physics **213** (2018) 508-517.