Radiation shielding study of tellurite tungsten glasses with different antimony oxide as transparent shielding materials using MCNPX code

M.I. Sayyed\textsuperscript{a,b,⁎}, H.O. Tekin\textsuperscript{b,c}, Elif Ebru Altunsoy\textsuperscript{c,d}, Shamsan S. Obaid\textsuperscript{e}, M. Almatari\textsuperscript{a}

\textsuperscript{a} Department of Physics, Faculty of Science, University of Tabuk, Tabuk, Saudi Arabia
\textsuperscript{b} Department of Radiotherapy, Vocational School of Health Services, Uskudar University, Istanbul 34672, Turkey
\textsuperscript{c} Medical Radiation Research Center (USMERCA), Uskudar University, Istanbul 34672, Turkey
\textsuperscript{d} Department of Medical Imaging, Vocational School of Health Services, Uskudar University, Istanbul 34672, Turkey
\textsuperscript{e} Department of Physics, Dr. Babasaheb Ambedkar Marathwada University, Aurangabad 431004, India

1. Introduction

Tellurite based glasses have gained increasing attention from researchers for optical, thermal, structural and radiation shielding studies. This attention of the tellurite glasses is attributed to their unique properties such as high thermal stability, high refractive index, low melting temperature and low photon energy [1–5].

Until now, numerous applications of radiation sources have been found in different fields such as accelerator technologies, nuclear reactors, industries, agriculture, radiotherapy, nuclear medicine …etc. Hence, it is necessary to study some parameters related to shielding against the ionizing radiation. One of the most important parameters to study the interaction between the ionizing radiation and any material is the mass attenuation coefficient ($\mu/\rho$). This important parameter is needed in order to solve different aspects in gamma ray shielding applications [6–11]. Lead is the common material used for the purpose of radiation protection to shield humans from gamma radiation. However, lead is a hazardous material and has disadvantages in both its weight and lack of environmental friendliness. Hence, it is logical that the application of glasses in gamma radiation protection technology is growing steadily [12].

Recently, different researchers have attempted to study tellurite-based glasses for gamma radiation shielding. Issa and Mustafa [13] studied the effects of Bi$_2$O$_3$ in borate-tellurite-silicate glass system. The authors measured the $\mu/\rho$ of this glass system experimentally at different photon energies using $^{133}$Ba, $^{137}$Cs and $^{60}$Co sources. Ersundu et al. [14] prepared WO$_3$-MoO$_3$-TeO$_2$ glass system and measured the mass attenuation coefficients of this system experimentally at 80.8, 276.4, 302.8, 356 and 383.8 keV photon energies. They found that 10WO$_3$-10MoO$_3$-80TeO$_2$ glass sample has superior shielding properties when compared to concrete. Issa et al., [16] measured the shielding performance of TeO$_2$-ZnO glass system at 0.662, 1.173 and 1.33 MeV photon energies. The authors compared their experimental results with the results obtained from WinXcom and good agreement between the two approaches was reported. El-Mallawany et al. [17] used MCNP5 Monte Carlo simulation code and reported the shielding properties of 21 tellurite glass samples. They compared their results with other glasses such as silicate and borate glasses to investigate the superior shielding properties of tellurite glasses from radiation than other types of glasses. Recently, Ersundu et al. [18] evaluated structural and shielding properties for K$_2$O-WO$_3$-TeO$_2$ glass system. They used WinXcom software to calculate the mass attenuation coefficients and some relevant parameters such as half value layer and discussed the variation of these parameters with the addition of WO$_3$ in the glass composition. The authors stated that a large WO$_3$ concentration would be required to improve the shielding performance of the K$_2$O-WO$_3$-TeO$_2$ glass system. Besides, Sayyed [19] used the G-P fitting method and...
calculated the exposure buildup factor of tellurite glasses with different oxides (PbO, MgO, ZnO, BaO and Ag₂O). The author found that TeO₂-PbO glasses have superior shielding ability against gamma radiation. The G-P fitting method has allowed Lakshminarayana et al. [20] successfully to calculate the buildup factors for titanate bismuth borotellurite glasses.

This work is devoted to investigating the radiation shielding performance of tellurite tungsten glasses with different antimony oxide (Sb₂O₃) content using Monte Carlo simulation MCNPX. The glass compositions and their density values are summarized in Table 1 [21]. These glasses are termed as TSW5 (5 mol% Sb₂O₃), TSW10 (10 mol% Sb₂O₃), TSW15 (15 mol% Sb₂O₃), and TSW20 (20 mol% Sb₂O₃). The mass attenuation coefficients of the present samples were computed for 0.662, 1.173, 1.274 and 1.332 MeV photon energies.

### Table 1

<table>
<thead>
<tr>
<th>Code</th>
<th>TeO₂</th>
<th>Sb₂O₃</th>
<th>WO₃</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSW5</td>
<td>75</td>
<td>5</td>
<td>20</td>
<td>6.01</td>
</tr>
<tr>
<td>TSW10</td>
<td>75</td>
<td>10</td>
<td>15</td>
<td>5.89</td>
</tr>
<tr>
<td>TSW15</td>
<td>75</td>
<td>15</td>
<td>10</td>
<td>5.76</td>
</tr>
<tr>
<td>TSW20</td>
<td>75</td>
<td>20</td>
<td>5</td>
<td>5.71</td>
</tr>
</tbody>
</table>

#### 2.2. MCNPX geometry and input file

In the present investigation, the geometry was employed as a square prism for the modeling of tellurite tungsten glass samples. The edge lengths of this square prism are defined as 5 cm while the axial z-length is defined for each simulation in different sizes due to the thickness of the glass sample. The mass attenuation coefficients of the each studied glass samples were calculated in a narrow beam transmission geometry using a point isotropic radiation source with collimated and mono-energetic beam. The photon energies have been defined at 0.662, 1.173, 1.274 and 1.332 MeV for each calculation. In addition, geometric center of detection cell on central axis was considered for location of point source which emit gamma rays perpendicularly to the front face of the glass samples in the direction of z-axis. MCNPX simulation geometry can be seen from Fig. 1. On the other hand, another important definition is the material specification considering the atomic number, mass number, elemental mass fraction and density for compounds or mixtures. The compositions and densities of each glass samples were presented in Table 1. To obtain the average photon flux in the detection cell, average flux tally mesh (F4) was utilized. F4 tally mesh gives the sum of average flux in cell. The quantity of gamma ray is set as 10¹⁰ particle. The screenshot of modeled MCNPX simulation setup can be seen in Fig. 2. The mass attenuation coefficient calculations were done by using Intel® Core™ i7 CPU 2.80 GHz computer hardware. The error rate has been observed < 0.1% in the output file.

#### 2.3. Transmission

The term of tally cards (Fn) are used to define what type of information the user wants to obtain from the MCNPX simulation; that is, current across a surface, average flux at a point, heating, etc. One can say that tally cards are kind of detection tool to obtain required output from the interactions. To obtain tally results in MCNPX Monte Carlo simulation, the definition of F4 card should be required. Further in this section, the conditions of use of the F4 tally mesh for calculation of transmission factor in the present study will be explained. In addition to calculation of mass attenuation coefficients, transmission factors of each glass samples in used photon energies have been investigated. The transmission factor of an attenuator material is the ratio of the radiation flux (F) passing through the attenuation medium to the flux incident upon the surface of attenuator material. In the present investigation, transmission factor for a glass sample T(E,d) for a certain gamma energy (E), through the thickness x cm of the attenuator glass sample can be obtained by dividing the value of average photon flux in detection field (F4 tally mesh) by average value of photon flux in uniform detection field as shown in Eq. 1 [14].

\[
T(E,x) = T(E,0) F(E,x)/F(E,0)
\]  
(1)

To obtain the F(E,0) value, an F4 Tally has been defined just before attenuator glass sample. Thus, the average flux of incoming photon beam before attenuated by glass sample was obtained. Moreover, to obtain the F(E,x) value, another F4 Tally has also been defined behind of the attenuator glass sample. Thus, the transmission factors of investigated glass samples were obtained by dividing those two average fluxes by considering Eq. (1) for each measurement, respectively. The average flux data of F4 Tallies were obtained from MCNPX output file.

#### 3. Results and discussion

The attenuation effects of the TSW glasses were illustrated in Fig. 3 as TF versus thickness at 0.662, 1.173, 1.274 and 1.173 and 1.332 MeV photon energies, respectively. The justification of photon energies used in this study can be explained by well-known experimental radioactive isotopes. We chose those energies as they are frequently used in experimental investigations, not only in the industrial field but also in the medical field as well such as in external beam radiotherapy using Cobalt-60. On the other hand, we chose some other energies which are the characteristics gamma energies of different
isotopes. It can be seen that TSW5 has the least transmission (most attenuation), while TSW20 has the most transmission (least attenuation). The high attenuation of TSW5 is a result of the high weight fraction of the highest atomic numbers (i.e. W, Z = 74) as well as its high density. Since WO₃ has a higher effective atomic cross section than Sb₂O₃, so the probability of photonic interaction with TSW5 glass sample is very high, which means the attenuation of photons by this glass is very high, thereby making this glass sample effective for gamma shielding.

In addition, it is obvious from Fig.3 that the TF of the TSW glasses at the selected photon energies span from 0.11 to < 0.28.

Fig.4 presents the calculated TF as a function of thickness at the studied energies for TWS20 glass sample. As can be seen in Fig.4, the TF decreased quickly with the increase of sample thickness at 0.662 MeV while decreasing at a slower rate over the material thickness for 1.173, 1.274 and 1.332 MeV energies. Generally, at low photon energy (0.662 MeV in our work) the photoelectric is the most possible interaction to happen within a material. In this process, an incident photon will give its total energy to an electron in the glass sample (or any material) on which it collides. As a result of this, the electron gets sufficient energies to liberate from the material and then may subject to multiple scattering events with adjacent atoms. The probability of photoelectric interaction is inversely proportional to $E^3$. For this reason we found dramatic decreasing in TF at 0.662 MeV.

This result (Dependent of transmission factor on the thickness of the sample) is corresponds with published literature on several materials such as glasses [36] and concrete [37, 38].

From the incident and transmitted photon intensities values obtained from MCNPX geometry, the mass attenuation coefficients ($\mu/\rho$) were calculated with the help of Lambert–Beer law. In addition, the $\mu/\rho$ for the TSW glasses have been calculated using WinXCOM program [39]. The simulated and WinXCOM values of $\mu/\rho$ of TSW5, TSW10,
TSW15 and TSW20 glasses were compared and shown in Fig. 5 (a-d) and we used the correlation theory to validate the linearity of the MCNPX and WinXCOM values. The correlation coefficients for TSW5, TSW10, TSW15 and TSW20 glasses have been found to be 0.981, 0.994, 0.998 and 0.997, respectively. It can be said that the MCNPX and WinXCOM results are in good agreement.

On the other hand, the half value layer (HVL) is a common quantity used to characterise radiation shielding property of a certain material. HVL represents the thickness of glass sample which exactly can attenuate half of the original photon intensity (i.e. $I = 50\% I_0$). Lower HVL indicates smaller glass thickness used to shield half of the incident photon intensity. Fig. 6 exhibits the variation of HVL with photon energy of the Sb$_2$O$_3$ added tellurite tungsten glasses. From Fig. 6, the HVL values of the glasses under investigation are found to be increased with the increasing of photon energy. This indicates that as the energy of photon increases, the photon penetration through the glass sample increases and hence more photons transmitted through the glass sample. In addition, the results show that the HVL of TSW glasses decrease from 1.57 to 1.44 cm, from 2.26 to 2.12 cm, from 2.37 to 2.22 cm and from 2.43 to 2.27 cm at 0.662, 1.173, 1.274 and 1.332 MeV respectively, when the Sb$_2$O$_3$ content increase from 5 to 20 mol% (in other words, the WO$_3$ decreases from 20 to 5 mol%), which means that the glass sample should be contained as much as possible of WO$_3$ to get superior shielding properties. The lower HVL values of TSW5 glass sample are ascribed to the higher percentage of the high Z-element versus W in this sample, which able to increase the possibility of interaction between gamma radiation and absorbing atom. In addition, the results in Fig. 6 showed that the HVL of the present glasses is inversely proportional to the density of the samples which agreed with previous studies [40–42].

The radiation shielding efficiency of the TSW glasses has been compared with radiation shielding glasses developed by SCHOTT [43]. For this purpose, the mean free path (MFP) for the selected glasses were calculated at 0.662 MeV (MFP is the reciprocal of the linear attenuation coefficients). The MFP of TSW glasses, RS 253, RS 323 G19, RS 360 and RS 520 glasses are listed in Table 2. From the comparison of MFP values in Table 2, it is obvious that all TSW glasses have better shielding properties than RS 253, RS 323 G19 and RS 360 glasses. Hence the TSW glasses are more effective shielding materials.

Fig. 3. Transmission factor of TSW glasses for 0.662, 1.173, 1.274 and 1.332 MeV photon energies.

Fig. 4. Transmission factor of studied photon energies through an TSW20 glass sample.
4. Conclusion

The radiation shielding properties of tellurite tungsten glasses with different antimony oxide (Sb$_2$O$_3$) content were studied using Monte Carlo simulation MCNPX for photon energies 0.662, 1.173, 1.274 and 1.332 MeV. The transmission factor (TF) of the TSW glasses was evaluated at a various thickness from the incident and transmitted photons. In order to enhance shielding properties of TSW glasses, the amount of WO$_3$ should be added as much as possible. The results showed that the TSW5 glass sample of high density is more effective shielding material. It can be also concluded that modeled and validated standard MCNPX geometry can be useful for scientific community for similar future studies since radiation shielding properties of different type of glassy systems have been investigated more frequently.

References

[8] B.O. El-Bashir, M.I. Sayyed, M.H.M. Zaid, K.A. Matori, Comprehensive study on physical, elastic and shielding properties of ternary BaO-Bi$_2$O$_3$-P$_2$O$_5$ glasses as a


