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Investigation of Gamma Radiation Shielding Properties of Bi_2O_3-TeO_2-Li_2O-Al_2O_3 Coated Glasses With Geant4-Monte Carlo Gate and XCOM Simulation

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ABSTRACT

This article aims to investigate the effect of Bi_2O_3-TeO_2-Li_2O-Al_2O_3 coated glasses on radiation attenuation properties and to develop alternative materials for radiation protection. The shielding properties of glass materials coated with oxides were calculated theoretically using the XCOM computer program and the Geant4-Monte Carlo-GATE simulation codes. By calculating mass attenuation coefficients (MAC) at 662 keV, 1173 keV, and 1332 keV energies, linear attenuation coefficient (LAC), half-value thickness (HVL), and mean free path (MFP) values were calculated. When the mass attenuation coefficient of the materials is calculated, the average of both simulation results is 0.087 cm^2/g and this value belongs to the LiAlTeBi4 compost material. In line with these results, it is seen that the radiation shielding feature of the LiAlTeBi4 mixture is better than other materials and can be an alternative shielding material.

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1. INTRODUCTION

Today, the use of ionizing radiation has increased considerably with the development of technology. The increased use of ionizing radiation brings health risks. The risk of cancer and congenital abnormalities increases, especially if embryonic tissue is exposed to harmful levels of radiation[1]. Distance, shielding, and time are important parameters in radiation protection. The selection of appropriate materials with shielding properties is an important parameter in protection from ionizing radiation for the protection of living things. The choice of shielding material depends on the type and energy of ionizing radiation[2-3]. Depending on the type and energy of ionizing radiation, different materials have been recommended for shielding purposes[4]. The development of radiation usage areas has led to the search for new radiation shielding materials. Since applications such as concrete are not opaque and pose difficulties in applicability, they are replaced by glass coatings that give a transparent appearance. The toxic effects of lead and lead oxide types have made it inevitable to turn to new materials. Heavy metal oxide (HMO) additive on tellurite can change the elastic properties of the glass and also improve its radiation shielding properties[5]. In one study, TiO_2, Pb0 and Pb0 doped TiO_2 glasses at 511, 662, 1274 keV gamma energies were calculated. In line with these results, it is possible to say that 50% Pb0 additive increases the shielding properties of TiO_2 glasses. The shielding properties of glass materials coated with oxides were calculated experimentally with a gamma spectrometer with NaI(Tl) detector and theoretically with XCOM computer program and GATE simulation program[6]. In another study, it was observed that the attenuation of neutron, electron, and gamma radiation increased with the increase in the content of bismuth, especially in TeO_2–B_2O_3–Bi_2O_3 glass systems[7]. In the study conducted by Shah et al., Bi_2O_3-(75-x)TeO_2–20Li_2O–5Al_2O_3 glasses were synthesized by the melt quenching method and X-Ray Diffraction (XRD), Fourier Transform Infrared (FTIR) and Ultrasonic measurements were performed and Phy-X theoretical application was also performed. They examined gamma radiation shielding properties in the range of 0.01–10000 MeV [8].

In this study, we investigate the gamma radiation shielding properties of xBi_2O_3-(80–x)TeO_2–15Li_2O–5Al_2O_3 mixture in Geant4- Monte Carlo based GATE simulation and open access XCOM simulation programs.

2. MATERIAL AND METHOD

The XCOM and GATE simulations used in the study were made with the same method in the article on the effects of BiO_2 additive on the radiation attenuation of PbO [9]. The radiation shielding properties of the glass samples have been investigated in terms of linear attenuation coefficient (LAC). This was done using Beer Lambert's law as given in Eq.(1) and based on the LAC values and other related parameters such as HVL and MFP obtained through Equations In Eq. (2), μ is the linear attenuation coefficient in this equation, x is the material thickness, I is the number of gamma-rays reaching the detector after interacting with the material, and I_0 is the number of gamma-rays reaching the detector without interacting with the material [10].

$$I = I_0 e^{(-\mu x)} \quad (1)$$

$$\mu = 1/x \ln(I_0/I) \quad (cm^{-1}) \quad (2)$$

I, is the intensity of the transmitted light, I_0, is the intensity of the incoming light, and x, is the thickness of the material that the light reaches.

The mass attenuation coefficient of a material characterizes how easily it can be penetrated by a radiation beam and it is given by Eq.(3). ρ is the density of the material [10].

$$\mu_m = \mu/\rho \quad (cm^2/g) \quad (3)$$

The material thickness required to halve incident gamma radiation is referred to as the Half Value Layer (HVL) [11]

$$HVL = \ln(2)/\mu \quad (cm) \quad (4)$$

$$MFP = 1/\mu \quad (cm) \quad (5)$$

MFP is the average distance a photon travels before being absorbed or scattered in the material. As the energy level increases, the MFP values increase, indicating that the probability of photons passing through the material increases at higher energies.

3. RESULTS AND DISCUSSIONS

The mixing ratios and densities of the materials used as mixtures are given in Table 1 below.

Table 1. Material density and molar ratios

Material	Density(g/cm^3)	Li_2O (mol)	Al_2O_3		
LiAlTeBi1	2,81	0,15	0,05		
LiAlTeBi2	2,97	0,15	0,05	0,50	0,30
LiAlTeBi3	3,18	0,15	0,05	0,50	0,50
LiAlTeBi4	3,26	0,15	0,05	0,70	0,10

In Table 2, mass attenuation coefficients obtained by GATE and XCOM simulations are given according to energy values.

Table 2. Mass attenuation coefficient (MAC) value. *keV

	GATE (MAC)cm^2/g			XCOM (MAC)cm^2/g		
Material	662*	1173*	1332*	662*	1173*	1332*
LiAlTeBi1	0,08	0,05	0,05	0,08	0,05	0,05
LiAlTeBi2	0,08	0,05	0,05	0,08	0,06	0,05
LiAlTeBi3	0,08	0,06	0,05	0,09	0,06	0,05
LiAlTeBi4	0,08	0,06	0,05	0,09	0,06	0,05

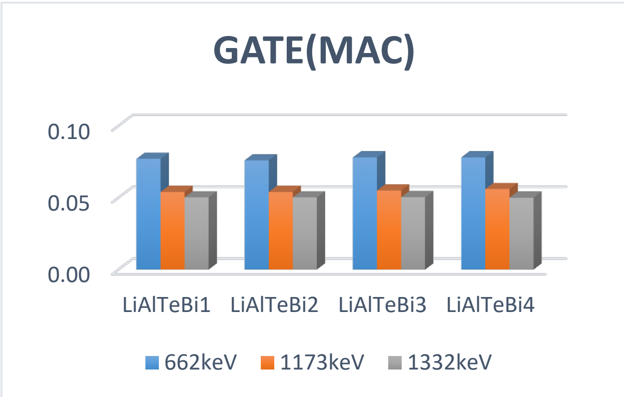

Figure 1. Mass attenuation coefficient (MAC) values calculated with Geant4-GATE.

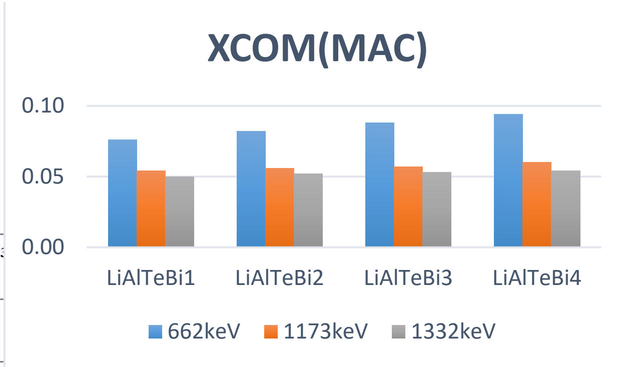

Figure 2. Mass attenuation coefficient (MAC) values calculated with XCOM

Figures 1 and 2 give the results of the mass attenuation coefficients according to energy. According to the data obtained, the mass attenuation coefficients obtained from both simulations are compatible with each other. It is seen that the attenuation feature is especially high at the energy value of 662 keV. This indicates that the possible situation at low energies is the photoelectric effect. As the energy increased, the attenuation coefficient value decreased because Compton scattering became dominant.

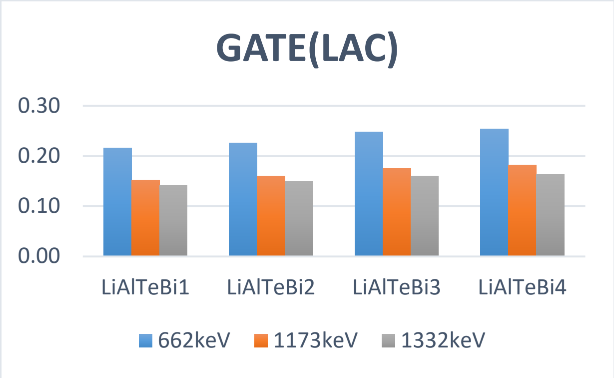

Figure 3. Linear attenuation coefficient (LAC) values

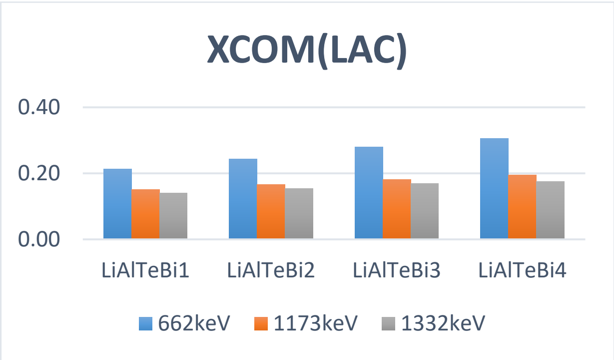

Figure 4. Linear attenuation coefficient (LAC) values

In Figures 3 and 4, comparative values of the linear attenuation coefficients obtained using Equation 3 are given.

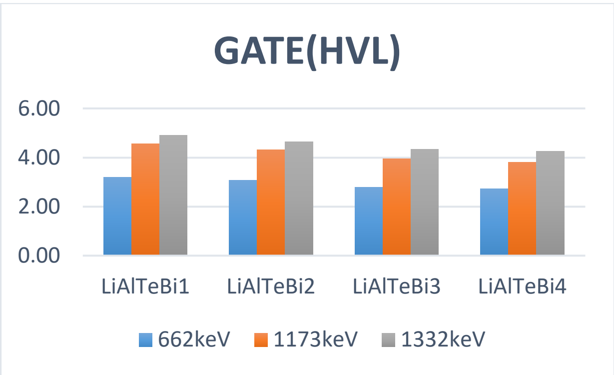

Figure 5. Half value layer (HVL) values

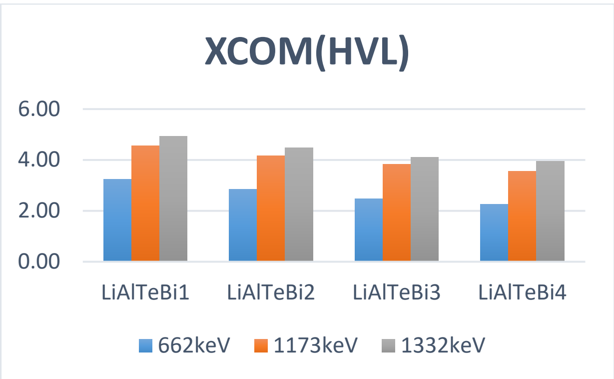

Figure 6. Half value layer (HVL) values

The half-value layer graphs found by substituting the linear attenuation coefficient using Equation 4 are given in **Figures 5 and 6**.

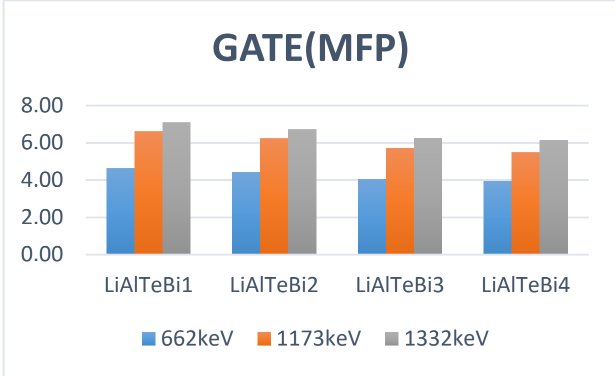

Figure 7. Mean free path (MFP) values

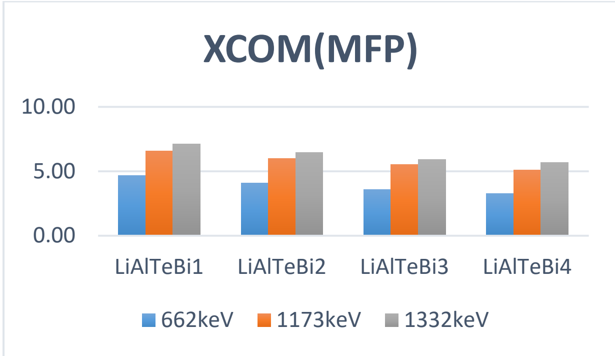

Figure 8. Mean free path (MFP) values

In Figures 7 and 8, graphs of the mean free path, energy distribution and its variation according to material are given. Mean free path refers to the average path that gamma radiation travels through the material. It is calculated by inverting the linear attenuation coefficient according to multiplication, as given in Equation 5. High HVL and MFP values indicate that the radiation attenuation of the material is low. In the study conducted by Shah et al., they found the mass attenuation coefficient (MAC) for glass samples evaluated by Phy-X/PSD software when they took x = 5%mol in the xBi_2O_3-(75–x)TeO_2–20Li_2O–5Al_2O_3 mixture, and found its highest value at 40keV energy [8].The dependence of bismuth content and other heavy metal oxides on HVL values are also reported on previous research [12-13] When Alalawi et al. examined the radiation shielding properties of telluride glass systems consisting of oxide composites in their studies, they found that the gamma and neutron properties of PbO-TeO2 glasses in particular changed with the increase in PbO doping [14]. In the literature, glass systems formed using materials containing Te, Si, V, Pb, W and Bi have been used very frequently as alternative shielding materials to Pb [15-17].

Increasing the bismuth oxide contribution increases the gamma radiation attenuation feature. In addition, as the energy increases, the interaction properties with matter change. There are three types of photon interaction involved which are dependent with the energy range. The photoelectric effect is the prevailing phenomenon in the lower energy range (<0.1 MeV), and its occurrence is dependent on the atomic number of the material, denoted as Z4-5. Compton scattering, on the other hand, interacts in the intermediate energy range (0.1 MeV< E < 2 MeV) and exhibits a linear dependence on the atomic number. Pair production, which takes place in the higher energy region (>2MeV), is proportional to Z2.

As the energy increases, the mass attenuation coefficient decreases because the photoelectric effect is replaced by Compton scattering or pair formation.

4. DISCUSSION

When **Figures 1 and 2** are examined, it is seen that the MAC values of all materials are high at 662 keV energy. Especially LiAlTeBi4 (0.0783 cm²/g) gives the highest MAC value, while LiAlTeBi2 (0.0760 cm²/g) shows the lowest value. With the increase in energy, LiAlTeBi4, LiAlTeBi1 and LiAlTeBi2 materials give the values of 0.0560 cm²/g, 0.0540 cm²/g and 0.0540 cm²/g, respectively. Shielding the prepared LiAlTeBi materials, LiAlTeBi4 has the highest mass attenuation coefficient (MAC) values at each energy level and stands out as the most effective armor material against gamma radiation. LiAlTeBi2 generally has the lowest MAC values and shows the lowest radiation attenuation performance. When the LAC values given in **Figures 3 and 4** are analysed, LiAlTeBi4 has the highest LAC values at all energy levels with increasing energy. This shows that LiAlTeBi4 attenuates radiation more effectively than other compounds. The LAC value of LiAlTeBi4 at 662 keV is 0.2540 cm^{-1}, while the lowest value is 0.2164 cm^{-1} for LiAlTeBi1. LiAlTeBi1 exhibits the lowest LAC values at all energy levels. This indicates that LiAlTeBi1 is less effective than the other compounds. At 1173 keV, the linear attenuation coefficient for all materials decreases, with LiAlTeBi4 having the highest value (0.1823 cm^{-1}) and LiAlTeBi1 having a lower value (0.1517 cm^{-1}). At 1332 keV, the LAC values decrease further, indicating that the probability of photons interacting with matter decreases with increasing energy. LiAlTeBi4 has the highest value (0.1628 cm^{-1}), while LiAlTeBi1 has the lowest value (0.1411 cm^{-1}). This is due to the fact that the photoelectric effect is more dominant at low energies. The photoelectric effect allows the material to absorb photons more effectively at low energies. At higher energies (1173 keV and 1332 keV), the photoelectric effect is replaced by compton scattering.

When we look at **Figures 5 and 6**, it is seen that the HVL values increase with increasing energy, which shows that the effectiveness of the material in attenuating high-energy photons decreases. As seen in the graphs, the highest HVL value is for LiAlTeBi1 and these values are 3.20 cm at 662 keV, 4.57 cm at 1173 keV and 4.91 cm at 1332 keV. The lowest values are for LiAlTeBi4: 2.73 cm at 662 keV, 3.80 cm at 1173 keV, 4.26 cm at 1332 keV. The lowest HVL value belongs to LiAlTeBi4, indicating that it is the best shielding material. **Figures 7 and 8** show that the mean free path values increase with increasing energy. As can be seen from the graphs, especially LiAlTeBi4 has the lowest MFP values at all three energy levels. This reveals that LiAlTeBi4 has the ability to attenuate gamma radiation at a high rate. These values are 3.9375 cm at 662 keV, 5.4844 cm at 1173 keV and 6.1425 cm at 1332 keV. Mean free path (MFP) values increase in all materials as the energy increases. This shows that high energy photons can pass through the material more easily and the attenuation performance decreases. LiAlTeBi4 was found to have the lowest MFP values at all energy levels.

Competing interests

The authors declare that they have no competing interests.

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