Investigation of the radiation-shielding properties of lithium-antinomy-Lead-germanate glasses modified with chromium oxide

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Abstract. The Phy-X/PSD software has been used to explore the effect of chromium oxide (Cr_2O_3) on the radiation shielding properties of glass systems with the chemical composition $10Li_2O$+(30-x)Sb_2O_3+20PbO+40GeO_2+xCr_2O_3, where x = 0.1, 0.2, 0.3, 0.4, 0.5 mol%. The key properties examined include the mass attenuation coefficient (MAC) and tenth value layer (TVL). These parameters were examined over an energy range of 20 to 300 keV. The results indicate that increasing the Cr_2O_3 content enhances the shielding properties of the glass systems examined. The analysis reveals that the sample with the highest Cr_2O_3 content demonstrates the highest MAC, along with the lowest TVL. This suggests that it offers better radiation shielding capabilities compared to the other samples.

1 Introduction

The increasing utilisation of nuclear technology in research, medical facilities, nuclear reactors, and various industries offers significant benefits but also poses potential risks due to ionising radiation [1, 2]. Careful oversight is necessary to mitigate these risks. One crucial safety measure is the application of radiation shielding materials. Different types of radiation require different shielding materials and techniques. For instance, highly penetrating gamma rays require materials with high density, such as lead or concrete, for effective shielding. However, these conventional materials have drawbacks, including a lack of transparent structure, which restricts their applications. Researchers have sought alternative materials that minimise these disadvantages. Glasses, ceramics, alloys, and polymers have been proposed as alternatives, each offering distinct advantages. Notably, glasses possess unique properties, such as transparency and high chemical resilience, making them viable options for radiation protection [3]. Effective radiation shielding materials must attenuate photons, which are highly penetrative. This can be achieved by utilising materials with high atomic numbers and densities. Researchers evaluate the potential of materials by assessing their physical properties such as linear attenuation coefficients, mass attenuation coefficients, mean free path, half-value layer, tenth-value layer, and effective atomic number [4].

Many studies have analysed the radiation shielding parameters of various glass systems, including germinate [5], borosilicate [6], boro-tellurite [7], and heavy metal oxide [8] glasses, at low, medium, and high energy levels. By analysing these parameters, researchers can identify which types of glass offer the most effective radiation shielding.
A recent study conducted by Sayyed et al. [9] examined the effect of chromium ions on the radiation-shielding properties of germanate glasses using the Phy-X/PSD software. The study focused on energies ranging from 0.284 to 1.33 MeV, revealing that the incorporation of chromium ions enhances the shielding performance of these glasses. However, their behavior at lower energies remains unexplored. Thus, the present study seeks to investigate the influence of adding chromium oxide to lithium-antimony-lead-germanate glasses within the 20 - 300 keV energy range, utilising the Phy-X/PSD simulation software. The study provides insights into the potential application of these glasses for X-ray and gamma-ray shielding.

2 Simulation Methods

The Phy-X/PSD software has been used in the present work to investigate the radiation-shielding parameters of the five glass samples (S1-S5). The Phy-X/PSD program has been used to simulate the MAC and TVL radiation shielding properties of the S1-S5 samples. Phy-X/PSD is a user-friendly online photon shielding and dosimetry (PSD) software that was developed for calculating radiation shielding parameters in the 1 keV - 100 GeV energy region [4, 10]. To run the program, the chemical composition of the glass sample as well as its density are required. The chemical compositions and density of each of the investigated samples (S1-S5) used for running the program are listed in Table 1.

Table 1: The chemical composition of the investigated glass samples and their densities.

Glass code	Glass composition	Density (gm/cm^3)
S1	$10Li_2O$-$29.9Sb_2O_3$-20PbO-$40GeO_2$-$0.1Cr_2O_3$	3.07
S2	$10Li_2O$-$29.8Sb_2O_3$-20PbO-$40GeO_2$-$0.2Cr_2O_3$	3.15
S3	$10Li_2O$-$29.7Sb_2O_3$-20PbO-$40GeO_2$-$0.3Cr_2O_3$	3.16
S4	$10Li_2O$-$29.6Sb_2O_3$-20PbO-$40GeO_2$-$0.4Cr_2O_3$	3.18
S5	$10Li_2O$-$29.5Sb_2O_3$-20PbO-$40GeO_2$-$0.5Cr_2O_3$	3.20

The radiation shielding properties of Li_2O+Sb_2O_3+PbO+GeO_2+Cr_2O_3 glass samples were investigated using their mass attenuation coefficients and tenth-value layers. These parameters are mathematically related to the photon linear attenuation coefficient (μ), given by equation 1,

$$I = I_0 e^{-\mu t}, \tag{1}$$

where I is the intensity of the attenuated photons after passing through the absorber with thickness, t, and I_o is the intensity of the initial photons. The attenuation of photons in an absorber occurs through photoelectric absorption, Compton scattering, and pair production. The mass attenuation coefficient parameter is related to μ through the following equation,

$$MAC = \frac{\mu}{\rho}, \tag{2}$$

where ρ is the density of the shielding material. The MAC represents the attenuation of a photon per unit mass of a material.

The TVL parameter characterises the thickness of a material at which the intensity of photons transmitted through it is reduced to 90% of the initial intensity. This parameter is mathematically related to μ, according to,

$$TVL = \frac{\ln 10}{\mu}. \tag{3}$$

3 Results and Discussion

The results from Phy-X/PSD simulation software are presented and discussed in this section. The obtained results for the five investigated glass samples are discussed in terms of mass attenuation coefficients and tenth value layer within the 20 - 300 keV. Figure 1 shows the mass attenuation coefficient (MAC) for the investigated samples, plotted as a function of energy. The figure shows that the MAC values at low energies are high for all glass samples (S1-S5). These high values of MAC range from 36,692 - 36,731 cm^2/g at 20 keV, as clearly illustrated in the inset. These MAC values decrease with the increase of energy, reaching the lowest values at 300 keV. The slight increase in MAC values at energies around 30 keV and 90 keV is attributed to the binding energies for the electrons related to K-shell absorption of Sb ($\sim$ 32.9) and Pb ($\sim$ 88 keV) elements, respectively.
The ability of the investigated glass materials to attenuate radiation is minimal at 300 keV. The radiation, at this energy, is less attenuated by the material compared to lower energies because, as the energy of radiation increases, the probability of interaction with the atomic electrons of the materials decreases. Instead, the radiation interacts more with the atomic nucleus, which generally leads to lower attenuation. Similar behavior was observed in the study conducted by Kheswa [11].
In Figure 1, it should be noted that sample S1, containing a low concentration of chromium oxide (0.1 mol%), exhibits the lowest MAC values. The sample (S5) with the highest chromium oxide content (0.5 mol%) shows the highest MAC values (see the inset). Since higher MAC values indicate better radiation shielding performance, these results suggest that increasing chromium oxide content enhances the shielding effectiveness of the germanate glasses.

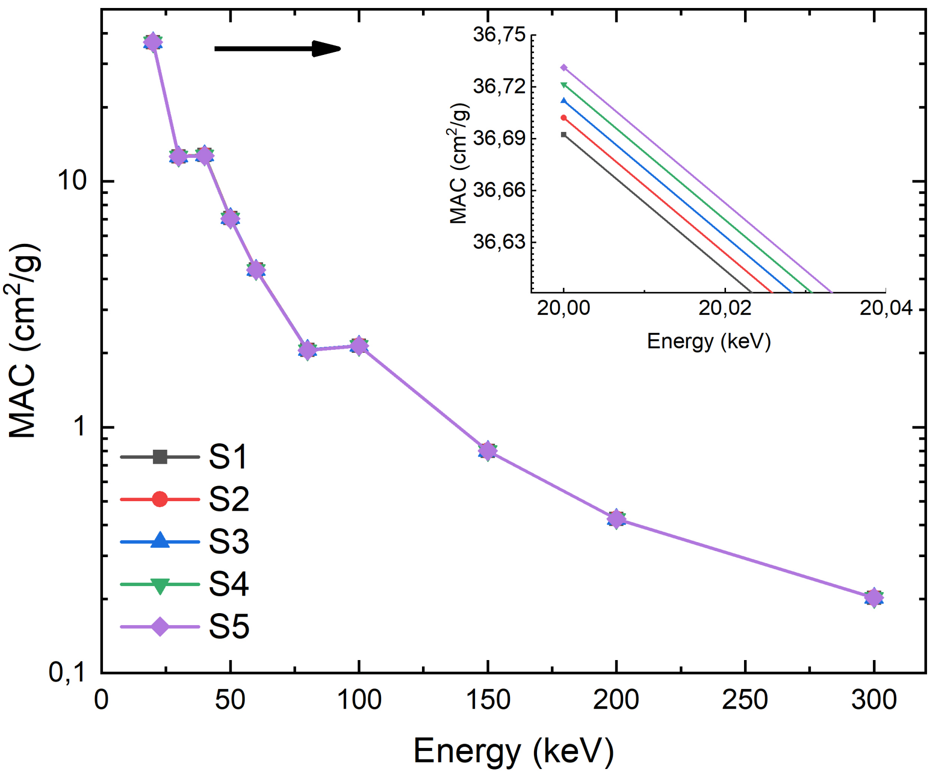

Figure 1: Mass attenuation coefficients for the S1-S5 glass samples.

Figure 2 illustrates the tenth-value layers for all investigated samples within the 20 - 300 keV. The lowest TVL values for all samples are observed at 20 keV. The TVL values increase with the increase in energy. The highest values of TVL for the S1-S5 samples, ranging from 3.708 to 3.558 cm, are observed at 300 keV. From the TVL figure, it can be seen that a small thickness of glass material is needed to absorb 90% of the initial intensity of radiation with low energies. As the energy of incoming radiation increases, the thickness of the glass material needed to absorb 90% of the incoming photons' intensity increases. In the figure, it is observed that the material thickness needed to absorb 90% of the initial photons is about 0,02 cm at 20 keV. The thickness of the material has to be increased to approximately 3,708 cm to be able to stop 90% of the incoming radiation with an energy of 300 keV, as clearly illustrated in the enset.

It is worth noting that the sample (S1) with the lowest content of Cr_2O_3 (0.1 mol%) has the highest values of TVL, and the sample (S5) with the highest Cr_2O_3 content (0.5 mol%) has the lowest values of TVL. Lower values of TVL suggest better radiation shielding capabilities. These results demonstrate that the glass sample (S5) has better shielding performance than the other investigated samples. This is consistent with the results obtained from the MAC parameter.

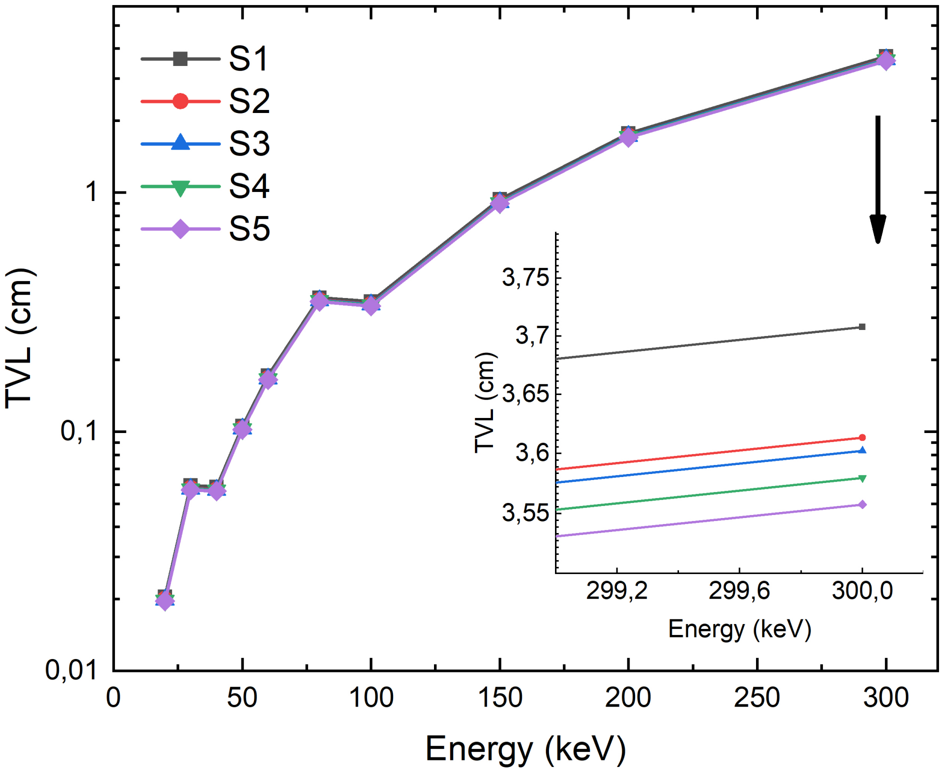

Figure 2: Tenth value layer for the S1-S5 glass samples.

4 Conclusions

The impact of chromium oxide on the radiation-shielding properties of germanate glasses has been investigated using the Phy-X/PSD simulation software. The properties have been studied within the 20 - 300 keV energy range. The results indicate that increasing the Cr_2O_3 content enhances the shielding properties of the glass systems examined. The analysis reveals that the sample with the highest Cr_2O_3 content demonstrates the highest MAC, along with the lowest TVL. This suggests that it offers better radiation shielding capabilities compared to the other samples.

References

[1] V. Venugopal, “Societal applications of nuclear technology in health care, industry and water resource management in india,” *Energy Procedia*, vol. 7, pp. 553–559, June 2011.

[2] F. A. Mettler, “Medical effects and risks of exposure to ionising radiation,” *Journal of Radiological Protection*, vol. 32, no. 1, p. N9, March 2012.

[3] M. Kurudirek, “Radiation shielding and effective atomic number studies in different types of shielding concretes, lead base and non-lead base glass systems for total electron interaction: A comparative study,” *Nuclear Engineering and Design*, vol. 280, pp. 440–448, September 2014.

[4] E. Şakar, F. Özpolat, B. Alım, M. I. Sayyed, and M. Kurudirek, “Phy-x/psd: development of a user friendly online software for calculation of parameters relevant to radiation shielding and dosimetry,” *Radiation Physics and Chemistry*, vol. 166, p. 108496, September 2020.

[5] M. I. Sayyed, K. M. Kaky, E. Şakar, U. Akbaba, M. M. Taki, and O. Agar, “Gamma radiation shielding investigations for selected germanate glasses,” *Journal of Non-Crystalline Solids*, vol. 512, pp. 33–40, May 2019.

[6] D. Ş. Baykal, H. O. Tekin, and R. B. Ç. Mutlu, “An investigation on radiation shielding properties of borosilicate glass systems,” *International Journal of Computational and Experimental Science and Engineering*, vol. 7, no. 2, pp. 99–108, July 2021.

[7] M. Halimah, A. Azuraida, M. Ishak, and L. Hasnimulyati, “Influence of bismuth oxide on gamma radiation shielding properties of boro-tellurite glass,” *Journal of non-crystalline solids*, vol. 512, pp. 140–147, March 2019.

[8] P. Kaur, D. Singh, and T. Singh, “Heavy metal oxide glasses as gamma rays shielding material,” *Nuclear Engineering and design*, vol. 307, pp. 364–376, August 2016.

[9] M. I. Sayyed, K. M. Kaky, and R. A. Anaee, “Chromium ions effects on Sb2O3-PbO-GeO2 glass properties for radiation protection,” *Journal of Theoretical and Applied Physics*, vol. 17, p. 182413, January 2024.

[10] https://phy-x.net/.

[11] B. V. Kheswa, “X-ray shielding properties of bismuth-borate glass doped with rare earth ions,” *Open Chemistry*, vol. 21, no. 1, p. 20220345, June 2023.