

## Gamma-Ray Shielding Capacity of Bi<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-B<sub>2</sub>O<sub>3</sub> Glass Powders with Different Bi<sub>2</sub>O<sub>3</sub> Contents

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### Abstract

The study investigated the shielding properties of Bi<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-B<sub>2</sub>O<sub>3</sub> glass powders with varying Bi<sub>2</sub>O<sub>3</sub> levels (45-60 mass%) against ionizing radiation using GAMOS (version 6.2). The simulation geometry produced by GAMOS was validated by comparing the results to conventional XCOM data for mass attenuation coefficients of glass particles. The Monte Carlo simulations were used to score photons that traveled in an absorber within the energy range of 0.01 MeV to 20 MeV, depending on the parameter under study. The simulation model involved a monoenergetic point source producing a pencil beam, absorber, and detector. We have calculated the mass attenuation coefficient (MAC), Half-value layer (HVL), Tenth-value layer (TVL), and Mean Free Path (MFP). The greatest linear attenuation coefficients in the whole energy range are related to 60Bi and the lowest were to 45Bi. The obtained results were compared, and these results are in good agreement with the obtained values from the XCOM program.

## 1. Introduction

The use of radiation in nuclear technology, medicine, agriculture, and industry has become widespread. As a result, the significance of radiation protection and research on protective materials has increased. To minimize potential radiation exposure, the ALARA principle is applied along with three main rules: time, distance, and shielding. Time and distance are manageable parameters for individuals. However, providing maximum protection from radiation requires investigating various types of materials, compounds, and mixtures for radiation shielding. The literature contains various theoretical, experimental [1]-[10], and simulation evaluations [11]-[23] investigations on shielding materials.

To determine the amount of shielding necessary for a specific target environment, it is necessary to consider the attenuation features of radiation. An absorber's mass attenuation coefficient (MAC) ( $\mu/\rho$ ) indicates the likelihood of a photon

undergoing scatter or absorption interactions per unit distance and unit density of the material. This information is useful in estimating the thickness of a material needed to shield a known type and energy of an ionizing photon beam [24], [25]. The attenuation of material is determined using the transmission method, which follows the Lambert-Beer law. This law is formulated as in Equation 1;

$$\frac{\mu}{\rho} = \left(-\frac{1}{x\rho}\right) \ln\left(\frac{I(x)}{I_0}\right) \quad (1)$$

Where  $I_0$  and  $I_x$  denote the initial and reduced photon intensity, respectively. The variable  $x$  denotes the magnitude of the attenuator material's thickness.

The choice of shielding method primarily relies on the radiation energy and charge characteristics of the shielding materials. The choice of shielding material is contingent upon several factors, such as the nature of the radiation, system specifications, resilience to radiation-induced harm,

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economic circumstances, and mechanical characteristics [26]. Low-melting glass is a common binder phase in advanced electronics technology due to its low sealing temperature, heat resistance, and air tightness [27], [28]. PbO-based glasses are particularly popular due to their low glass transition temperature and excellent thermal and electrical properties [29]. Due to the negative effects of lead on health and the environment, many research projects are evaluating lead-free high-density glasses. Several studies on ternary Bi<sub>2</sub>O<sub>3</sub>-containing glass have been undertaken [30]-[33].

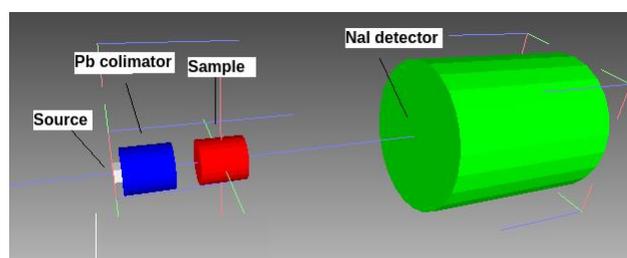
The purpose of this study is to compute the gamma-ray shielding parameters of Bi<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-B<sub>2</sub>O<sub>3</sub>-ZnO-Al<sub>2</sub>O<sub>3</sub> glasses. with different Bi<sub>2</sub>O<sub>3</sub> contents are calculated utilizing the GAMOS simulation tool. The computations use Monte Carlo simulations for a wide range of photon energies, and the examined values are compared to XCOM results.

## 2. Material and Method

In problems involving the transport of photons, a Monte Carlo code uses interaction cross sections, along with the geometrical and material descriptions of the medium, to compute estimates of dosimetric quantities such as flux and dose [34], [35].

The investigation utilized the Monte Carlo software package GAMOS 6.2 to model the geometry of the source, absorber, and detector. GAMOS is a CERN-developed derivative of Geant4 commonly used by medical physicists for investigating ionizing

radiation sources in diagnostic or therapeutic contexts [36]. For each sample, representing a separate simulation, photon energies ranging from 0.01 MeV to 20 MeV were studied. All Monte Carlo runs were performed using 10<sup>6</sup> particle histories/tracks, resulting in statistical errors below 0.1%. The simulations did not utilize any variance reduction technique. As seen in figure 1, the simulations involved a mono-energetic photon beam emitted from a pencil beam photon source. The beam was directed towards a disk shape absorber positioned 50 cm away from the source. To prevent any photon interactions with materials other than the sample, all irradiation geometry components were enclosed within a vacuum sphere with a radius of 100 cm.



**Figure 1.** GAMOS Simulation geometry obtained with Paraview.

This work investigates the gamma shielding capabilities of four glasses with varying fractions of Bi<sub>2</sub>O<sub>3</sub>, which are significant in radiation protection. Table 1 shows the compositions and densities of each sample.

**Table 1.** Compositions of the Bi<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-B<sub>2</sub>O<sub>3</sub>-ZnO-Al<sub>2</sub>O<sub>3</sub> glasses (mass%).

Sample	$\rho$ (g/cm <sup>3</sup> )	Bi <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	B <sub>2</sub> O <sub>3</sub>	ZnO	Al <sub>2</sub> O <sub>3</sub>
45Bi	5.82	45	10	35	7	3
50Bi	5.93	50	10	30	7	3
55Bi	6.16	55	10	25	7	3
60Bi	6.32	60	10	20	7	3

## 3. Results and Discussion

Four glass samples were performed MAC Monte Carlo tests. The simulations were conducted at twenty-eight different photon intensities, ranging from 0.01 MeV to 20 MeV. The values obtained from the Monte Carlo simulations were inputted into Equation (1) to produce GAMOS code results, which are presented in Table 2.

We calculated the LAC for each sample at different energies, ranging from 0.01 MeV to 20 MeV, using the GAMOS code and XCOM. The

results obtained from both codes were in good agreement with each other.

Figure 2 shows that 60Bi has the highest LAC across the entire energy range, while 45Bi has the lowest. Increasing the amount of Bi<sub>2</sub>O<sub>3</sub> in the material increases its density and therefore its linear attenuation coefficient.

The MAC provides information about the material's performance based on its elemental makeup, regardless of its density. Figure 3 illustrates the variation in  $\mu/\rho$  values in the 0.01-20 MeV energy range.

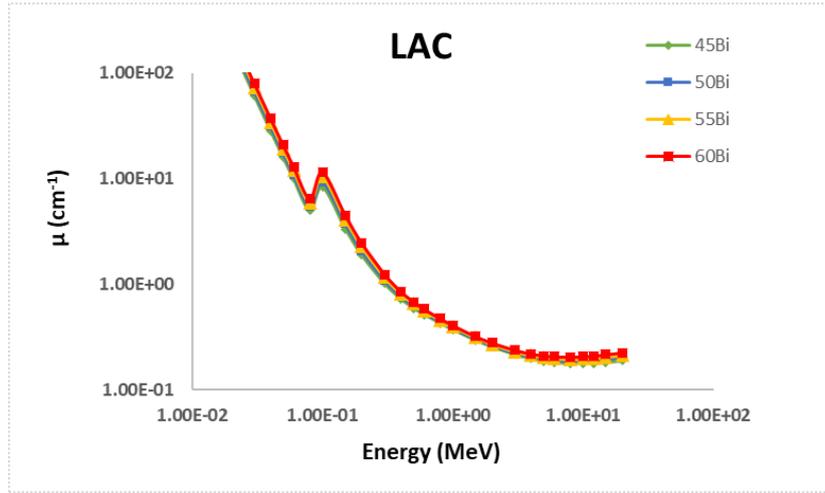


Figure 2. LAC ( $\text{cm}^{-1}$ ) in terms of photon energy for glasses.

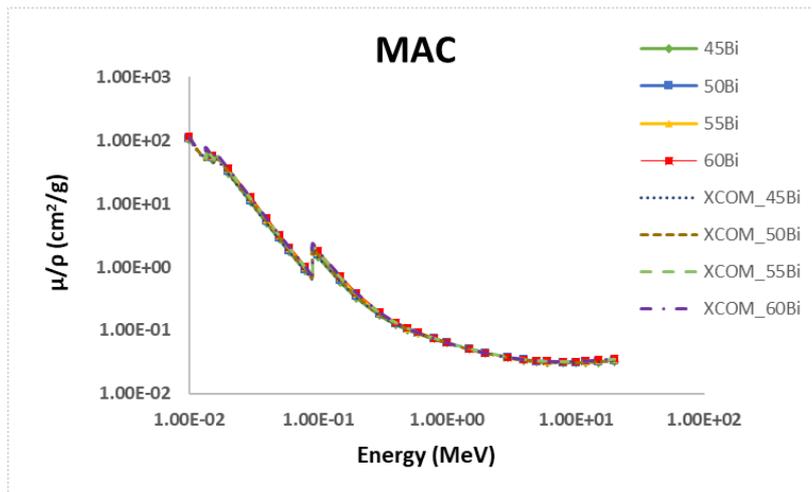


Figure 3. MAC ( $\text{cm}^2/\text{g}$ ) in terms of photon energy for glasses (GAMOS and XCOM).

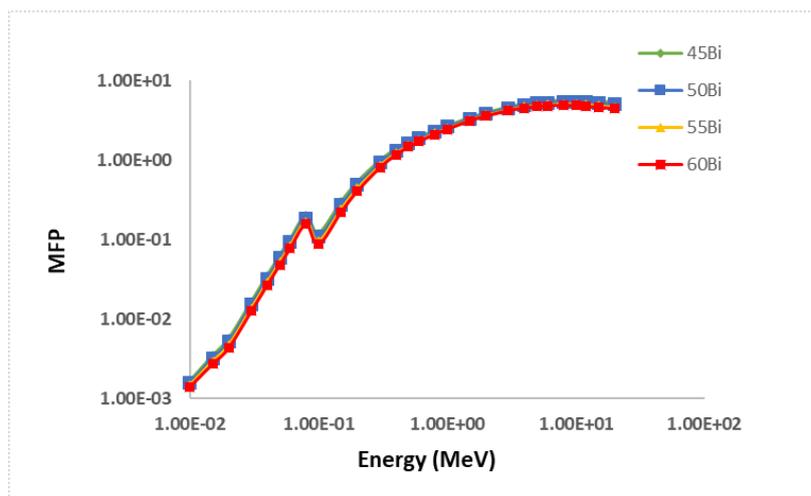


Figure 4. MFP (cm) in terms of photon energy for glasses.

The MFP is an important parameter for evaluating photon shielding characteristics. It refers to the distance that a particle travels between two consecutive collisions, which affects the direction, energy, and other properties of the particle. The MFP is calculated using Equation 2 and is determined by the photon energy, as shown in Figure 4. Increasing the gamma photon energy escalates the MFP of the material. The changes are shown in the energy range of 0.01-20 MeV. At lower energies of 1 MeV, the mean free path (MFP) increases modestly with slope, but at higher energies the slope increases more. The MFP moves relatively smoothly between 0.1 and 1 MeV. As shown in figure 4, 45Bi and 50Bi have a higher average free distance than other materials. This indicates that their materials have less interaction with atoms and may not be the best option for use in shields.

$$MFP = \left(\frac{1}{\mu}\right) \tag{2}$$

The shield thicknesses that reduce the intensity of the incident beam by 50% and 10% are referred to as HVL and TVL, respectively. Equations 3 and 4 are related to LAC.

$$HVL = \left(\frac{\ln 2}{\mu}\right) \tag{3}$$

$$TVL = \left(\frac{\ln 10}{\mu}\right) \tag{4}$$

Radiation shielding is considered adequate when the HVL value is low. Figure 5 shows that HVL and TVL values increase with energy, with 45Bi and 50Bi having the highest values compared to other materials. 60Bi has the lowest value compared to other materials due to its MFP.

**Table 2.** MAC (cm<sup>2</sup>/g) of glasses at various photon energies determined by GAMOS simulation.

Energy (MeV)	45Bi		50Bi		55Bi		60Bi	
	XCOM	GAMOS	XCOM	GAMOS	XCOM	GAMOS	XCOM	GAMOS
0.01	1.03E+02	1.04E+02	1.06E+02	1.07E+02	1.09E+02	1.10E+02	1.12E+02	1.13E+02
0.015	5.02E+01	5.01E+01	5.29E+01	5.27E+01	5.56E+01	5.54E+01	5.83E+01	5.81E+01
0.02	3.07E+01	3.05E+01	3.28E+01	3.26E+01	3.49E+01	3.47E+01	3.70E+01	3.67E+01
0.03	1.05E+01	1.05E+01	1.13E+01	1.12E+01	1.20E+01	1.19E+01	1.27E+01	1.27E+01
0.04	4.93E+00	4.88E+00	5.28E+00	5.22E+00	5.63E+00	5.56E+00	5.97E+00	5.91E+00
0.05	2.76E+00	2.72E+00	2.95E+00	2.91E+00	3.14E+00	3.09E+00	3.34E+00	3.28E+00
0.06	1.74E+00	1.71E+00	1.85E+00	1.83E+00	1.97E+00	1.95E+00	2.09E+00	2.06E+00
0.08	8.69E-01	8.58E-01	9.25E-01	9.12E-01	9.80E-01	9.66E-01	1.04E+00	1.02E+00
0.1	1.44E+00	1.43E+00	1.58E+00	1.56E+00	1.71E+00	1.69E+00	1.84E+00	1.82E+00
0.15	5.78E-01	5.75E-01	6.24E-01	6.21E-01	6.70E-01	6.67E-01	7.16E-01	7.11E-01
0.2	3.28E-01	3.25E-01	3.49E-01	3.46E-01	3.71E-01	3.68E-01	3.92E-01	3.89E-01
0.3	1.74E-01	1.74E-01	1.82E-01	1.81E-01	1.89E-01	1.89E-01	1.96E-01	1.96E-01
0.4	1.25E-01	1.25E-01	1.29E-01	1.28E-01	1.32E-01	1.32E-01	1.36E-01	1.35E-01
0.5	1.03E-01	1.02E-01	1.04E-01	1.04E-01	1.06E-01	1.06E-01	1.08E-01	1.08E-01
0.6	8.90E-02	8.89E-02	9.02E-02	9.01E-02	9.13E-02	9.13E-02	9.25E-02	9.25E-02
0.8	7.32E-02	7.34E-02	7.37E-02	7.39E-02	7.42E-02	7.44E-02	7.47E-02	7.49E-02
1	6.38E-02	6.37E-02	6.40E-02	6.41E-02	6.42E-02	6.44E-02	6.45E-02	6.46E-02
1.5	5.07E-02	5.06E-02	5.07E-02	5.06E-02	5.08E-02	5.07E-02	5.08E-02	5.07E-02
2	4.41E-02	4.39E-02	4.41E-02	4.40E-02	4.42E-02	4.40E-02	4.43E-02	4.41E-02
3	3.73E-02	3.71E-02	3.75E-02	3.72E-02	3.77E-02	3.74E-02	3.79E-02	3.77E-02
4	3.41E-02	3.39E-02	3.44E-02	3.41E-02	3.47E-02	3.44E-02	3.49E-02	3.47E-02
5	3.23E-02	3.22E-02	3.27E-02	3.26E-02	3.31E-02	3.30E-02	3.35E-02	3.33E-02
6	3.13E-02	3.12E-02	3.18E-02	3.17E-02	3.22E-02	3.22E-02	3.27E-02	3.27E-02
8	3.05E-02	3.05E-02	3.11E-02	3.11E-02	3.17E-02	3.17E-02	3.23E-02	3.23E-02
10	3.04E-02	3.05E-02	3.12E-02	3.11E-02	3.19E-02	3.19E-02	3.26E-02	3.26E-02

12	3.07E-02	3.06E-02	3.15E-02	3.15E-02	3.23E-02	3.23E-02	3.32E-02	3.32E-02
15	3.14E-02	3.12E-02	3.23E-02	3.23E-02	3.33E-02	3.31E-02	3.42E-02	3.42E-02
20	3.27E-02	3.24E-02	3.38E-02	3.35E-02	3.49E-02	3.45E-02	3.60E-02	3.57E-02

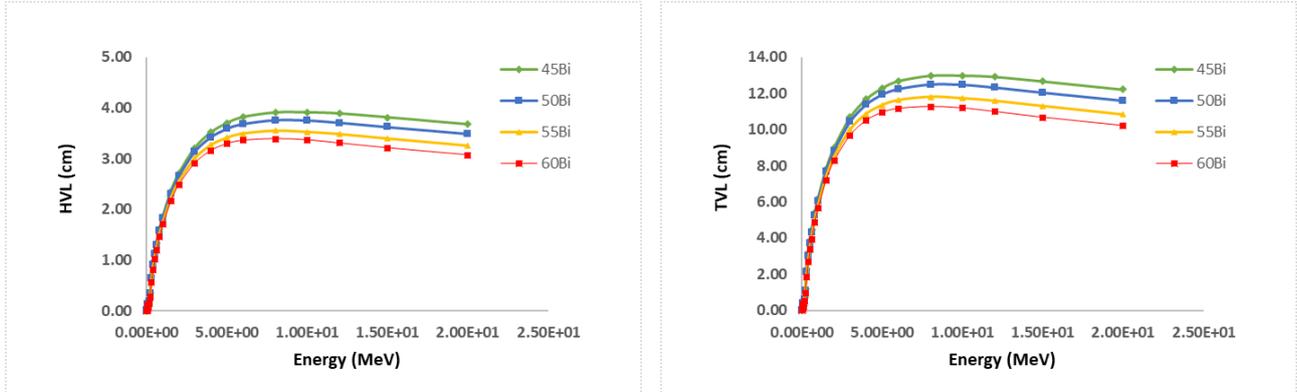


Figure 5. HVL and TVL (cm) in terms of photon energy for glasses.

Figure 6 shows that for the four cases analyzed in this study, the results obtained from GAMOS and XCOM agree with each other by <0.5%.

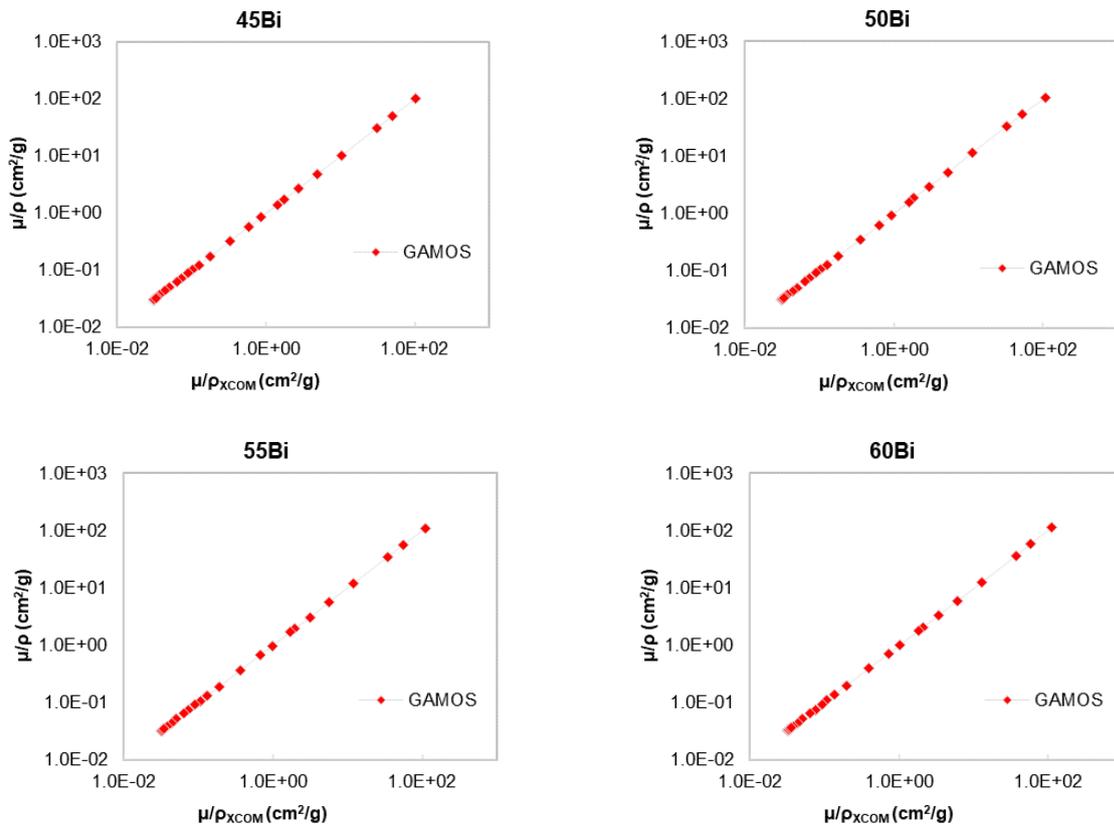


Figure 6. MAC (cm<sup>2</sup>/g) of glasses obtained from Monte Carlo simulations (GAMOS) plotted against data from XCOM database.

#### 4. Conclusion and Suggestions

This study presents a Monte Carlo method to calculate the MAC of  $\text{Bi}_2\text{O}_3\text{-SiO}_2\text{-B}_2\text{O}_3$  glass with varying quantities of  $\text{Bi}_2\text{O}_3$ . The shielding properties of ionizing radiation, such as LAC, MAC, HVL, TVL and MFP, were investigated for glasses in the photon energy range of 0.01-20 MeV. The Monte Carlo simulations yielded results that are in excellent agreement with theoretical data, suggesting that this technique can be used for calculating interaction parameters for materials of interest. Increasing the  $\text{Bi}_2\text{O}_3$ , even in small amounts, had a significant effect on the attenuation of radiation performance. The attenuation coefficients of the selected materials, namely HVL, TVL, and MFP, increase with photon energy. Therefore, these materials are more effective in attenuating low-energy photons.

This approach can serve as an alternative when measuring attenuation coefficients is challenging due to the unavailability of certain gamma energies or difficulties in producing physical

samples. This tool enables the generation of attenuation coefficient data for any given photon energy and material thickness.

#### Contributions of the Authors

The methodology was creating, findings were interpreted, and the article was written by A.S. The idea was developed, the findings were interpreted, and the article was written by İ. A.

#### Conflict of Interest Statement

There is no conflict of interest between the authors.

#### Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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