Investigating the photon shielding factors of the silicate glass system from 1 MeV up to 15 MeV, Using the Phys-X/PSD simulation

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Abstract. This study investigates the photon shielding properties of calcium aluminosilicate glass systems in the energy range of 1–15 MeV using Phys-X/PSD simulation. Four glass samples (S1–S4), differing in CaO and Al_2O_3 concentrations, were analyzed based on key radiation shielding parameters: linear attenuation coefficient (LAC), half-value layer (HVL), and mean free path (MFP). Results show a clear inverse relationship between photon energy and LAC, with S1 exhibiting the highest attenuation due to its higher CaO content and density. Similarly, HVL and MFP values increase with photon energy but remain lower in CaO-rich samples, indicating better shielding performance. These findings are consistent with previous studies conducted in the lower energy range (0.284–1.33 MeV), confirming the reliability of the simulation. Overall, calcium aluminosilicate glass demonstrates excellent potential as a non-toxic, transparent, and effective shielding material for energy photon applications.

1. Introduction

Ionizing radiation is essential to numerous fields, including space exploration, industry, and nuclear medicine [1]. It is widely utilized in diagnostic imaging, cancer treatment, sterilization of medical equipment, and non-destructive testing in engineering [2]. Moreover, ionizing radiation is produced as a byproduct of nuclear power generation in many industrial facilities, and research institutions employ it to create radioactive isotopes for various applications [3].

However, exposure to ionizing radiation poses serious biological risks, including cellular damage, genetic mutations, and increased risk of cancer [4]. Prolonged or high-dose exposure can lead to acute radiation syndrome or long-term health complications [5]. Consequently, the need for effective radiation protection and shielding materials is paramount. Shielding serves as a critical line of defense, reducing the intensity of radiation to safe levels and ensuring the safety of personnel, patients, and the surrounding environment. As such, shielding has become a key consideration in many fields involving ionizing radiation [6, 7, 8]. Traditional shielding materials such as lead (Pb), concrete, and water present several drawbacks. For instance, these materials lack optical transparency, which limits real-time visual monitoring in experimental or medical settings. Lead, while effective, is toxic and poses health and environmental risks during handling and disposal. Concrete and water, although widely available and cost-effective, are often bulky, heavy, and difficult to integrate into compact or specialized shielding designs.

These limitations have prompted many scientists across the world to explore alternative radiation shielding materials that are non-toxic, transparent, lightweight, and more versatile in certain environments.

One of the most widely explored alternatives is glass, primarily due to its unique optical properties, such as transparency, refractive control, and structural tunability. These characteristics make glass materials particularly attractive for applications that require both effective radiation shielding and visual monitoring. Hence, this work investigates the photon shielding properties of the calcium aluminosilicate glass system in the higher energy region from 1 to 15 MeV. This glass system has previously been investigated in the energy range of 0.284 to 1.33 MeV by M.I. Sayyed [9].

2. Method and Data Analysis

The calcium aluminosilicate glass samples analyzed in this study were prepared by Takashi *et al.* [10]. Their chemical compositions and densities are summarized in Table 1. The samples, labeled S1 through S4, differ primarily in the concentration of CaO and Al_2O_3.

Table 1. Chemical composition and density of the calcium aluminosilicate glass samples

Sample	**CaO (mol%)**	**Al_2O_3 (mol%)**	**SiO_2 (mol%)**	**Density, ρ (g/cm^3)**
S1	50.3	16.7	33	2.90
S2	41.9	27.6	33	2.82
S3	35.3	31.7	33	2.80
S4	29.0	38.0	33	2.76

Previous studies, such as the one by Sayyed, investigated the photon shielding characteristics of these glasses in the low-energy range (0.284-1.33 MeV) using the Phys-X/PSD simulation toolkit [9]. The current study extends this investigation to the energy range of 1–15 MeV, focusing on the following photon shielding parameters:

- Linear Attenuation Coefficient (LAC)
- Half-Value Layer (HVL)
- Mean Free Path (MFP)

These parameters were simulated using the Phys-X/PSD platform to evaluate the shielding effectiveness of the glass systems over the specified energy range [11]. Each parameter and its relevance to radiation protection are discussed in the following subsections.

2.1. Linear Attenuation Coefficient (LAC)

The linear attenuation coefficient is the most fundamental radiation shielding parameter that is used to measure the amount of radiation that passes through a medium. In other words, it is the measure of the amount of radiation intensity that passes through the radiation shielding material. This parameter is derived from the Beer-Lambert law as shown in equation 1 [12].

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

Where I_0, and I are respectively the intensities of radiation before and after it passes through material, x is the thickness of the material measured in centimeters cm, and μ is the linear attenuation coefficient (LAC) measured in per centimeter ($cm^{-1}$and can be mathematically expressed by the following equation 3 [13]:

$$\mu = \frac{1}{x} ln \left(\frac{I_0}{I} \right), \tag{2}$$

2.2. Half-Value Layer (HVL)

The half-value layer is a radiation shielding parameter that describes the thickness of a material needed to attenuate the radiation intensity by half of its initial value. In simple words, it is the thickness of a material required to shield radiation intensity by 50% of the initial radiation intensity and can be calculated using the following equation 3. Generally lower values of the HVL profile indicate effective shielding capability.

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

where μ is the linear attenuation coefficient, and HVL is the half-value layer as described.

2.3. Mean Free Path (MFP)

The last radiation shielding measure evaluated is the mean-free path, which is the average distance that radiation travels before interactions. In real utilization lower values of the mean free path suggest effective shielding. The mean free path can be mathematically calculated using the following equation:

$$MFP, \lambda = \frac{1}{\mu}, \tag{4}$$

where λ is the mean free path (MFP) measured in centimeter cm.

3. Results and Discussion

3.1. Linear Attenuation Coefficient (LAC)

The plot of the Linear Attenuation Coefficient (LAC) as a function of photon energy for the four calcium aluminosilicate glass samples (S1–S4) reveals a clear inverse relationship between energy and LAC across the 1–15 MeV range. As the photon energy increases, the LAC values for all samples consistently decrease. This trend is expected due to the shift in dominant photon interaction mechanisms at higher energies from photoelectric absorption to Compton scattering and eventually pair production. These processes are less likely to fully absorb photons per unit thickness, resulting in a decrease in the overall photon attenuation efficiency of a material. Among the samples, we observed that S1 exhibits the highest LAC values across the energy range, followed by S2, S3, and S4, see Figure 1.

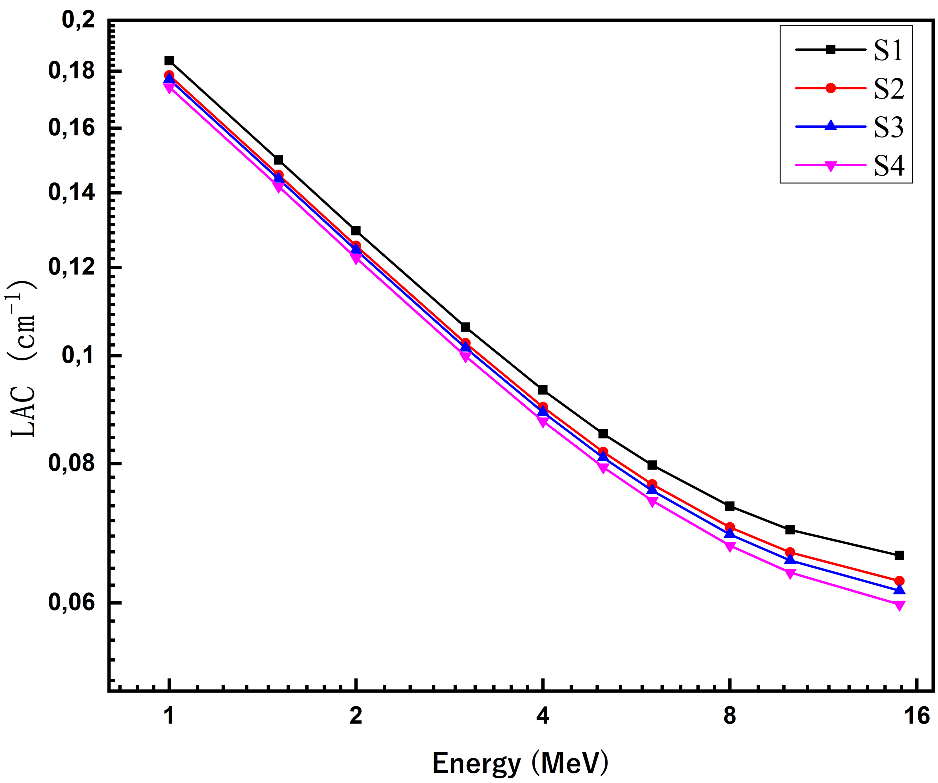

Figure 1. Variation of the linear attenuation coefficient (LAC) with photon energy (1–15 MeV) for calcium aluminosilicate glass samples S1–S4, simulated using Phys-X/PSD.

This ordering corresponds directly to the decreasing concentration of CaO and increasing Al_2O_3 content from S1 to S4, as denser and more absorptive components like CaO contribute to greater attenuation. The small but consistent differences in LAC values highlight the role of composition and density in enhancing photon shielding. Overall, these results indicate that S1 offers the most effective shielding performance in the energy range, making it a promising candidate for applications requiring enhanced radiation protection.

3.2. Half-value layer (HVL)

From the table of chemical composition and densities, Table 1, it can be seen that the density of the glass systems (S1–S4) decreases with decreasing CaO concentration (ranging from 50.3 to 29.0 mol%). This proportionality indicates that increasing the amount of CaO has a direct impact on the density of the calcium aluminosilicate glass samples. In conjunction with this, we have also investigated how these glass systems can effectively attenuate ionizing radiation, specifically by reducing its intensity to 50% (HVL) of the initial value across the energy range of 1 to 15 MeV. Figure 2 illustrate the half-value layer (HVL) of the glass systems (S1–S4).

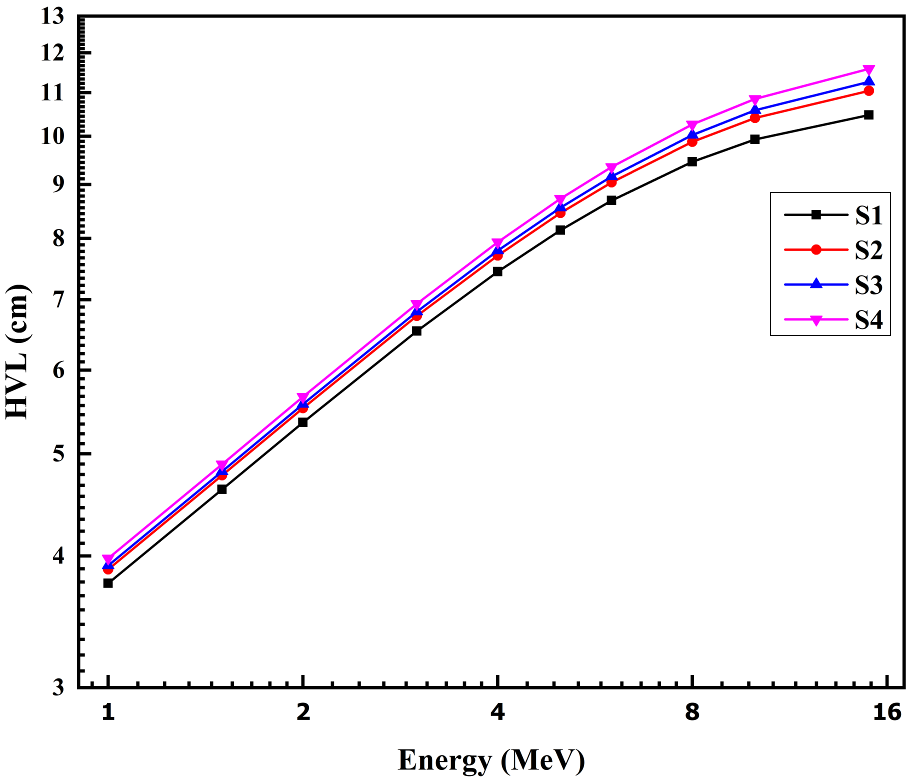

Figure 2. Variation of the half-value layer (HVL) of the calcium aluminosilicate glass system across photon energies ranging from 1 to 15 MeV.

From the plot of the HVL, it can be seen that glasses with a higher content of CaO have lower HVL values compared to those with a higher content of Al_2O_3 across the energy region. From the glass samples with the highest amount of CaO to the lowest (S1-S4), we recorded the HVL at 1 MeV as 3.76758 cm, 3.88481 cm, 3.91705 cm, and 3.97937 cm. While at maximum energy (15 MeV), the HVL for all the glass systems (S1-S4) was recorded as 10.47399 cm, 11.04235 cm, 11.26316 cm, and 11.5883 cm, indicating that the glass systems can strongly attenuate the intensity of ionized radiation by half of its initial value at lower energies and require a thinner layer to attenuate, but as the energy increases, there is a need to thicken the layer to effectively reduce the intensity by 50%. In other words, at higher energies around 15 MeV, the thickness of the glass for all the samples needs to be increased to almost three times the layer at lower energies. Furthermore, reducing the concentration of Al_2O_3 and adding more CaO content could improve the shielding properties of (S2-S4), as this will have a significant impact on the density of glass systems.

3.3. Mean Free Path (MFP)

The last shielding factor investigated in this work is the mean-free path, as defined in the previous section, which is the average distance that a photon can travel without interacting with matter. It is important to understand this property in the development of radiation shielding materials. Materials with low MFP are preferable for shielding purposes. Therefore, when developing radiation shielding materials, it is crucial to consider factors that can affect this shielding property, such as the density, atomic number, radius of the atoms, energy, etc. Because of the decreasing density of the selected glasses of silicate when the amount of CaO is dropped from 50 to 29.0 mol% (from S1 to S4), one can conclude about the MFP as it can be seen in Figure 3.

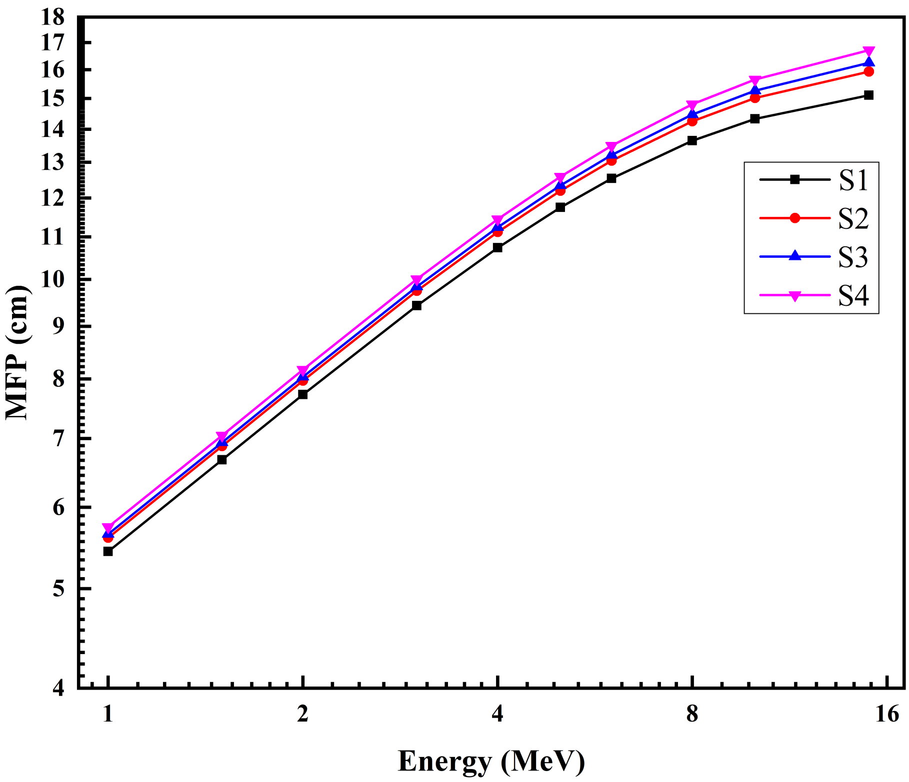

Figure 3. Mean free path (MFP) of the calcium aluminosilicate glass systems as a function of photon energy in the 1–15 MeV range.

Generally, as the density decreases, the number of molecules decreases, creating free space for photons to move before being interrupted. The MFP values for the selected silicate glasses increases with increasing energy. It can be seen that from 1 to 15 MeV, samples with a high content of CaO have preferable MFPs than those with a high content of Al_2O_3. This provides more evidence that adding more content of Al_2O_3 while lowering that of CaO impacts negatively on the density of the glass system. Therefore, we suggest that for desirable MFP values, the amount of CaO should be kept higher than that of aluminium oxide. This is accompanied by recorded evidence of the MFP values, which, the minimum MFP at 1 MeV, is 5.44 cm for S1 and rises to 5.60 cm for S4.

4. Conclusion

The investigated calcium aluminosilicate glass samples exhibit strong photon shielding capabilities across all evaluated parameters. Notably, even within the studied energy range of 1 to 15 MeV, samples with higher CaO content demonstrate superior shielding effectiveness. Furthermore, the results obtained from this work are in strong agreement with the results obtained in the lower energy region (0.284 to 1.33 MeV) by M.I. Sayyed [9]. this reinforces the reliability and accuracy of our findings. Therefore, we conclude that calcium aluminosilicate glass is a promising candidate for energy radiation shielding applications.

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