

EFFECT OF ADDING Cs₂O ON γ -RAY SHIELDING PERFORMANCE OF IRON PHOSPHATE GLASS USING FLUKA AND WINXCOM PROGRAMS

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Abstract

Gamma-ray shielding materials play an important role in reducing the γ -ray intensity to a safety level. In this work, the gamma-ray shielding parameters such as linear (μ) and mass (μ_m) attenuation coefficients, mean free path (MFP), half value layer (HVL), The effective atomic number (Z_{eff}), and the effective electron number (N_{eff}) of the Cs₂O-Fe₂O₃-P₂O₅ glass systems were investigated by FLUKA and WinXcom programs. The addition of Cs₂O into Fe₂O₃-P₂O₅ glass results in the increase of μ , μ_m , Z_{eff} , and N_{eff} of the glass samples, while MFP and HVL values of the glass decrease. Moreover, the γ -ray shielding potential of the glass was compared with the traditional materials in terms of HVL.

Keywords: Cs₂O; FLUKA; Iron Phosphate Glass; Shielding Materials; WinXcom

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Introduction

Gamma-ray shielding materials are crucial in minimizing the intensity of gamma radiation to a level that is secure for human health. Lead and concrete were commonly the shielding materials used in protecting radiation from various areas, including, nuclear power plants, research institutions, radiotherapy rooms, etc. However, they have many limitations. Concrete is an opaque material that is susceptible to long-term radiation-induced fracture and density loss. Lead has a detrimental impact on the biochemical processes inside the human body (Eid and Zawia, 2016). Thus, the development of alternative lead-free shielding materials is an excellent topic (Poltabtim *et al.*, 2018; AbuAlRoos *et al.*, 2019; AbuAlRoos *et al.*, 2020).

In recent years, numerous researchers have persistently endeavored to synthesize gamma-ray shielding glass (Boonin *et al.*, 2020) as an alternative to conventional materials. Glass materials are viable alternatives due to their uniformity, exceptional transparency, and ability to shield against radiation, in addition to their straightforward fabrication process. Moreover, the gamma-ray shielding can be adjusted by adding high-atomic-number compounds such as SrO, TeO₂, BaO, PbO, WO₃, Bi₂O₃ (Tekin *et al.*, 2022), Cs₂O, etc.

In general, the investigation of gamma-ray interaction with matter is separated into three methods: Monte Carlo simulation, theoretical calculation, and experimental approach. The aim of this work focuses on the study of the γ -rays shielding properties of Cs₂O-Fe₂O₃-P₂O₅ by FLUKA (Monte Carlo simulation) and by WinXcom (theoretical calculation). The linear (μ) and mass (μ_m) attenuation coefficients, mean free path (MFP), half value layer (HVL), The effective atomic number (Z_{eff}), and the effective electron number (N_{eff}) of the Cs₂O-Fe₂O₃-P₂O₅ glass systems were investigated in an energy range of 15 keV to 15 MeV.

Theoretical Background

The FLUKA simulation required the setting geometry, materials, radiation sources, and scoring as follows from the previous work (Mutuwong *et al.*, 2018). The chemical composition and density of the Cs₂O-Fe₂O₃-P₂O₅ glass were obtained from experimental studies (Dutta *et al.*, 2021). Shown in Table 1.

The linear attenuation coefficients (μ) refer to the ability of materials to attenuate the radiation intensity per their thickness as described by the following equation:

$$\mu = \ln(I_0/I)/d \quad (1)$$

where I_0 and I are the incident and outgoing intensity of gamma-ray. The d is the thickness of the samples.

The mass attenuation coefficients (μ_m) were computed by FLUKA as described by the following equation:

$$\mu_m = \frac{\ln(I_0/I)/d}{\rho} \quad (2)$$

where the I_0 and I values correspond to the fluence of the photon when there is no sample and when there is a sample, respectively. The ρ indicate the density of the sample.

The theoretical μ_m for mixtures are different from experimental and Monte Carlo methods because they can be obtained by a weighted summation of the constituents in the NIST database by the WinXcom program (Gerward *et al.*, 2004). This can be expressed mathematically as follows:

$$\mu_m = \sum w_i (\mu_m)_i \quad (3)$$

where the variable w_i represents the normalized weight fractions of i^{th} element. The $(\mu_m)_i$ is the mass attenuation coefficient of i^{th} element.

Table 1. Physical properties of the Cs₂O-Fe₂O₃-P₂O₅ glass (Dutta *et al.*, 2021)

Name	Mol%			Density g/cm ³
	Fe ₂ O ₃	P ₂ O ₅	Cs ₂ O	
S0	40	60	0	2.940
S1	38.25	57.03	4.72	3.012
S2	36.62	54.57	8.81	3.102
S3	33.64	50.16	16.2	3.295
S4	31.11	46.29	22.6	3.440
S5	28.67	41.57	29.76	3.590

In addition, the theoretical μ_m values are a summation of the μ_m of partial interactions (Photoelectric effect: $(\mu_m)_{PE}$, Compton scattering: $(\mu_m)_{CS}$, Pair production: $(\mu_m)_{PP}$), as calculated following equation:

$$\mu_m = (\mu_m)_{PE} + (\mu_m)_{CS} + (\mu_m)_{PP} \quad (4)$$

The mean free path (MFP) and half-value layer (HVL) can be mathematically expressed as follows:

$$\text{MFP} = \frac{1}{\mu}, \quad (5)$$

$$\text{HVL} = \frac{\ln(2)}{\mu} \quad (6)$$

The total atomic cross-section ($\sigma_{t,a}$) were expressed by the following equation (Hubbell, 2006):

$$\sigma_{t,a} = \frac{(\mu_m)_{\text{sample}}}{N_A \sum_i^n (w_i/A_i)} \quad (7)$$

where N_A is Avogadro's number. The A_i is the atomic weight of the constituent elements of the mixture. The total electronic cross-section ($\sigma_{t,el}$) is the cross section by which photons interact with the electron, as expressed by the following equation (Alzahrani *et al.*, 2023):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{z_i} (\mu_m)_i \quad (8)$$

where f_i denotes the fractional abundance of the element i with respect to the number of atoms ($\sum f_i = 1$) and z_i is the atomic number of i^{th} elements.

The effective atomic number (Z_{eff}) and the effective electron number or electron density (N_{eff}) of the composite material, as calculated using the following relation (Mutuwong *et al.*, 2023):

$$Z_{\text{eff}} = \frac{\sigma_{t,a}}{\sigma_{t,el}}, \quad (9)$$

$$N_{\text{eff}} = \frac{\mu_m}{\sigma_{t,el}}. \quad (10)$$

Results and Discussion

The μ and μ_m of the S0 to S5 glass samples were illustrated in Figure 1 and Figure 2, respectively. The figure illustrates that the values of μ and μ_m for both calculations are identical. The Cs_2O compounds added in the $\text{Fe}_2\text{O}_3\text{-P}_2\text{O}_5$ host glass results in increasing the μ and μ_m at the same

energy. The μ and μ_m decline as the increasing gamma-ray energy, except for the energy around 3.598×10^2 MeV, the μ and μ_m dramatically increase due to the K-absorption edges of Cs.

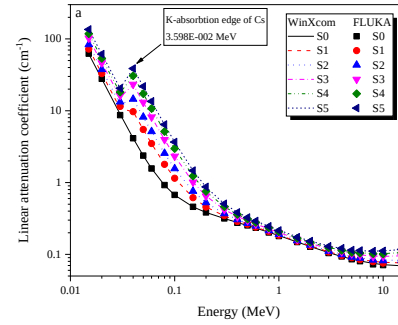


Figure 1. Linear attenuation coefficients of the $\text{Cs}_2\text{O-Fe}_2\text{O}_3\text{-P}_2\text{O}_5$ glass computed by WinXcom and FLUKA programs

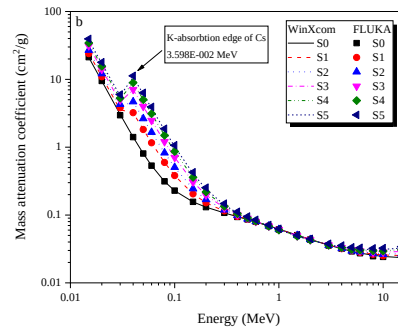


Figure 2. Mass attenuation coefficients of the $\text{Cs}_2\text{O-Fe}_2\text{O}_3\text{-P}_2\text{O}_5$ glass computed by WinXcom and FLUKA programs

To detailed understanding, the partial interactions of the S5 glass sample was considered as shown in Figure 3. The variation in μ_m as the energy of the incident photon changes can be ascribed to the three primary photon interaction processes that occur in distinct energy regions with the S5 glass. At $E < 0.2$ MeV, the μ_m values are significantly high because the photoelectric effect process is main interaction. At $0.2 \text{ MeV} < E < 10$ MeV, the main interaction that results in μ_m value is the Compton scattering process, while the photoelectric effect process has a lower influence to μ_m . Behind the energy of 10 MeV, the photoelectric effect and Compton scattering processes are lower influent to μ_m . Pair production becomes the main interaction, resulting in a slight increase in μ_m .

The comparisons between the MFP and HVL of the $\text{Cs}_2\text{O-Fe}_2\text{O}_3\text{-P}_2\text{O}_5$ glass and the standard concretes obtained from the experiment (Singh *et al.*, 2018), including ordinary, hematite-serpentine, ilmenite-limonite, and basalt-magnetite,

was showed in Figure 4. and Figure 5. The results found that the MFP and HVL of all glass samples are lower than the standard concretes at the energy range of the 2 MeV to 5 MeV. Except for S4 and S5, the glass samples have the MFP and HVL lower than ordinary and hematite-serpentine concretes. Thus, the S4 and S5 are a candidate for use as gamma-ray shielding materials instead of concretes.

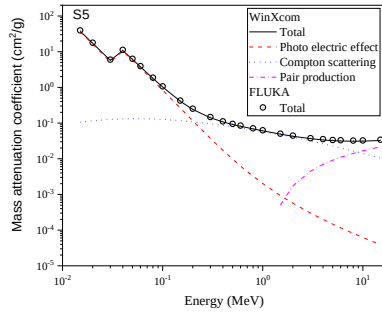


Figure 3. Patial interaction of the Cs₂O-Fe₂O₃-P₂O₅ glass

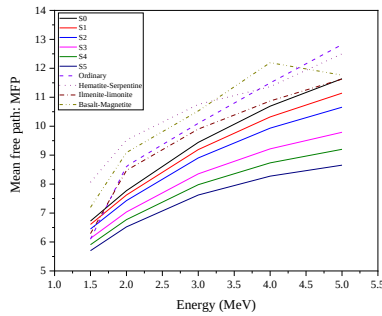


Figure 4. MFP of the Cs₂O-Fe₂O₃-P₂O₅ glass

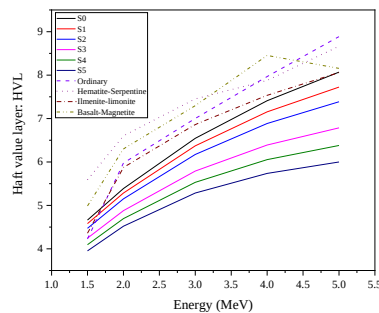


Figure 5. HVL of the Cs₂O-Fe₂O₃-P₂O₅ glass

The Z_{eff} and N_{eff} for Cs₂O-Fe₂O₃-P₂O₅ glass are depicted in Figure 6 and Figure 7, respectively. Clearly, the Z_{eff} are between 11.62 and 50.84 (electrons/atom), fluctuating dramatically with photon energy. The higher Z_{eff} of the glass samples leads to a higher probability of photon interaction. The N_{eff} values range from 2.89 to 8.58 ($\times 10^{23}$ electrons/g) and vary considerably with photon energy.

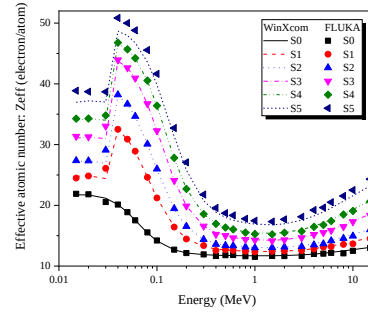


Figure 6. Z_{eff} of the Cs₂O-Fe₂O₃-P₂O₅ glass

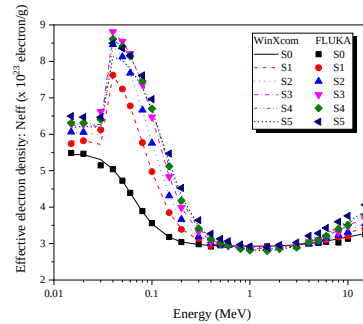


Figure 7. N_{eff} of the Cs₂O-Fe₂O₃-P₂O₅ glass

Conclusion

Shielding materials against gamma rays are crucial for reducing the intensity of gamma rays to a level that is secure for human health. The present study utilized the FLUKA and WinXcom programs to analyze the gamma-ray shielding parameters of the Cs₂O-Fe₂O₃-P₂O₅ glass systems, including the μ , μ_m , MFP, HVL, Z_{eff} , and N_{eff} parameters. The range of photon energy from 15 keV to 15 MeV was determined. The results demonstrated that adding Cs₂O into Fe₂O₃-P₂O₅ glass increases the μ , μ_m , Z_{eff} , and N_{eff} of the glass samples, while MFP and HVL values of the glass decrease. The S4 and S5 glass samples in this research exhibit a lower MFP and HVL than the standard shielding concretes: ordinary, hematite-serpentine, ilmenite-limonite, and basalt-magnetite. To sum up, the Cs₂O-Fe₂O₃-P₂O₅ glass is a candidate for use as gamma-ray shielding materials instead of concretes.

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