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Research Article

The Gamma Ray, Thermal and Fast Neutrons Shielding Properties of Gd_2O_3-SiO_2-Y_2O_3-CaO-B_2O_3 Glass Series Using FLUKA Simulation Code

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ABSTRACT

The γ-ray, thermal and fast neutrons shielding properties of Gd_2O_3-SiO_2-Y_2O_3-CaO-B_2O_3 glass series have been studied. The mass attenuation coefficients (μ_m) for γ-ray of this glass series have been obtained at an energy range 59.6-1332 keV using Phy-X software and FLUKA Monte Carlo code simulation. The obtained results were found to be in good agreement. The $50Gd_2O_3$-$20SiO_2$-$5Y_2O_3$-10CaO-$15B_2O_3$ glass sample showed the highest μ_m value with the lowest half value layer (HVL) and mean free path (MFP) value compared with the other ones in this glass series. As for the case of thermal and fast neutron shielding properties, the FLUKA Monte Carlo code and partial density method were used for stimulation, respectively. It was found that $50Gd_2O_3$-$20SiO_2$-$5Y_2O_3$-10CaO-$15B_2O_3$ glass sample showed the mass attenuation coefficients (μ_m) for thermal neutrons decreased with increasing Gd_2O_3 content for fast neutrons, and the removal cross section ($\sum_R$) showed the highest value while half value layer (HVL) and the relaxation lengths showed the lowest value. These results indicated that this glass series has high Gd_2O_3 content possesses excellent γ-ray and fast neutron shielding properties, while the $20SiO_2$-$5Y_2O_3$-10CaO-$65B_2O_3$ glass sample possesses superb thermal neutrons shielding.

Keywords: FLUKA, Gamma-ray shielding, Thermal neutrons, Fast neutrons, Glass

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Introduction

Gamma (γ) ray is ionizing radiation. It poses a threat to both the environment and human health. For this reason, γ-ray shielding researchers are interested in investigating new materials for the development of γ-ray shielding materials [1]. Glass is a great alternative material due to its opaque concrete and the toxicity of lead (Pb) as a radiation shielding material [2,3]. The significant factors are the high degree of transparency of the glasses, lack of health hazards, resistance to corrosion, and environmental friendliness. Concrete frequently has issues including being opaque to visible light, having cracks, and losing water when exposed to radiation from nuclear reactors for an extended period of time. Pb−based glass is a fantastic option since it has superior and stable chemical and physical characteristics [4−6]. However, since Pb and the toxicity of its compounds are site-specific, therefore it is forbidden to use it as radiation shielding.

Because heavy rare earth oxides can be employed as an effective γ-ray absorber, heavy rare earth oxides glasses are currently very promising for γ-ray shielding applications. One of the heavy rare earth ions that offers the platform to co-dope with other rare earth for their effective energy transfer properties included in glasses as activators is gadolinium oxide (Gd_2O_3, density = 7.41 g/cm^3). Moreover, Gd_2O_3 will not develop a color center in the glass matrix and is therefore chosen to be added to glass structures. The Gd_2O_3's high atomic number and high density can increase the probability that photon energy will interact with glasses [7−9]. The study also discovered that the effectiveness of shielding against neutrons and γ-ray can be improved by the addition of Gd_2O_3 [10,11]. Furthermore, gadolinium has a high atomic number (Z = 64), high density (density = 7.90 g/cm^3), high absorption cross-section for thermal neutron (49700b), high refractive index, and high stopping power [12].

FLUKA (FLUktuirende KAskade) is the Monte Carlo computing code that simulates the transport of particles and their interactions with matter [13]. About 60 distinct particles constitute FLUKA, which can be employed for a variety of tasks like radiation therapy, design, and shielding [14−17]. Collaboration between CERN (European Council for Nuclear Research) and INFN (Istituto Nazionale di Fisica Nucleare) was used to create FLUKA. It has two modes of operation: a biased mode and an entirely analog mode. Other Monte Carlo codes do not offer this feature. To the best of our knowledge, no author has used FLUKA to study various shielding parameters of composite glasses, despite the fact that certain writers [18,19] have reported the mass attenuation coefficients of soil samples and concretes using the FLUKA Monte Carlo code. The fundamental benefit of the simulation technique is the generation of theoretical data for the experiment's flexible geometry and the number of primary radiations, which can be used to assess the feasibility of specific experimental measurements.

The xGd_2O_3-$20SiO_2$-$5Y_2O_3$-$10CaO$-$(65-x)B_2O_3$ glass system, where x = 0, 10, 20, 30, 40 and 50 mol% were analyzed for the γ-ray shielding properties using FLUKA Monte Carlo code. The characteristics that needed to be examined were the mass attenuation coefficient (μ_m), half value layer (HVL) and mean free path (MFP). In this work, ^{241}Am, ^{22}Na, ^{133}Ba, ^{137}Cs, and ^{60}Co are the radiation sources to simulate a radiation transmission event. The thermal and fast neutrons shielding properties were also simulated using the FLUKA Monte Carlo code and partial density method, respectively, to cover applications in practice.

Materials and Methods

Glasses description

The theoretical glass series of this work is in formula xGd_2O_3-$20SiO_2$-$5Y_2O_3$-10CaO-(65-x)B_2O_3, which x increased from 0-50 mol% in 10 mol% increments, and they have been displayed in Table 1.

Table 1 The chemical composition for glass series (mol%).

Elements	Glass code (mol%)					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**
Gd_2O_3	0	10	20	30	40	50
SiO_2	20	20	20	20	20	20
Y_2O_3	5	5	5	5	5	5
CaO	10	10	10	10	10	10
B_2O_3	65	55	45	35	25	15

Physical parameter

The density (ρ ; g/cm^3) of the glass series is an important quantity for the evaluation of the other values and can be calculated using equation (1) [20]:

$$\rho = (0.53)\frac{\left(\sum M_i x_i\right)}{\left(\sum V_i x_i\right)} \tag{1}$$

where M_i, V_i and x_i are molecular weight, packing density factor, and molar fraction of i^{th} component, respectively.

Gamma-ray interaction

The mass attenuation coefficients (μ_m) express the probability of interaction of γ-ray with the interacting medium. The μ_m of the selected glass samples were derived from Phy-X software for γ-ray energy range 356-1332 keV using the following equation (2) [21,22]:

$$\mu_m = \sum_i w_i (\mu_m)_i \tag{2}$$

where $(\mu_m)_i$ is the mass attenuation coefficient for the i^{th} element, and w_i is the weight fraction of the i^{th} element in the mixture.

Half value layer (HVL) is defined as the thickness of the sample that reduces the γ-ray intensity to half of its initial intensity and can be calculated from the linear attenuation coefficient (μ) by using equation (3) [21,22]:

$$HVL = \frac{0.693}{\mu} \tag{3}$$

Mean free path (MFP) is an average distance between two successive interactions of γ-ray in medium and can be simulated from equation (4) [21,22]:

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

FLUKA simulation

FLUKA (FLUktuierende KAskade) is favors used in particle-nuclear sciences. It is mainly in high energy experimental physics and engineering shielding. In this work, the FLUKA Monte Carlo code version 2011.2x-4 with schematic set up for simulate γ-ray and thermal neutrons are exhibited in Figures 1 and 2. The simulation for μ_m of material samples can be estimated using equation (5) [22,23]:

$$I = I_0 e^{-\mu x} \tag{5}$$

where I and I_0 are γ-ray and thermal neutrons intensity passed through without and with shielding material, respectively, and x is thickness of sample.

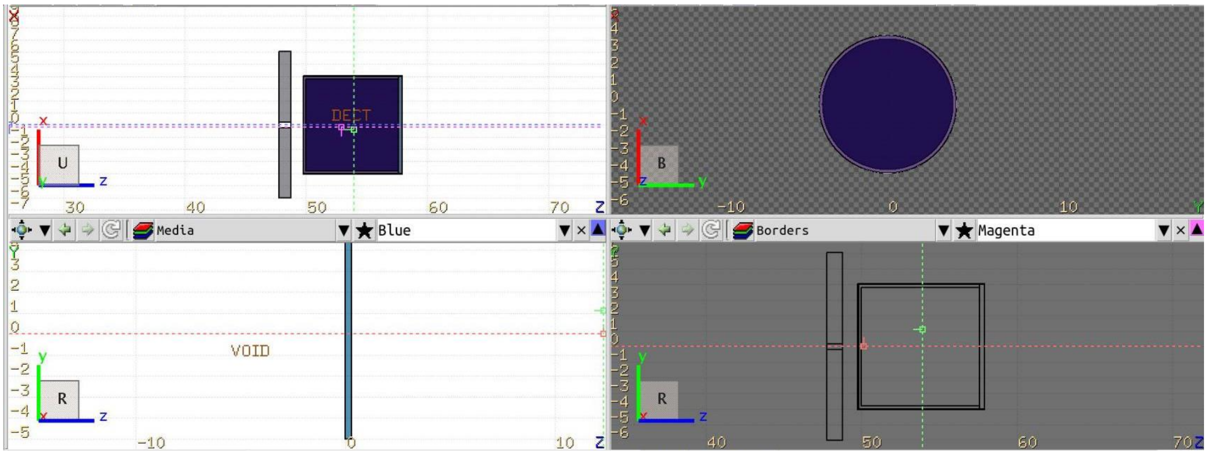
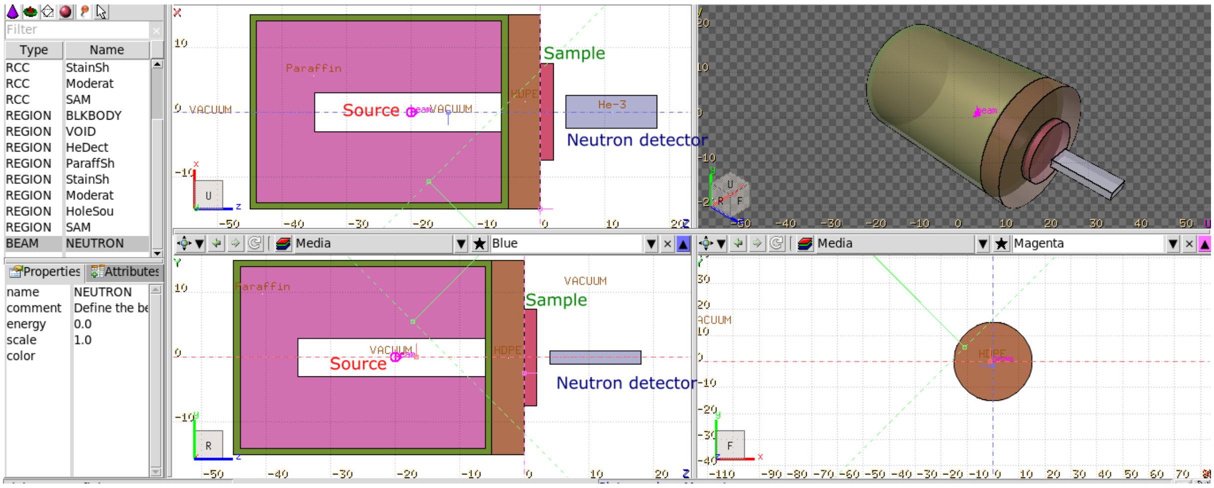


Figure 1 The schematic set up to simulate γ-ray.



Type	Name
RCC	StainSh
RCC	Moderat
RCC	SAM
REGION	BLKBODY
REGION	VOID
REGION	HeDect
REGION	ParaffSh
REGION	StainSh
REGION	Moderat
REGION	HoleSou
REGION	SAM
BEAM	NEUTRON

name	NEUTRON
comment	Define the be
energy	0.0
scale	1.0
color	

Figure 2 The schematic set up to simulate thermal neutrons.

Fast neutrons shielding properties

Microscopic cross section indicated the possibility of each type of the interaction between neutrons and medium consisting of transmission, absorption and scattering of neutrons. Those interactions are processes occurring through the microscopic cross section of the reaction [24,25].

The fast neutrons (E > 0.1 MeV) removal cross section ($\sum_R$) has been determined by applying relationship in equation (6):

$$\sum_R = \sum_i W_i \left(\sum_R / \rho \right)_i \quad (6)$$

where $W_i = \rho w_i$ refers to partial density, w_i and ρ refer to a fraction by weight of element i and total density of the medium, respectively. In addition, $\sum_R$ is the basic parameter using for the calculation of half value layer (HVL) and the relaxation lengths [25-27].

Results and Discussion

Physical parameter

The density is an important physical quantity to explain the changing formation of glass. As exhibited in Figure 3, the density of the glass series increases with increasing Gd_2O_3 content. This event is due to the replacement of Gd_2O_3 with higher molecular mass and density than B_2O_3. That indicated the presence of Gd^{3+} ions in glass structure which adjusted the borate glass network by converting more $[BO_3]^{3-}$ triangles to BO^{4-} tetrahedral [28,29].

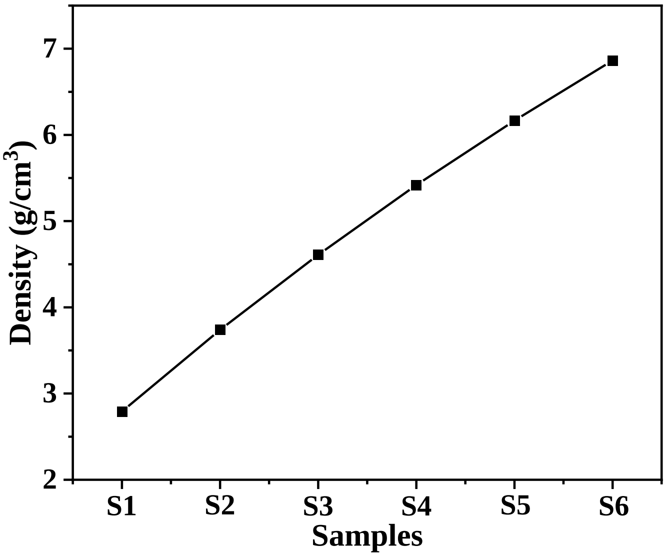


Figure 3 The density of glass series.

Gamma ray interaction

The mass attenuation coefficient (μ_m) for glass series at γ-ray energy is in the range 59.6-1332 keV at sample thickness 0.1-0.3 cm. The ^{241}Am (59.6 keV), ^{22}Na (511 and 1275 keV), ^{133}Ba (356 keV), ^{137}Cs (662 keV), and ^{60}Co (1173 and 1332 keV) are the radiation sources to simulate a radiation transmission event as exhibited in Figure 4. It can be seen that for the γ-ray energy range 59.6–356 keV, the value of μ_m increased with increasing Gd_2O_3 content, but above 356 keV these glass series properties were not good shielding anymore. From the results in Figure 4, the value of μ_m at energy range 600−1332 keV showed the same tendency of increasing μ_m value with these glasses series. These results were due to the replacement of the lower atomic number, B (Z = 4), with the higher atomic number, Gd (Z = 64), also, according to the main of photoelectric effect (PE) process at low energy ranges where the PE probability was large [28].

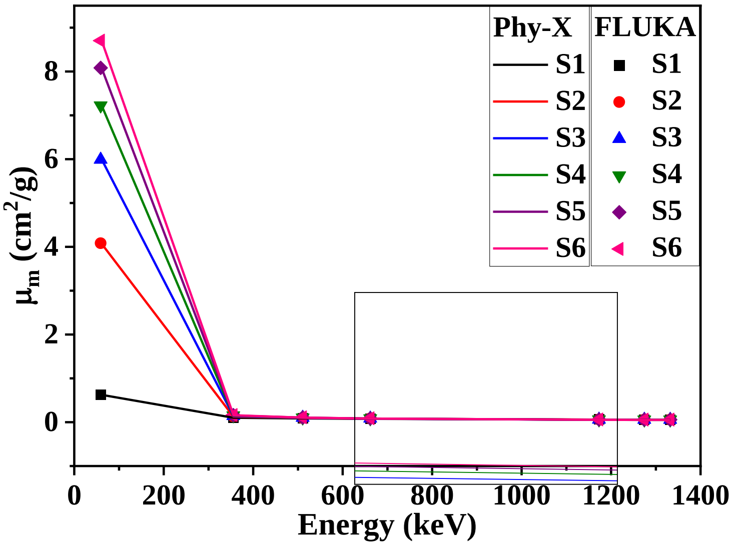


Figure 4 The mass attenuation coefficient for glass series at γ-ray energy range 59.6-1332 keV.

The HVL and MFP were plotted as shown in Figures 5 and 6. It was found that both values increased with increasing γ-ray energy, but S6 sample showed the lowest values of the HVL and MFP. It can be concluded that high density and high Z elements would be good γ-ray shielding [23,28].

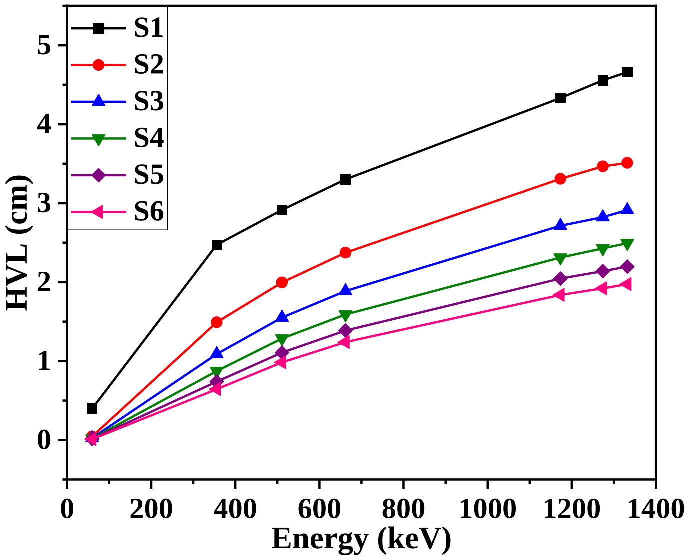


Figure 5 The HVL for glass series at γ-ray energy range 59.6-1332 keV.

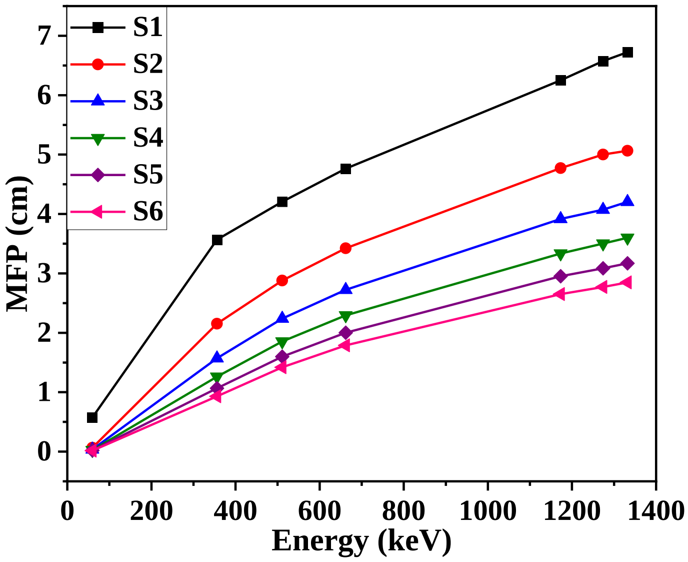


Figure 6 The MFP for glass series at γ-ray energy range 59.6-1332 keV.

Thermal neutrons shielding properties

The ^{241}Am-Be was used for the neutron source which was contained in a sealed thick paraffin cylinder and stacked 5 cm-HDPE sheets as a neutron moderator. He-3 was used for the neutron detector and all samples were placed between the neutron detector and the HDPE sheet [30]. This source emits neutrons at an energy range 1-12 MeV as a continuous spectrum because of (α, n) reaction with an average energy of 4.9 MeV as displayed in Figure 7 [31]. The thermal neutron passing through high density polyethylene (HDPE) for simulation use can be shown in Figure 8. It was found that thermal neutron had peak at energy of 0.024 eV.

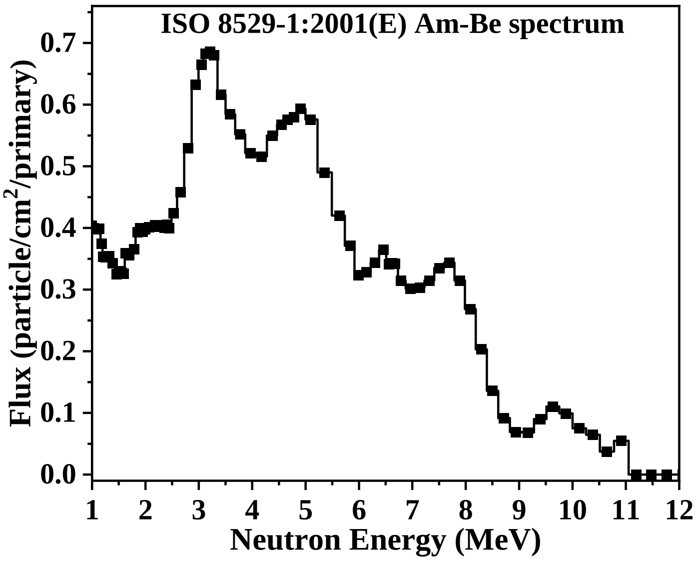


Figure 7 The Am-Be ISO spectrum.

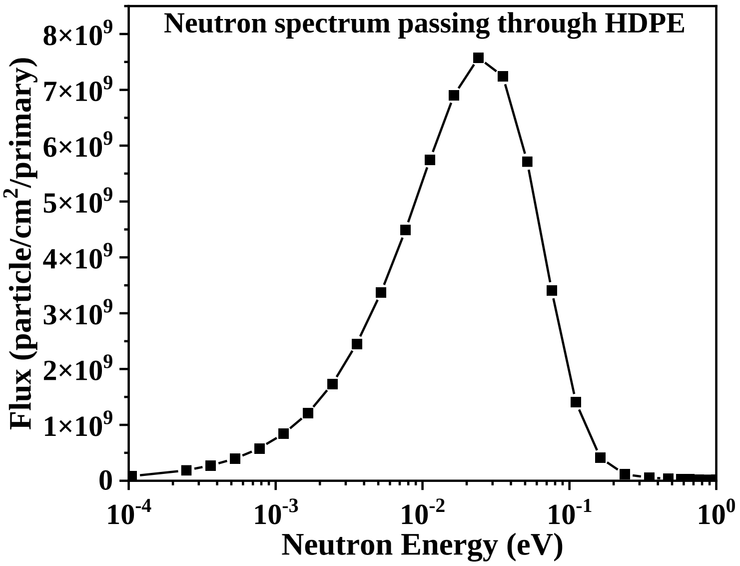


Figure 8 The thermal neutron spectrum passing through HDPE.

Figure 9 (a, b and c) shows the 2D graphs of the dose equivalent of thermal neutron. It was found that dose equivalent of thermal neutron did not pass though sample as exhibited in Figure 9 (a) better than the passed through the sample as exhibited in Figure 9 (b and c) and the dose equivalent of thermal neutron passed through the S1 more than S6 glass sample [32]. It was found that thermal neutrons were passing through S1 more than S6.

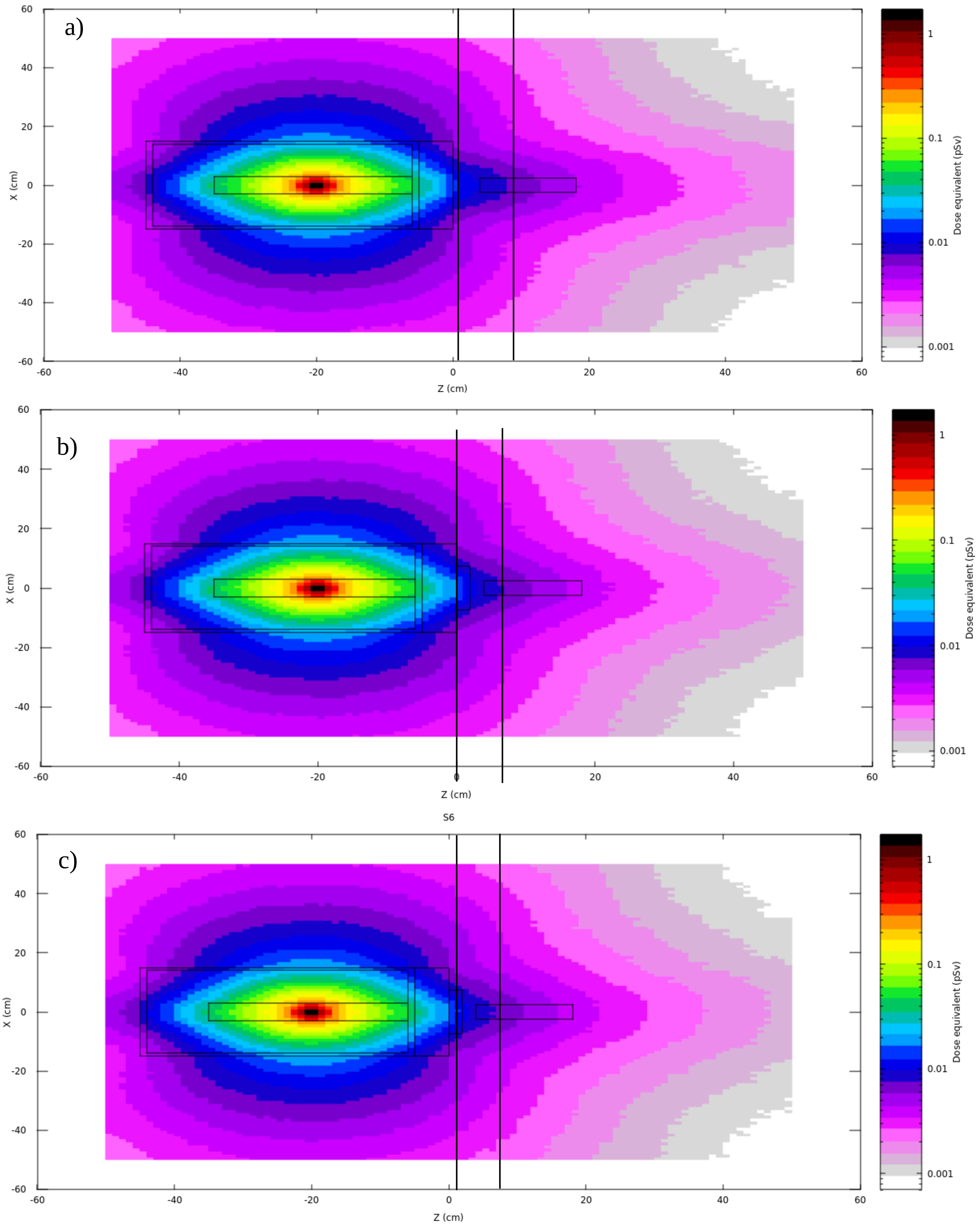


Figure 9 Typical dose equivalent of thermal neutron for a) I_0, b) and c) passing through S1 and S6.

The relationship between the mass attenuation coefficient (μ_m) for thermal neutron and Gd_2O_3 content at thickness 2 cm is shown in Figure 10. The trend of μ_m value decreased with increasing Gd_2O_3 concentration. It indicated that thermal neutron shielding was being attenuated at high Gd_2O_3 content.

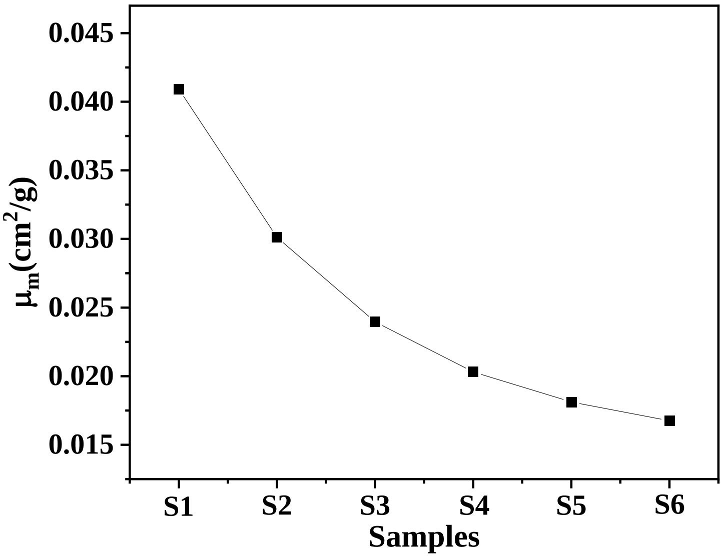


Figure 10 The mass attenuation coefficient of thermal neutron for glass series.

Fast neutrons shielding properties

The fast neutrons shielding properties for glass series were discussed on fast neutrons removal cross sections (Σ_R), HVL and the relaxation lengths as shown in Figures 11-13, respectively. It was found that Σ_R increased while HVL and the relaxation lengths decreased with increasing Gd_2O_3 content which increased the density of the glass series resulting in better fast neutrons shielding. These mean that the good fast neutrons shielding should be the heavy elements of high atomic number [27,33-36].

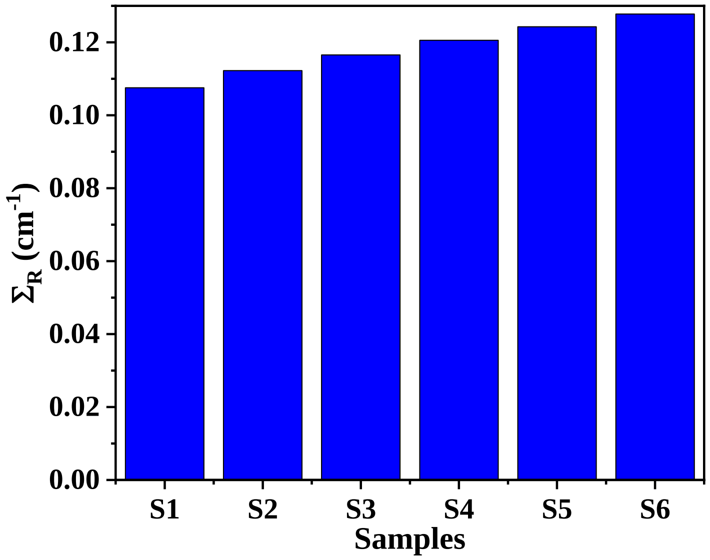


Figure 11 The removal cross section ($\sum_R$) for fast neutrons of glass series.

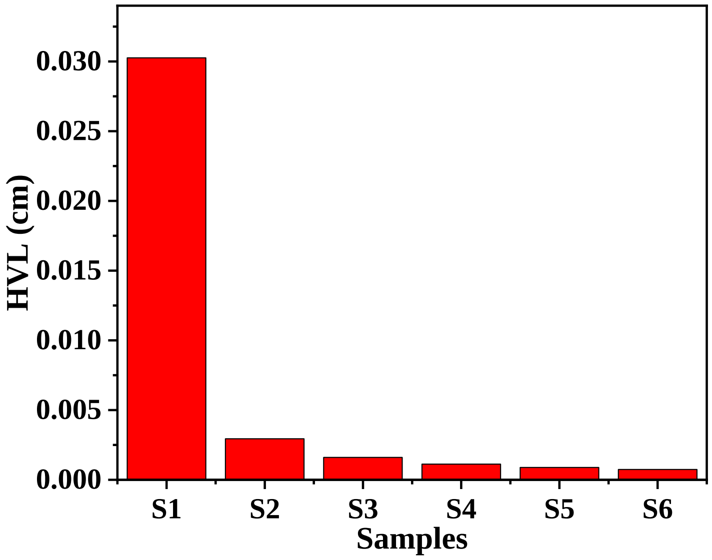


Figure 12 The HVL for fast neutrons of glass series.

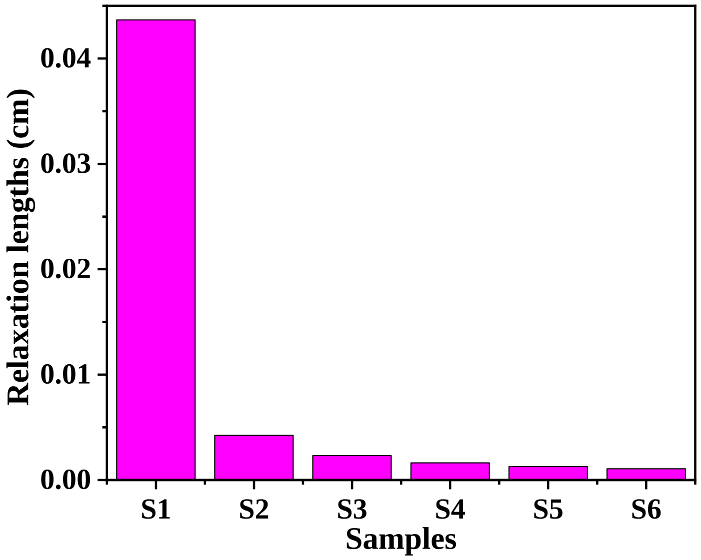


Figure 13 The relaxation lengths for fast neutrons of glass series.

Conclusions

From the available results of the study shielding properties for γ-ray, thermal and fast neutrons of the glass series. The results showed that the addition of Gd_2O_3 into Gd_2O_3-SiO_2-Y_2O_3-CaO-B_2O_3 glass series made the μ_m values increased while both HVL and MFP values decreased. These results indicated that the glass sample that contained 50Gd_2O_3 mol% was the excellent shielding γ-ray. For the thermal and fast neutron shielding properties, it can be seen that the 50Gd_2O_3 mol% glass sample showed the lowest value for thermal neutrons while the highest value for $\sum_R$ and the lowest value for HVL and the relaxation lengths for fast neutrons were observed. These results indicated that this glass series which high Gd_2O_3 content possessed excellent γ-ray and fast neutrons shielding properties, while 20SiO_2-5Y_2O_3-10CaO-65B_2O_3 glass sample possessed superb thermal neutrons shielding.

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