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Analysis of Radiation Shielding Properties of Dysprosium Doped Strontium Magnesium Borate Glasses

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ABSTRACT

Radiation exposure to patients has increased globally due to the growing use of medical imaging in diagnostic radiography. It has been demonstrated that ionizing radiation increases the long-term risk of cancer by causing tissue damage and changing the DNA structure. The radiation shielding properties of dysprosium doped strontium magnesium borate glasses were analyzed using Phy-X/PSD. The chemical composition of glass $20MgO+10SrO+(70–x)B_2O_3+yDy_2O_3$ with $0.5 \leq x \leq 1.0$ mol % glass, and are coded as S1, S2, and S3, in decreasing Dy2O3 content. Phy-X/PSD was used to determine the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half value layer (HVL), effective atomic number (Zeff) of the investigated glasses. The maximum values for all the glasses can be observed at the lowest tested energy, 0.015MeV and are equal to 76.034 cm^2/g, 7.535 cm^2/g, and 6.640 cm^2/g for the S1, S2, and S3 glasses, respectively. At this energy, the MAC of the glasses can be observed to decrease as the Dy_2O_3 concentration of the sample decreases as well, which could be due to the decrease in density that correlates with B_2O_3 content. The minimum HVL values occurred at the lowest tested energy, 0.2447 MeV, and increased with increasing energy, meaning that the glasses are more effective at lower energies. The results proved that the S1 glass, the glass with the greatest Dy_2O_3 content and density, has the greatest potential for radiation shielding application.

Keywords:
Radiation,
Shielding,
Dysprosium,
Strontium,
Magnesium,
Borate Glasses.

INTRODUCTION

Ionizing radiation, both electromagnetic and particle, is being widely used in more and more industrial and medicinal domains (Jain, 2021). Numerous institutions and groups have formed guidelines for the handling and safe application of this kind of radiation (Sandle,2013). Different kinds of materials are more practical for particular more specific types of radiation than others, as indicated by the way in which photons and essential characteristics of the protective substance (Tekin, 2022). Today, radiation shields can be made of a variety of materials, including concrete, glasses and alloys (Al-Hadeethia, 2019). Similar to other materials, glasses have the desired shielding qualities in addition to being transparent and available in a variety of compositions (Sayyed et al., 2021). In order to enhance the radiation shielding capabilities of eyewear, heavy metal The glass is doped with oxides(Alharshan, 2023). The most common materials used in radiation shielding are lead and concrete. Silicate and borate glasses are common heavy metal oxide glasses that have shown a lot of promise as materials of protection(Tekin et al., 2022). Tellurite eyewear has grown in popularity recently because of its low high heat capacity, low crystallization, strong chemical resistance, melting temperature and infrared radiation transmission, as well as a high dielectric constant (Gerward, 2004).

It is generally not possible for pure tellurium oxide to form glass. However, the glass becomes usable again when heavy metal oxide is added because of the increased chemical stability and devitrification resistance. Oxide of heavy metals, used to lead oxide is a dense, inexpensive material that can achieve this. Despite being widely while it is effective when used for defense, it has certain disadvantages, like being a heavy element being toxic and not being environmentally friendly. As seen from this angle, radiations shielding material researchers and engineers have been collaborating to create innovative Materials for radiation protection that don't contain lead, like polymers, glasses, concrete, and building ceramics, materials, etc. (Al-Hadeethia, 2019).

Radiation shielding developers are very interested in glasses for a variety of reasons, including their low cost of production, the fact that they are transparent shielding materials that are safe for the environment, and the simplicity with which heavy components like Pb, W, Bi, and Ba. B2O3are typically regarded as superior glass (Saleh, 2022). The borate-based glasses are becoming more popular due to their high refractive index, transparency, low melting temperature, low viscosity, and low index (Sayyed, 2021). Heavy elements and oxides are added to the borate-glass network as modifiers to enhance the material's ability to absorb radiation. Consequently, additional oxides like Bi2O3 (which was utilized in this project) to replace lead while maintaining the necessary level of effectiveness be looked into. In order to assess a material's ability to block radiation, several calculations are made for parameters. Among the typical shielding parameters are mass attenuation. Coefficients, equivalent atomic number, half value layer, and tenth value layer (Azuraida 2015). The aim of this study was to investigate and understand the radiation shielding properties of dysprosium doped strontium magnesium borate glasses.

MATERIALS AND METHODS

Glass Preparation

The glasses prepared by (Ichoja *et al*. 2020) with compositions and densities as shown in Table 1 were used in this work. The glasses have chemical composition of 20MgO+10SrO+(70–x) B_2O_3+xDy_2O_3, where y = 0.1, 0.3, 0.5, 0.7 and 1.0 mol %.The glasses were coded as S1, S2, S3, S4, and S5which correspond to 3.85%, 11.54%, 19.23%, 26.92%, and 38.46 % of Dy_2O_3, respectively.

Table 1: Doped chemical composition (mol %) of 20MgO+10SrO+ (70–x) B_2O_3+xDy_2O_3 with 0.1 ≤ y ≤ 1.0 mol % glass (Ichoja, 2020)

MgO	SrO_3	(70–*x*) B_2O_3	*x*Dy_2O_3	Density (g/cm^3)
20	10	69.00	1.00	3.20
20	10	69.30	0.70	2.18
20	10	69.50	0.50	1.15

Radiation Shielding Simulation

The radiation shielding parameters of the Dy_2O_3 doped strontium magnesium borate glass system was computed by utilizing user friendly online PHY-X/PSD software developed by (Sakar *et al* 2020). The shielding parameters such as mass attenuation coefficient (μm), effective atomic number (Zeff), mean free path (mfp), half-value layer (HVL), tenth value layer (TVL) were calculated in the energy range from 0.015 to 15 MeV.

PHY-X/PSD Software

PHY-X/PSD software, which is recently developed to determine the radiation shielding parameters of different materials, was used in the calculation. Calculation process started by defining the chemical composition and the density of the material in the program. In the software, the material composition can be entered as mole fraction or weight fraction as shown in Figure 3.1. The parameters are determined in a wide energy range by selecting the energy sources (55Fe, 60Co, 109Cd, 131I, 133Ba, 137Cs, 152Eu, 241Am and the K-shell energies of Cu, Rb, Mo, Ag, Ba and Tb elements (Sakar et al., 2020).

The software output the doped result including all the values of shielding materials.

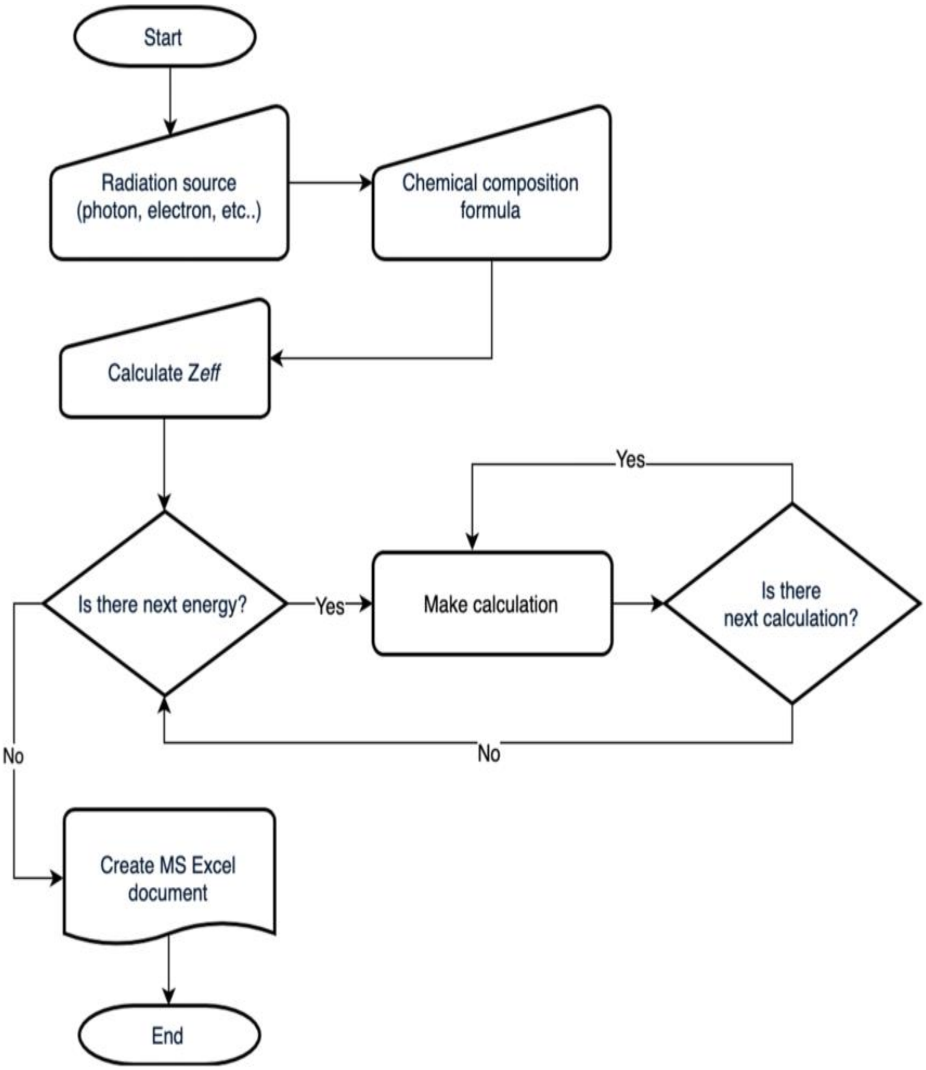

Figure 1: PHY-X/PSD online software interface

RESULTS AND DISCUSSION

Mass Attenuation Coefficient (MAC)

The mass attenuation coefficient (MAC) is the main shielding parameter that defines the capacity of the shielding medium to attenuate the incoming gamma-ray. The simulated values of mass attenuation coefficients are given in Table 2 for the studied gamma-ray energies of glass samples S1, S2, and S3 respectively.

Table 2: Gamma-ray energies of glass samples S1, S2, and S3

Energy(MeV)	Mass attenuation coefficient MAC (cm^2/g)		
	S1	S2	S3
0.015	76.034	7.535	6.640
0.02	36.713	10.380	10.021
0.03	12.541	3.580	3.458
0.04	5.865	1.707	1.650
0.05	3.283	0.987	0.956
0.06	9.420	0.978	0.867
0.08	4.517	0.523	0.471
0.1	2.539	0.344	0.315
0.15	0.918	0.194	0.184
0.2	0.474	0.147	0.143
0.2835	0.239	0.116	0.114

0.3	0.217	0.112	0.111
0.3471	0.173	0.104	0.103
0.4	0.142	0.096	0.096
0.5	0.110	0.086	0.086
0.6	0.092	0.079	0.079
0.6617	0.085	0.076	0.075
0.8	0.073	0.069	0.069
0.8261	0.071	0.068	0.068
1	0.062	0.062	0.062
1.173	0.056	0.057	0.057
1.333	0.052	0.053	0.053
1.5	0.049	0.050	0.050
2	0.043	0.043	0.043
2.506	0.040	0.039	0.039
3	0.038	0.035	0.035
4	0.036	0.031	0.031
5	0.036	0.028	0.028
6	0.036	0.026	0.026
8	0.037	0.024	0.024
10	0.039	0.023	0.023
15	0.042	0.021	0.021

Figure 2 illustrates the relationship between MAC and energy for the three investigated glasses.

Since MAC describes the ability for a material to attenuate radiation, a greater value denotes a more effective shield. The maximum values for all the glasses can be observed at the lowest tested energy, 0.015MeV and are equal to 76.034 cm^2/g, 7.535 cm^2/g and 6.640 cm^2/g for the S1, S2, and S3 glasses, respectively. At this energy, the MAC of the glasses can be observed to decreases as the Dy_2O_3 concentration of the sample decreases as well, which could be due to the decrease in density that correlates with B_2O_3 content.

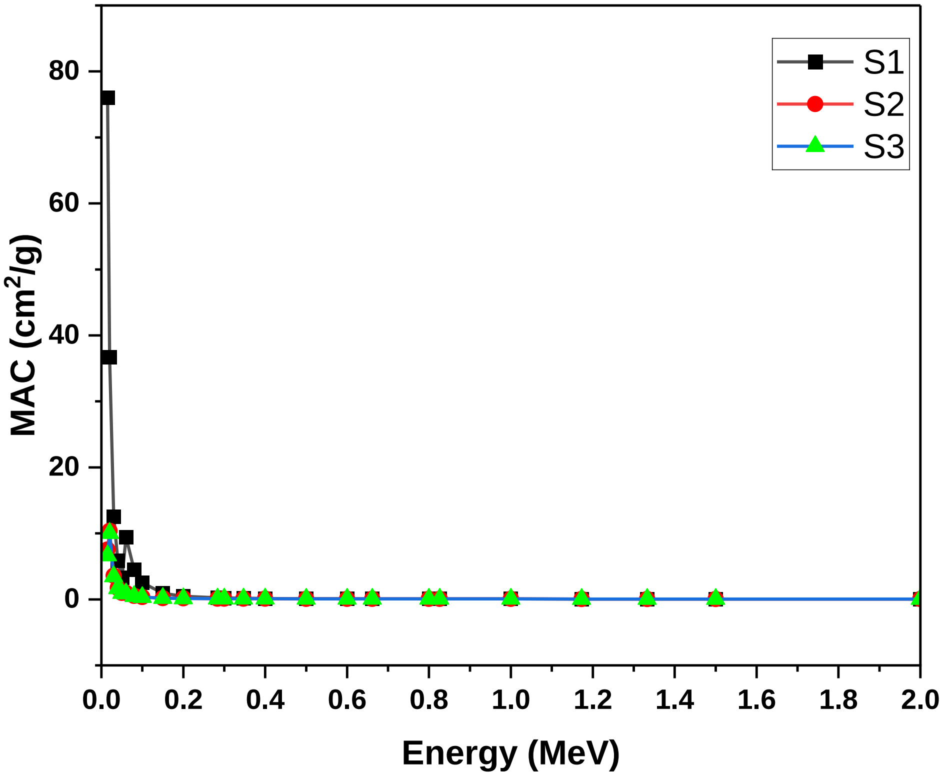

Figure 2: The mass attenuation coefficient (MAC) of the dysprosium doped strontium magnesium borate glasses against energy

The MAC of all the glasses rapidly decreases and then slows down and becomes almost constant. For instance, the MAC of the S1 glass sample decreases from 0.115 cm^2/g at 0.015 MeV, Other samples follow a similar pattern. The MACs of the glasses increase with the concentration of Dy_2O_3 and decreases as energy increases because as the incoming radiation has more energy, more photons can penetrate through the sample, decreasing its absorption ability, and decreasing MAC. This trend also demonstrates that at lower energies the samples are the most effective, with S1 being the most, and as energy increases, their shielding ability becomes less effective, to the point that at high energies the differences between the shields are negligible. Nevertheless, at most energies, the S1 glass can be concluded to have superior attenuation abilities over the other investigated samples.

The result of current research agrees with one reported by Alajerami *et al*. (2020). "The mass attenuation coefficient (MAC) increases with increasing density of composition and decrease with increasing energy of an incident photon".

Linear Attenuation Coefficient (LAC)

Efficiency of photo attenuation by material significantly depends on exposure time, distance, type of radiation occupying and materials attenuation power such as LAC and MAC (Powar 2013).

Figure 3 shows the Linear attenuation coefficient (LAC) of the dysprosium doped strontium magnesium borate glasses against energy. The results shows that LAC depends on photon energy which is in good agreement with various studies (Reza 2020). It also revealed that LAC is low at high energy, meaning that photons with high energy can easily penetrate in the materials. Therefore, our findings shows that LAC is directly proportional to the density of the glass sample.

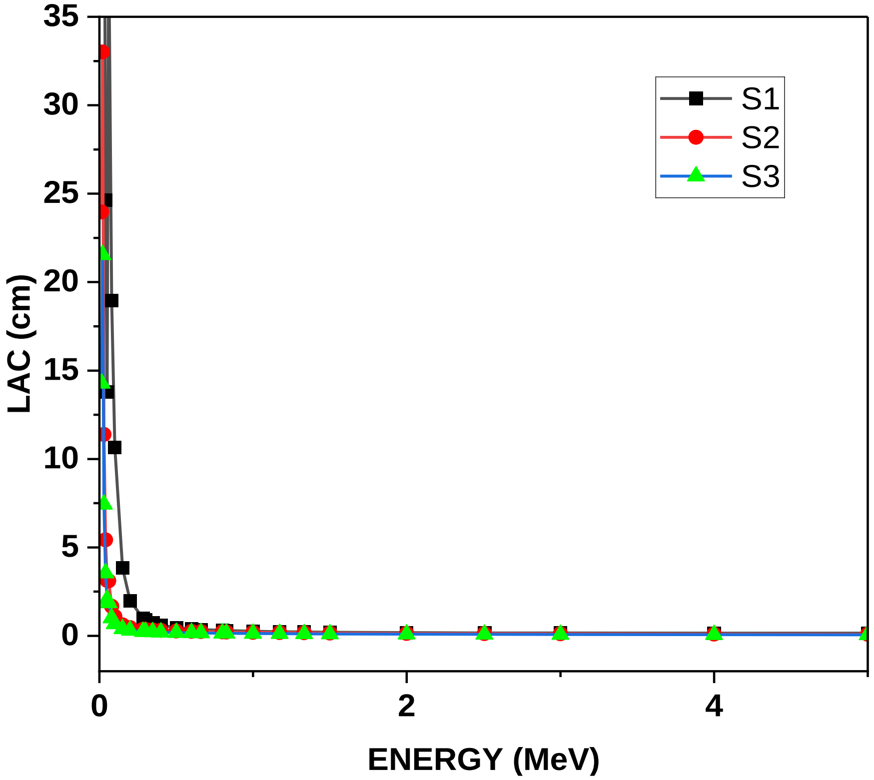

Figure 3: The Linear attenuation coefficient (LAC) of the dysprosium doped strontium magnesium borate glasses against energy

The results shows that the LAC values also correlate with the density of the glass and Dy2O3 content, which causes S1 glass to have the greatest LAC. It can be concluded that the S1 glass has the most desirable radiation shielding properties. This results is in accordance with the one reported by (Mahmoud et al.,2020).

Half Value Layer (HVL)

The half value layer (HVL) provides conclusive information about the shielding ability of material as it designated the thickness needed to half the number of photons arriving (Askin 2020)

Fig 4 shows the half value layer (HVL) of the dysprosium doped strontium magnesium borate glasses against energy, the required shielding material is inversely proportional to the HVL values. It also shows the relationship between HVL and the incoming photon energy. HVL is the thickness of the material required or needed to reduce the intensity of the incoming radiation by half.

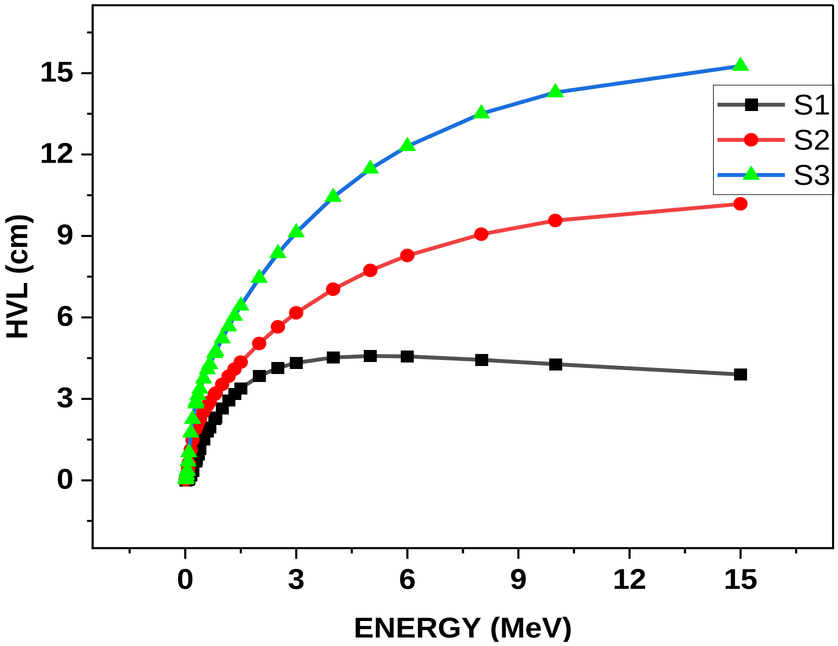

Figure 4: The Half value layer (HVL) of the dysprosium doped strontium magnesium borate glasses against energy

The results follow an increasing trend with energy, with the minimum energy values at the lowest tested energy level (0.015MeV), equal to 0.244cm For S1, 0.476cm For S2 and0.76cm for S3. The maximum HVL can be traced at 15MeV and equal to 3.024cm,9.23cm and 15.17cm for S1, S2 and S3 respectively. At the energy level S1 glass possess the lowest HVL, while S3 has the greatest. These results show that for the same photon energy, S1 requires a much smaller thickness than the others to reduce the intensity of radiation by half. This result is in line with (Bagheri et al.,2018).Superior attenuation against incoming radiation is the result of a drop in HVL as glass density increases. Small thickness is hence appropriate for preventing low energy photons. With respect to high energy photons, the thickness of the doped glass must be sufficiently increased.

The Effective Atomic Number (Z_{eff})

Considering the fact that materials like glasses enclose divers' type of element in their structures (Askin et al., 2020), computation of the effective atomic number Z_{eff} provides selective data for the applicability of glass in gamma shielding application. Figure 5 shows the effective atomic number of the dysprosium doped strontium magnesium borate glasses against energy.

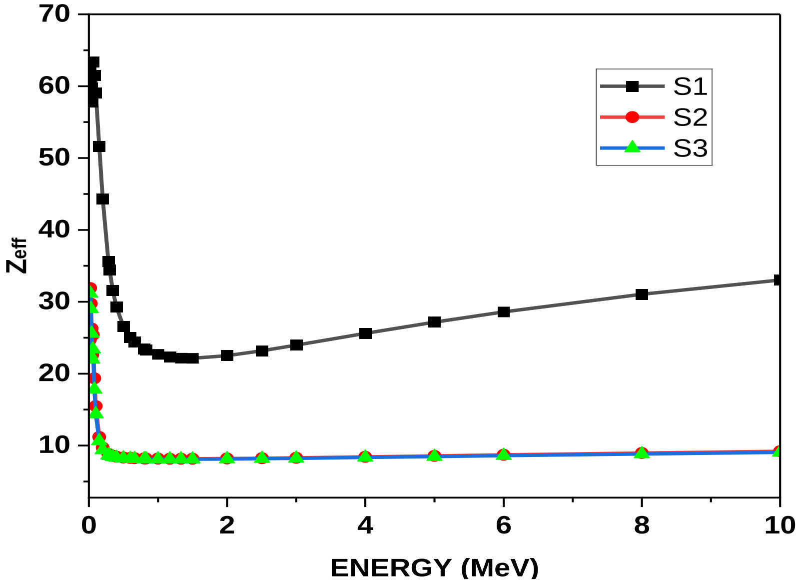

Figure 5: The effective atomic number of the dysprosium doped strontium magnesium borate glasses against energy

As can be seen in this figure 5, Z_{eff} decreases with decreasing Dy_2O_3 fraction and the increase in the fraction of B_2O_3 molecules. At 15 MeV, Z_{eff} values of S_1, and S_3 were found to be 64cm and 33cm respectively. Lowering the amount of molecules containing high Z element weakens the shielding ability and the existence of high Z element in the glass structures is essential for enhanced attenuation characteristics (Askin et al.,2020).

Mean Free Path

This is the most significant quantity which identifies the potential of any barrier to photon attenuation. Previous report revealed that materials with low mean free path are good for stopping incoming radiations.

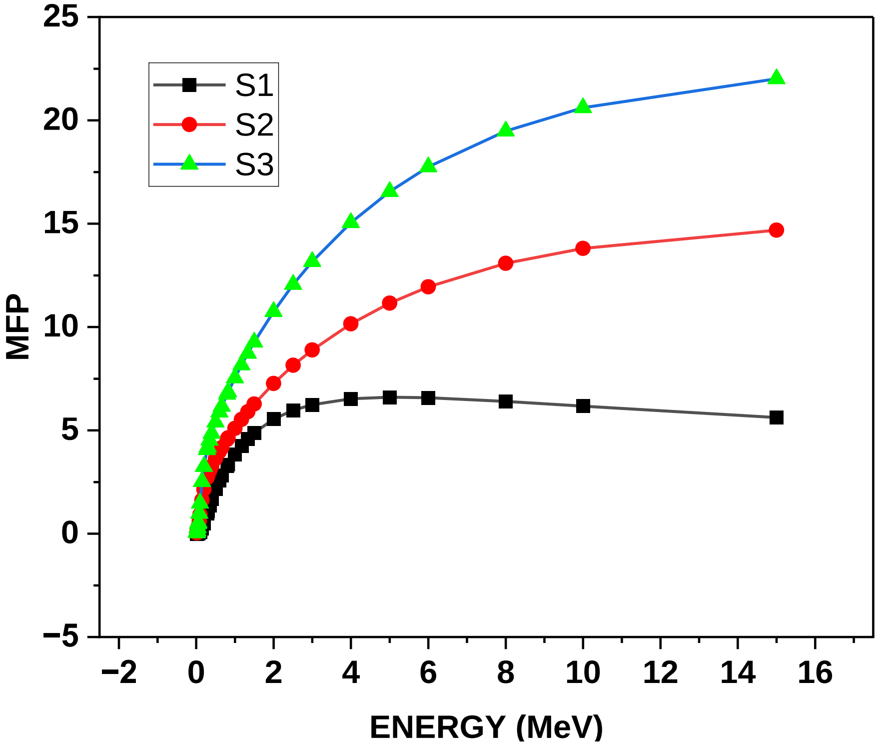

Figure 6: Mean Free Path

As seen from the Figure 6 above, large number of photons can enter the sample at higher energy values because, as the above figure illustrates, the mean free path varies directly with photon energy. Additionally, when the concentration of Dy_2O_3 increases, the MFP value drops; hence, the density of the glass samples also influences the mean free path. The mean free path decreases as density increases. Additionally, it was discovered that the density of the SrO/Dy_2O_3 glass increased as the Dy_2O_3concentration increased, which is in line with studies carried out by Abouhaswa et al (2021).

CONCLUSION

The radiation shielding parameters such as mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), and effective atomic number (Z_{eff}) were determined theoretically using Phy-X/PSD software. The MAC of the glasses increases with the concentration of Dy_2O_3 and decreases as energy increases because as the incoming radiation has more energy, more photons can penetrate through the sample, decreasing its absorption ability, and decreasing MAC. This trend also demonstrates that at lower energies the samples are the most effective, with S1 being the most, and as energy increases, their shielding ability becomes less effective.

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