Research Article

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Effect of dysprosium on the radiation-shielding features of SiO_2–PbO–B_2O_3 glasses

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Abstract: In a variety of applications using ionizing radiation, it is essential to ensure the safety of both individuals and equipment. To this end, excellent radiation shielding materials, including glasses and rare earth elements, such as Dy_2O_3, are currently being researched. The goal of this study is to explore the effect of Dy_2O_3 on the radiation-shielding properties of the SiO_2–PbO–B_2O_3–Dy_2O_3 glass system; for clarity, it is abbreviated as Dy-X. Dy_2O_3 is a good choice for use as a modifier in radiation shielding glasses since it has high density. Additionally, Dy_2O_3 has good thermal stability and can be added to glass matrices without substantially affecting their physical features. The influence of increasing the amount of Dy_2O_3 present in the glasses from 0 to 5 mol% on the linear attenuation coefficient (LAC) and effective atomic number (Z_{eff}) was studied using glasses with five distinct compositions and densities. In order to achieve this, the Phy-X program was utilized. The results demonstrate that Dy5 (with a composition of $55B_2O_3$–25PbO–$20SiO_2$–$5Dy_2O_3$) has the highest LAC value of the prepared glasses, while Dy0 has the lowest. We investigated the influence of Dy_2O_3 on Z_{eff} at 0.284 MeV. The results show that the Z_{eff} values increase with increasing Dy_2O_3 content. The Z_{eff} values were found to be 27.35, 27.94, 28.52, 29.09, 29.65, and 30.20 for Dy0, Dy1, Dy2, Dy3, Dy4, and Dy5, respectively. From the Z_{eff} results, we observed that increasing the Dy_2O_3 content in the samples leads to an improvement in the shielding ability of the glass system. We compared the LAC of the Dy-X glasses with six glass systems at 0.662 MeV. All Dy0–Dy3 glasses have lower LAC values than all the TeO_2–Li_2O–ZnO glasses, but Dy4 has an LAC value greater than those of three of these glasses.

Keywords: effective atomic number, photons, nuclear technology, Dy_2O_3

1 Introduction

Radiation has applications in different fields, including scientific research, applications in industry, the medical field, aerospace, agriculture, and other fields. Despite its benefits, radiation causes serious health dangers and thus it is crucial to understand its characteristics and suitable handling procedures [1]. The search for one-of-a-kind, non-traditional materials is one of the most critical concerns in nuclear-shielding technologies, particularly in light of the growing number of radioisotope sources, nuclear energy generators, and other devices that emit radiation. Because of their amazing advantages, such as low cost, simple installation, strong mechanical attributes, and the capacity to limit, the risks posed by gamma photons, lead and special forms of concrete are the principal materials that are used for shielding purposes. Since many present technological uses make greater utilization of radioactive isotopes and equipment that generate ionizing radiation, it is crucial to expand the research and advancement of radiation-protective composites [2,3]. In building the window for radiology facilities and glasses to protect the face and eyes from radiation, it is particularly vital to choose products that are transparent to visible light.

Glass is among the most important materials for use in radiological protection purposes because of its ability to be shaped into specimens of varied thicknesses in a number of shapes and due to the ease with which glass can be produced using a variety of methods [4–8]. As a shield, many glass systems were investigated, and it was revealed that glasses with high density had a lower mean free path than certain other commercialized glasses and concretes [9,10]. For the design of radiation shielding materials, especially those with high energy levels, it is essential to select the composition of the glasses that are most suited. In the past few years, a significant number of investigators have proved that glasses containing heavy metal oxides or

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rare-earth element oxides may be employed as radiation shielding materials due to the increased effective atomic number [11–14]. Borate glass that has been treated with bismuth oxide possesses exceptional dielectric properties, in addition to high densities and refractive indices. Compared to other modifiers, rare-earth oxide modifiers show a substantial improvement. The optical, electrical, and thermal stability of glass is increased by rare-earth oxide modifiers. The rare-earth oxide modifiers attracted a lot of attention due to their potential use in many applications [15,16]. It is anticipated that glasses that contain both heavy metal oxide and rare earth elements would prove to be efficient photon-reducing glasses. In addition, glass that contains such compositions becomes less hazardous than lead in its pure form, which motivates investigators and other individuals interested in the subject to utilize this type of glass, which is non-toxic and favorable to the environment, in commercial and medical fields [17,18]. Therefore, conventional shielding materials may be substituted by advanced materials that are not only superior in terms of their optical and chemical qualities but also provide greater efficiencies and reduced risks to the surrounding environment.

Determining a number of physical parameters like the linear attenuation coefficient (LAC) and effective atomic number (Z_{eff}) is one method for precisely assessing the radiation-protective characteristics of new kinds of glass that are being developed as shields [19,20]. In the research of radiation shielding materials, the LAC and Z_{eff} values are significant because they are connected to the material's capacity to absorb or attenuate ionizing radiation. The LAC represents the probability of a photon interaction with a given material per unit path length, while the Z_{eff} is an essential variable, especially for materials consisting of many elements. Z_{eff} takes into consideration the distinct atomic numbers and relative abundances of every element in the material, as opposed to individual atomic numbers, which reveal the total number of protons in an atom. It is worth mentioning that materials with higher LAC and Z_{eff} are more effective in shielding the incoming photons, as they are better capable of absorbing the photons.

These parameters can either be approximated on a theoretical level or tested in practice in research facilities. In many cases, it is not possible to conduct experimental research because there are insufficient resources available, including the lack of radioactive sources. In addition, the execution of practical testing is hampered by a number of impediments, including the impending closure of educational establishments and research facilities in the year 2020 as a consequence of the spread of the coronavirus pandemic.

In every instance described above, the theoretical component becomes crucial when it comes to determining the physical values associated with the investigation of the radioactive material characteristics of various materials [21,22]. Accordingly, the theoretical approach is a good choice in evaluating the radiation shielding characteristics of glassy materials. So, a theoretical method is adopted in this work to determine the radiation shielding features of SiO_2–PbO–B_2O_3 glasses with different concentrations of Dy_2O_3. Because of its well-established characteristics as a radiation-shielding material and its compatibility with an extensive range of alteration techniques, the utilization of SiO_2–PbO–B_2O_3 glass as a base material for modification is motivated by the fact that it already possesses this reputation. Moreover, this glass system is a desirable option for use in a range of radiation shielding applications due to its low cost and commercial availability.

2 Materials and methods

In order to find the appropriate glass that can provide practical and safe protection from radiation exposure, it is required to report the radiation shielding parameters for a number of different glasses [23–25]. The Phy-X/PSD program [26] was used in our research to perform theoretical analysis on the gamma-ray attenuation properties of B_2O_3–PbO–SiO_2–Dy_2O_3 glass systems.

There are three steps that are necessary for the calculation using the Phy-X/PSD program and are listed as follows:

2.1 Definition of materials

The first step is to accurately define the composition of the material to be used in calculations. In the software, the material composition can be entered in two different ways such as mole fraction and weight fraction. Additionally, the density (g/cm^3) of the materials must be given in this step.

2.2 Selection of energies

Two energy regions have been predefined in the software: 15 keV to 15 MeV and 1 keV to 100 GeV. Also, some well-known radioactive sources (^{22}Na, ^{55}Fe, ^{60}Co, ^{109}Cd, ^{131}I, ^{133}Ba, ^{137}Cs, ^{152}Eu, and ^{241}Am) along with their energies are available in the software and can be selected by the user.

2.3 Selection of parameters to be calculated

Users can choose which parameter(s) they want to calculate depending on their studies. The users are free to choose both the energies and the number of parameters to be calculated.

After completing these three steps successfully, users can save the calculation results in a well-designed MS Excel file.

For simplification, we will refer to the glass samples as Dy-X. The effect the change in the percentage of Dy_2O_3 from 0 to 5 mol% had on the efficiency with which these systems attenuated radiation was investigated. Gaafar *et al.* [27] had earlier manufactured these glasses. They provided a detailed explanation of the glass manufacturing process, as well as the acoustic and physical properties of the glasses. The following are the codes for the selected samples:

Dy0: $55B_2O_3$–25PbO–$20SiO_2$, density = 3.722 g/cm^3
Dy1: $54B_2O_3$–25PbO–$20SiO_2$–$1Dy_2O_3$, density = 3.862 g/cm^3
Dy2: $53B_2O_3$–25PbO–$20SiO_2$–$2Dy_2O_3$, density = 3.943 g/cm^3
Dy3: $52B_2O_3$–25PbO–$20SiO_2$–$3Dy_2O_3$, density = 4.021 g/cm^3
Dy4: $51B_2O_3$–25PbO–$20SiO_2$–$4Dy_2O_3$, density = 4.099 g/cm^3
Dy5: $50B_2O_3$–25PbO–$20SiO_2$–$5Dy_2O_3$, density = 4.184 g/cm^3.

The Phy-X program was used to calculate the LAC values of the samples described above. We investigated the effect the change in the amount of Dy_2O_3 from 0 to 5 mol% had on the LAC values of the glasses that were under investigation. Moreover, we determined the effective atomic number (Z_{eff}) by using the LAC values that we had obtained. Because of these two parameters, we are able to determine whether or not there has been an increase in the samples' capacity to shield radiation as a result of a change in the composition of the samples. More details about the radiation shielding parameters are available elsewhere [28–30].

3 Results and discussion

The LAC values of the Dy-X glasses were calculated at various gamma energies, and the results are plotted in Figure 1. The energy range utilized in this study was selected because Cs-137 and Co-60, the two radioactive materials frequently used in commercial and medicinal applications, release energies in this range. The results demonstrate that Dy5 has the highest LAC value of the prepared glasses, while Dy0 has the lowest. More specifically, Dy5 has LAC values of 1.168 cm^{-1} at 0.284 MeV, 0.833 cm^{-1} at 0.347 MeV, 0.500 cm^{-1} at 0.511 MeV, and 0.386 cm^{-1} at 0.662 MeV, while Dy0 has values of 1.030, 0.737, 0.446, and 0.345 cm^{-1}, at the same respective

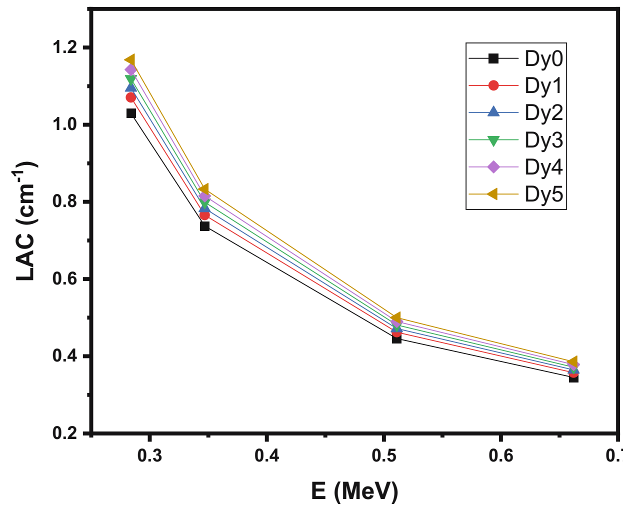

Figure 1: The LAC values of the Dy-X glasses.

energies. These results show that Dy5, the prepared sample with the greatest amount of Dy_2O_3, also has the highest LAC values at all tested energies. The replacement of B_2O_3 with Dy_2O_3 causes an increase in the LAC since the Dy has a higher atomic number and higher density than B. The aforementioned values also show that the LAC values of the glasses decrease with increasing energy, which the maximum values at 0.284 MeV, the lowest tested energy, and the minimum at 0.662 MeV, the highest tested energy. The other four glasses follow the same trends as well.

A reduction in LAC values can be because higher energy gamma radiation is more probable to move *via* the glass without interacting and are less likely to be absorbed by it.

The effective atomic number, Z_{eff}, of the six tested glass samples at 0.284 MeV is shown in Figure 2. The figure shows that the Z_{eff} values increase with increasing heavy metal oxide content. Moreover, they were found to be 27.35, 27.94, 28.52, 29.09, 29.65, and 30.20 for Dy0, Dy1, Dy2, Dy3, Dy4, and Dy5, respectively. This trend is expected as Dy with an atomic number of 66, replacing B with an atomic number of 5. Thus, it can be concluded that increasing the Dy_2O_3 content in the samples leads to an improvement in the shielding ability of the glass system.

In Figures 3–8, the LAC values of the prepared glasses are compared with other glasses at 0.662 MeV to gain a better understanding of the shielding capabilities of the Dy-X glasses against other previously investigated glass samples. In Figure 3, the Dy-X glasses are compared with four Bi_2O_3–TiO_2–V_2O_5–Na_2O–TeO glasses [31] with varying Bi and Ti contents. Three of the glasses, with Bi_2O_3 contents of 14, 16, and 18, all have LAC values less than Dy0. More specifically, they are equal to 0.227, 0.288, and 0.323 cm^{-1},

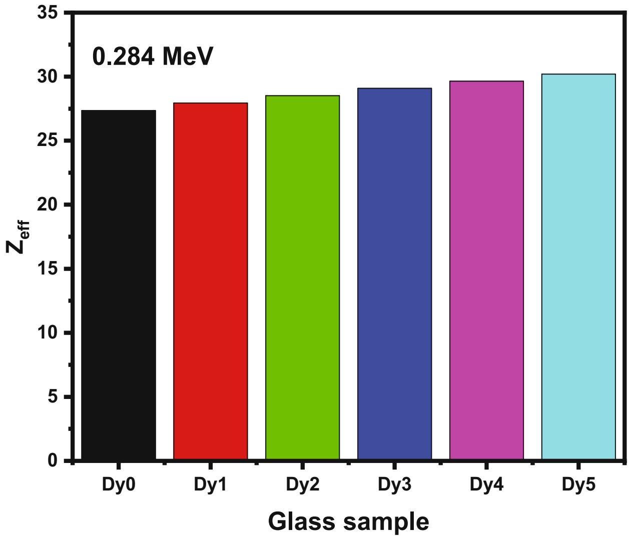

Figure 2: The effective atomic number of the Dy-X glasses at 0.284 MeV.

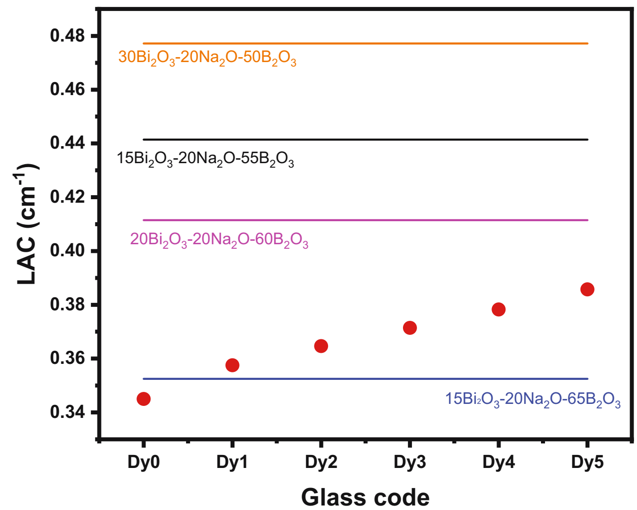

Figure 4: Comparison between the LAC for the Dy-X glasses with Bi_2O_3–Na_2O–B_2O_3 glasses at 0.662 MeV.

respectively, while the LAC of Dy0 is equal to 0.345 cm^{-1}. The glass with $20Bi_2O_3$ has an LAC value slightly higher than Dy1 (<0.001 cm^{-1} of a difference), while Dy2, Dy3, Dy4, and Dy5 all have LAC values higher than all the prepared glasses. These results demonstrate an overall good shielding ability for the Dy samples compared to these previously tested glasses.

In Figure 4, the Dy-X glasses were compared against Bi_2O_3–Na_2O–B_2O_3 glasses [32] with varying Bi contents. All the glasses except Dy0 had an LAC value greater than the glass with the least Bi content, while all of the others had a greater LAC than this glass but had lower LAC values than the other three glasses with 15, 20, and 30% Bi_2O_3, which had values of 0.411, 0.441, and 0.477 cm^{-1}, respectively, where the glass with 30% Bi_2O_3 has the highest LAC value.

The tested glasses were also compared against the glass system BaO–Li_2O–B_2O_3 [33] with different amounts of BaO in Figure 5. Of these previously investigated glasses, the one with the greatest BaO content and least Li_2O amount had the highest LAC of 0.293 cm^{-1}. Nevertheless, the four glasses all had lower LAC values compared to the Dy prepared glasses.

Figure 6 shows the LAC of the tested glasses with four glasses composed of SrO–PbO–B_2O_3 [34]. The figure shows that all the Dy-X glasses had a higher LAC than $20SrO$–$10PbO$–$70B_2O_3$

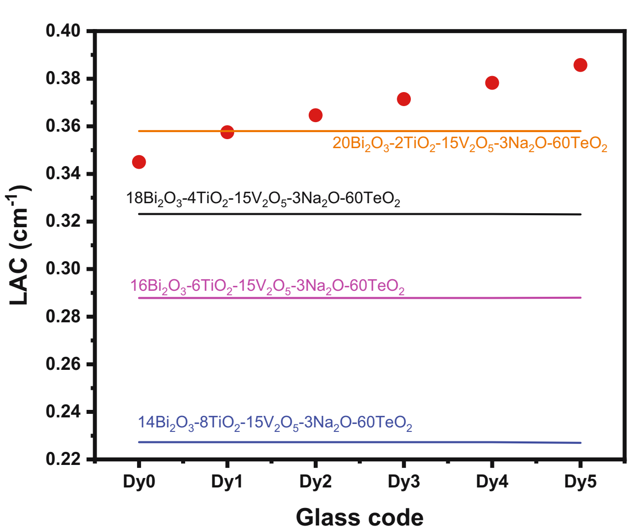

Figure 3: Comparison between the LAC for the Dy-X glasses with Bi_2O_3–TiO_2–V_2O_5–Na_2O–TeO_2 glasses at 0.662 MeV.

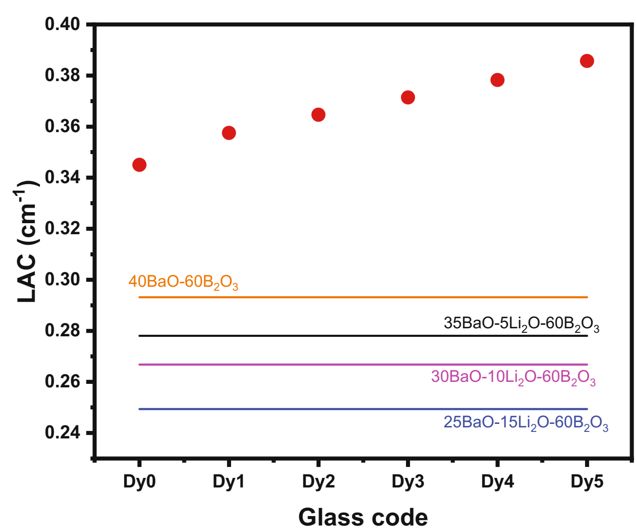

Figure 5: Comparison between the LAC for the Dy-X glasses with BaO–Li_2O–B_2O_3 glasses at 0.662 MeV.

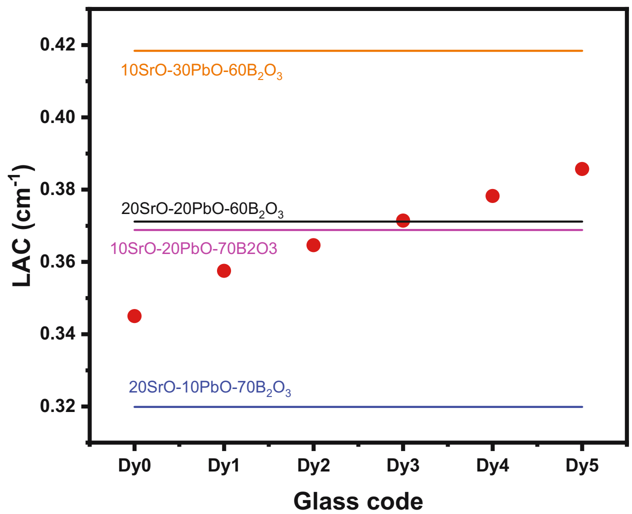

Figure 6: Comparison between the LAC for the Dy-X glasses with SrO–PbO–B_2O_3 glasses at 0.662 MeV.

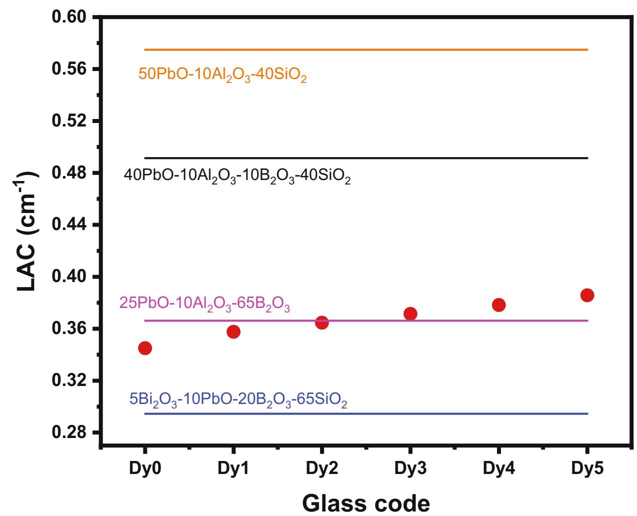

Figure 8: Comparison between the LAC for the Dy-X glasses with different glasses at 0.662 MeV.

with an LAC of 0.320 cm^{-1}, while Dy0–3 had LAC values lower than 10SrO–20PbO–70B_2O_3, with an LAC of 0.369 cm^{-1}. Meanwhile, Dy3–5 had higher LACs than 20SrO–20PbO–60B_2O_3, which has an LAC of 0.371 cm^{-1}, but none of the glasses had an LAC as high as 10SrO–30PbO–60B_2O_3, equal to 0.418 cm^{-1}. Therefore, the Dy-X glasses are fairly even with this glass system.

Figure 7 illustrates the LACs of the glasses against TeO_2–Li_2O–ZnO glasses [35]. The Dy0–Dy3 glasses all have lower LAC values than those of all the TeO_2–Li_2O–ZnO glasses; however, Dy4 has an LAC value greater than three of these glasses, while the LAC of Dy5 is greater than all four of these compared glasses, with the closest one having an LAC value of 0.381 cm^{-1}.

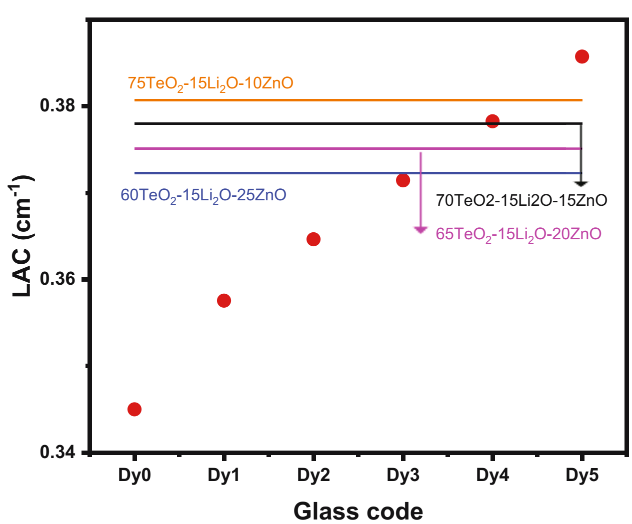

Figure 7: Comparison between the LAC for the Dy-X glasses with TeO_2–Li_2O–ZnO glasses at 0.662 MeV.

The tested glasses were also compared against a PbO–Al_2O_3 [36] glass system with other metal oxides in Figure 8. The 5Bi_2O_3–10PbO–20B_2O_3–65SiO_2 glass had the lowest LAC at 0.294 cm^{-1}, while the 50PbO–10Al_2O_3–40SiO_2 glass and the 40PbO–10Al_2O_3–10B_2O_3–40SiO_2 glass both had greater LAC values than the Dy-X glasses, with values of 0.574 and 0.491 cm^{-1}, respectively. Meanwhile, the 25PbO–10Al_2O_3–65B_2O_3 glass had a higher LAC than Dy0–2 but lower than Dy3–5. Overall, through these comparisons, we can conclude that the prepared glasses have a very respectable radiation shielding ability and can effectively go up against many other previously investigated glass systems.

4 Conclusion

The purpose of this research was to investigate the effectiveness of Dy_2O_3 on the radiation shielding performance of SiO_2–PbO–B_2O_3–Dy_2O_3 glass systems. The results demonstrate that Dy5 has the highest LAC value of the prepared glasses, while Dy0 has the lowest. The Z_{eff} values at 0.284 MeV increase with increasing heavy metal oxide content. The Z_{eff} values at 0.284 MeV are equal to 27.35, 27.94, 28.52, 29.09, 29.65, and 30.20 for Dy0, Dy1, Dy2, Dy3, Dy4, and Dy5, respectively. From both LAC and Z_{eff} results, it is evident that increasing the Dy_2O_3 content in the samples leads to an improvement in the shielding ability of the glass system. We compared the LAC of the prepared glasses with other previously investigated glass samples at 0.662 MeV. When we compared the Dy-X glasses with Bi_2O_3–Na_2O–B_2O_3 glass systems, we found that all the glasses except Dy0 had an LAC value greater than the glass with the least Bi content, while all of the others had a greater LAC than this glass but had lower LAC values than the other three glasses with 15, 20, and 30% Bi_2O_3. For the SrO–PbO–B_2O_3 glass systems, all the Dy-X glasses had a higher LAC than 20SrO–10PbO–70B_2O_3 with an LAC of 0.320 cm^{-1}, while Dy0–3 had LAC values were lower than 10SrO–20PbO–70B_2O_3, with an LAC of 0.369 cm^{-1}. The comparison with other glasses demonstrated an overall good shielding ability for the Dy samples compared to these previously tested glasses. Future studies might look into combining these substances with other heavy metal oxides to improve the radiation-shielding capabilities of the chosen glass system. The basic processes governing the shielding effectiveness of the examined glasses were analyzed by evaluating the impact of various HMOs on the LAC and Z_{eff} of those glasses, and novel strategies may be developed for enhancing the performance under various conditions.

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Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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