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Gamma, Fast Neutron, Proton, and Alpha Shielding Properties of Borate Glasses: A Closer Look on Lead (II) Oxide and Bismuth (III) Oxide Reinforcement

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Abstract: The purpose of this research was to investigate the shielding characteristics of high-amount heavy metal oxide and Eu^{3+} -activated borate glasses based on $10\text{La}_2\text{O}_3\text{--}50\text{HMO}\text{--}(40\text{--}x)\text{B}_2\text{O}_3\text{--}x\text{Eu}_2\text{O}_3$ ($x = 0, 0.5, 1, 2$, and $\text{HMO} = \text{PbO}, \text{Bi}_2\text{O}_3$). Critical gamma radiation attenuation characteristics, particularly mass attenuation coefficients of investigated heavy metal oxide glass samples, were determined using Monte Carlo simulations and the Phy-x/PSD software. Following that, we looked at the half-value layer, mean free path, effective atomic number, and build-up factors across a broad energy range (0.015–15 MeV). According to the study's results, the addition of Eu_2O_3 enhanced the mass attenuation coefficient and effective atomic number, while reducing the half-value layer, mean free path, and accumulation factors. In terms of gamma radiation attenuation, the LBi50BEu glass system surpassed the LPb50BEu glass system in terms of overall shielding properties against nuclear radiation. Additionally, the heavy metal oxide glass' efficacy as a neutron shield was determined using fast neutron removal cross-sections (Σ_R). LBi50BEu2 glass was shown to be more effective in preventing the penetration of charged particle radiation.

Keywords: HMO glasses; nuclear radiation shielding; glasses; MCNPX

1. Introduction

With today's extensive use of radiation sources and radioactive materials, it is extremely essential to use radiation sources cautiously and safely. Against gamma radiation, the most utilized shielding materials are lead (Pb) and lead-equivalent compounds. However, Pb's negative impacts on human health and the environment pose a serious concern. Subsequently, it has some disadvantageous material properties, such as optical non-transparency, low durability, high cost, and material durability in terms of shielding applications [1]. Another material used to attenuate gamma radiation is concrete. Its most serious shortcomings, however, are that it is exceedingly heavy, pricey, opaque, and cracks when overused [2]. In recent years, researchers have been attempting to investigate the

features of eco-friendly, very dense, and chemically homogeneous materials that could be utilized as a replacement for concrete and lead. Corrosion-resistant, biocompatible radiation shielding systems must be created that can be modelled into narrow, compact forms with outstanding structural integrity and endurance. Glass has been proven to be an efficient shielding material due to its transparency to visible light, ease of production, and ease of property change through composition and preparation techniques. Glasses are one of a kind in that they can handle a wide variety of elements. They can act as a shield against hazardous ionizing radiation because of this characteristic. Impurities in the form of metals were incorporated into regular glass to transform it into a radiation shield glass. This doping, especially with heavy metal oxides (Ba, Bi, Pb), enhances the glass' attenuation properties, making it ideal for shielding applications. Glass formers are oxides that serve as the structural backbone of the glass network and are needed for optimal operation. As potential substitutes, borate glasses and lead-free compounds with adequate chemical resistance, transparency, and radiation protection are being investigated [3]. Borate-based glasses have a higher melting point and resistance to temperature changes than other types of glasses. Because of their high solubility of rare earth ions, ease of mass production, and low cost, bore-based glasses are the greatest choice for developing new optical devices. Borate-based glass systems have good broad-band properties and demonstrate significant increases in luminescence intensity. Doping transition metal and rare earth ions into borate glasses improves optical transmittances, electric conductivities, thermal, and even magnetic characteristics [4–6]. Pb-based glasses are particularly fascinating due to their strong electrical conductivity, stability, and wide glass-forming range. Strong UV transmittances, low melting and glass transition temperatures, and great thermal stability are all advantages of Pb-based glasses [7,8]. According to a study conducted by Tekin et al. [9], phosphate-based glasses are ideal for the fabrication of optical fibres and shielding material for radiation detection, among many other applications. Agar et al. [10] conducted another significant study which revealed that doping glasses with erbium (Er) leads to an increase in the mass attenuation coefficient and a decrease in build-up factors and half-value layer. Subsequently, glasses doped with Er possess significant radiation-shielding properties. The goal of this novel study is to determine the nuclear-radiation-shielding properties of glass samples from the $10\text{La}_2\text{O}_3\text{--}50\text{HMO}\text{--}(40\text{--}x)\text{B}_2\text{O}_3\text{--}x\text{Eu}_2\text{O}_3$ ($x = 0, 0.5, 1$ and 2 mol percent and $\text{HMO} = \text{PbO}, \text{Bi}_2\text{O}_3$) system in a wide range of energies between 0.015 and 15 MeV using the MCNPX (version 2.7.0) general-purpose Monte Carlo code [11] and Phy-X/PSD [12] software. It also aims to establish the materials' mechanical qualities, as well as their suitability as shielding materials. The results of this study will be useful in the field of glass literature, notably in the field of radiation shielding. Researchers will gain a better understanding of the utility of HMO-doped glasses as nuclear-radiation-shielding materials as a result of the findings of this study.

2. Materials and Methods

In this research, eight different high amount HMO (PbO and Bi_2O_3)-added and Eu^{3+} -activated borate glass samples [13] were extensively investigated in terms of their radiation-shielding properties (see Table 1). The densities of the glass samples were reported as follows:

- $5.393\text{ g/cm}^3\text{-LPb50B}$;
- $5.36\text{ g/cm}^3\text{-LPb50Eu0.5}$;
- $5.103\text{ g/cm}^3\text{-LPb50BEu1}$;
- $5.043\text{ g/cm}^3\text{-LPb50BEu2}$;
- $6.812\text{ g/cm}^3\text{-LBi50B}$;
- $6.795\text{ g/cm}^3\text{-LBi50Eu0.5}$;
- $5.808\text{ g/cm}^3\text{-LBi50Eu1}$;
- $5.940\text{ g/cm}^3\text{-LBi50Eu2}$.

Table 1. Chemical compositions and density for glass samples.

Sample Code	mol%						wt%				ρ (g/cm ³)	
	La ₂ O ₃	PbO	Bi ₂ O ₃	B ₂ O ₃	Eu ₂ O ₃	B	O	La	Eu	Pb		Bi
LPb50B	10	50	-	40	0	0.0503	0.1860	0.1615	0	0.6022	-	5.393
LPb50Eu0.5	10	50	-	39.5	0.5	0.0492	0.1845	0.1602	0.0088	0.5973	-	5.36
LPb50BEu1	10	50	-	39	1	0.0482	0.1830	0.1589	0.0174	0.5925	-	5.103
LPb50BEu2	10	50	-	38	2	0.0462	0.1801	0.1564	0.0342	0.5831	-	5.043
LBi50B	10	-	50	40	0	0.0295	0.1636	0.0947	0	-	0.7123	6.812
LBi50Eu0.5	10	-	50	39.5	0.5	0.0290	0.1628	0.0942	0.0052	-	0.7088	6.795
LBi50BEu1	10	-	50	39	1	0.0285	0.1620	0.0938	0.0103	-	0.7055	5.808
LBi50BEu2	10	-	50	38	2	0.0275	0.1605	0.0929	0.0203	-	0.6988	5.94

2.1. Studied Radiation Shielding Parameters

Equation (1) describes the photon flux attenuation in narrow photon beam. As indicated in Equation (1), a connection exists between the radiation intensity (I) and the absorbent glass material's thickness (t), as well as the radiation intensity (I_0) prior to contacting the substance [14]:

$$I = I_0 e^{-\mu t} \quad (1)$$

In Equation (1), μ is the linear attenuation coefficient.

The term of mass attenuation coefficient (μ_m) is a measure of how likely incident photons are to interact with matter per unit density. The formula shown in Equation (2) is used to compute it:

$$\mu_m = \sum_i w_i \left(\frac{\mu}{\rho} \right)_i \quad (2)$$

where (μ_m) is the mass attenuation coefficient, (w_i) is the weight fraction of the i th constituent element, (μ) is the linear attenuation coefficient, and (ρ) is the density. The mean free path (MFP) is the mean distance travelled by a photon inside a shielding material prior to encountering an interaction. It is calculated using the following Equation (3):

$$MFP = \frac{1}{\mu} \quad (3)$$

The half-value layer (HVL) is the absorber thickness required to reduce the radiation intensity to half of its starting value, as determined by Equation (4):

$$HVL = \frac{\ln(2)}{\mu} \quad (4)$$

In composite materials, the term “effective atomic number” (Z_{eff}) cannot be stated as a single number; instead, it varies depending on the material and specific characteristics of the interacting radiation, and it provides information about the material. The direct method was used to compute the Z_{eff} values of the samples in this investigation:

$$Z_{eff} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho} \right)_i}{\sum_j f_j \left(\frac{A_j}{Z_j} \right) \left(\frac{\mu}{\rho} \right)_j} \quad (5)$$

In Equation (5), f_i is fraction by mole, A_i is atomic weight, and Z_j is atomic number of i th constituent element. When developing gamma radiation shielding, build-up factor (BUF) considerations are crucial. The energy absorption build-up factor (EABF) is a measure of the amount of time a material is exposed to air after it has been penetrated by a particle. The exposure build-up factor (EBF) is a measurement of the amount of exposure in air after it has passed through the shielding material. BUFs are often computed using the geometric progression (G-P) fitting technique, which is described in detail below. To begin, the equivalent atomic number (Z_{eq}) of a particular energy is determined by comparing

its (μ_m) Compton/ (μ_m) total ratio to the element's convenient ratio. In this study, the Z_{eq} values for the glasses were determined using the interpolation technique. The EBF and EABF values for a single-layered gamma-ray-shielding enclosure (GSE), with an OT of up to 100 mfp and an energy range of 0.015 to 15 MeV, are calculated using the following Equations (6)–(8).

$$B(E, X) = 1 + \frac{b-1}{K-1} (K^x - 1) \text{ for } K \neq 1 \quad (6)$$

$$B(E, X) = 1 + (b-1)x \text{ for } K = 1 \quad (7)$$

$$K(E, x) = cx^a + \frac{d \tanh \frac{x}{K-2} - \tanh(-2)1 - \tanh(-2)}{1 - \tanh(-2)} \text{ for } x \leq 40 \text{ mfp} \quad (8)$$

In the above equations:

E : Incoming photon energy;

X : Penetration depth in millimetres per second;

B : Accumulation factor at 1 millimetre per second;

K : Photon-dose multiplication factor.

The projected range is a critical parameter for analysing the shielding and interaction of nuclear radiation with different objects at different protons and alpha kinetic energies. The predicted range provides an explanation for the mean value of the depth at which alpha and proton particles begin to slow down and come to rest. The stopping power of a vehicle is defined as the quantity of energy lost over a certain distance. The mass stop power of a system is the amount of energy lost per unit of density. For the computation of ion deposition data in ion irradiation materials, the Stopping and Range of Ions in Materials (SRIM) equation was utilized, and Monte Carlo simulations were utilized for the computation of data using the SRIM equation. According to the findings of this study, attenuation characteristics of the glass produced were tested against charged particles, such as alpha and proton, with the results measured in terms of alpha/proton mass stopping power and alpha/proton projected range [15]. The last term to discuss is “effective neutron removal” (R), which refers to the process of removing neutrons from the material in a timely way. Following the definition of the cross-defined (or un-scattered) cross-section definition, the total amount of nuclear energy generated in a fission event from the first (or fast) neutron is equal to the average anticipated quantity of nuclear energy generated in a fission event. Calculating the R values of a material may be accomplished using the following Equation (9):

$$\Sigma_{R/\rho} = \sum w_i (\Sigma_{R/\rho}) \quad (9)$$

In Equation (9), $\Sigma_{R/\rho}$ is mass removal cross-section (cm^2/g), and w_i is partial density (g/cm^3) of the i th element [16].

2.2. Monte Carlo Simulations (MCNPX Version 2.7.0)

The mass attenuation coefficients of the LPbX and LBiX glasses were efficiently estimated using the general-purpose Monte Carlo algorithm MCNPX (version 2.7.0). To begin, input data for MCNPX were created utilizing the basic components as follows:

- Cell card;
- Surface card;
- Source information.

Figure 1a depicts the 3D view of the modelled setup obtained from MCNPX Visual Editor VE VisedX22S. Within a lead (Pb) shield block, a point isotropic gamma-ray source was placed. The glass specimens were then modelled using their elemental compositions (in percent weight) and material densities (in grams per cubic centimetre). The cylindrical form of the glass specimen had a radius of 5 cm and was made of clear glass. As a consequence of this evolution, the borders of cell cards were filled with the material qualities that were required for their construction (i.e., elemental mass fraction and material density). In Figure 1b, one can see a 2D perspective and the dimensions of the proposed

MCNPX simulation setup for determining the gamma-ray transmission capabilities of lenses, such as LPbX and LBiX (obtained from MCNPX Visual Editor VE VisedX22S). The modelled point isotropic source may alternatively be viewed as an extension of the overall gamma-ray transmission arrangement in Figure 1a, as can be seen in Figure 1b. Listed in Table 1 are the elemental mass fractions of the LPbX and LBiX glasses that were under investigation. MCNPX INPUT file, which was used to define the elemental composition of glass specimens, had a Mn variable, which should be noted. The term of Mn is an integral part of material definition of n th material, along with constituent elements, their atomic numbers, and their elemental mass fractions (wt.%). Using the results of the initial cell description procedure, we were able to determine the importance of photon and electron interactions (IMP: p, e) in the cell. LPbX and LBiX glasses were connected to the opposite side of the detector field (F4 Tally Mesh) for the purpose of counting the attenuated gamma rays that were produced. This kind of tally mesh is helpful for estimating the average photon flux in a point or cell, as well as for other applications. A total of 10^8 particles at different photon energies were collected for each glass sample after each run was repeated (i.e., from 0.015 MeV to 15 MeV). When running all simulations, the MCNPX model exhibited a relative error rate less than 1 percent (%).

Figure 1. MCNPX setup: (a) 3D view of gamma-ray transmission setup obtained from MCNPX Visual Editor; (b) 2D view of gamma-ray transmission setup with dimensional information obtained from MCNPX Visual Editor.

3. Results and Discussions

In this study, a comprehensive investigation on high-amount heavy metal oxide (HMO)-added and Eu^{3+} -activated borate glasses based on $10\text{La}_2\text{O}_3$ – 50HMO – $(40-x)\text{B}_2\text{O}_3$ – $x\text{Eu}_2\text{O}_3$ ($x = 0, 0.5, 1$ and 2 mol% and $\text{HMO} = \text{PbO}, \text{Bi}_2\text{O}_3$) system was carried out in terms of their individual and comprehensive gamma-ray and charged particle attenuation competencies. In total, eight different glass samples, encoded LPb50B, LPb50Eu0.5, LPb50BEu, LPb50BEu2, LBi50B, LBi50Eu0.5, LBi50Eu1, and LBi50Eu2, were classified considering HMO type in their structure. Material densities and chemical properties of the aforementioned glasses can be obtained from Table 1. It is clearly seen that material densities of PbO-reinforced borate glasses varied from 5.043 g/cm^3 to 5.393 g/cm^3 , whereas material densities of Bi_2O_3 -reinforced borate glasses varied from 5.940 g/cm^3 to 6.812 g/cm^3 . In the glass structure, $(40-x)\text{B}_2\text{O}_3$ – $x\text{Eu}_2\text{O}_3$ indicates that, in both glass groups, B_2O_3 has been replaced with Eu_2O_3 from 0 to 2 mole%. Therefore, one can say that Bi_2O_3 contribution (as 50% mole) has increased the material density more than PbO contribution in terms of their HMO structures. To begin, we calculated the mass attenuation coefficients (MAC) of the aforementioned glass samples using the MCNPX code, and then compared them to theoretical findings obtained using the Phy-X/PSD program. In Table 2, the findings of both techniques are listed, together with their respective relative variances. Additionally, Figure 2 illustrates the variation in the MAC values of the investi-

gated glasses throughout the energy range 0.015–15 MeV. From Table 2, it is seen that the MAC values of LPb50B and LPb50BEu2 glasses vary between 78.429 cm²/g–0.045 cm²/g and 79.045 cm²/g–0.045 cm²/g, while the MAC values for LBi50B and LBi50BEu2 glasses are between 89.281 cm²/g–0.048 cm²/g and 89.442 cm²/g–0.048 cm²/g. It is noticed from Figure 2 that the MAC values decrease rapidly at 0.015–0.1 MeV photon energies, and increase suddenly before reaching 0.1 MeV. This rapid drop is due to the impact of photoelectric absorption (PEA) in the low energy region and the changing in cross-section of interaction with $1/E^{3.5}$ in that zone. Besides, a sudden increase occurred around 88.00 keV and 90.52 keV, which are the absorption edges of Pb and Bi heavy elements in two glass systems, since the cross-section of PEA is proportional to Z^4 – Z^5 . It is regarded that the reduction in MAC values is slower at medium energies where the Compton scattering (CS) process (Z/E) is powerful. It is remarkable that after 1.022 MeV, where pair production (PP) occurs, the MAC values increased slowly with increasing energy. At high energy levels, most photons are annihilated, and MAC values vary depending on Z^2 . Therefore, the MAC values of glasses containing Bi and Pb elements with high Z at high energies increased. With the addition of Eu₂O₃ (0, 0.5, 1, 2 mol%), the MAC values are obtained at 0.015 MeV as 78.429 cm²/g, 78.586 cm²/g, 78.742 cm²/g, and 79.045 cm²/g and 89.281 cm²/g, 89.322 cm²/g, 89.362 cm²/g, and 89.442 cm²/g for LPb50B and LBi50B glass systems, respectively. From this, it can be deduced that the insertion of Eu₂O₃ increases MAC values in both glass systems, and the higher MAC values are obtained in glasses prepared with Bi₂O₃. The material thickness of LPb50BEu and LBi50BEu glasses for 0.015–15 MeV photon energies, which halves the incoming radiation intensity, is presented in Figure 3.

Table 2. Obtained mass attenuation coefficients from MCNPX code and Phy-X/PSD program.

Energy (MeV)	LPb50B		LPb50BEu0.5		LPb50BEu1		LPb50BEu2		LBi50B		LBi50BEu0.5		LBi50BEu1		LBi50BEu2	
	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP	Phy-X	MCNP
0.015	78.429	81.792	78.587	81.504	78.742	80.346	79.045	81.458	89.281	90.231	89.322	90.348	89.363	90.569	89.442	90.775
0.02	57.229	59.483	57.134	59.126	57.042	58.130	56.861	59.258	66.859	67.120	66.757	67.563	66.657	67.681	66.458	67.718
0.03	20.038	21.589	20.001	21.359	19.965	20.561	19.894	19.992	23.511	23.746	23.473	23.874	23.435	23.991	23.360	24.016
0.04	12.869	13.067	12.823	12.916	12.778	12.985	12.689	12.816	13.139	13.234	13.110	13.253	13.082	13.309	13.027	13.403
0.05	7.228	7.561	7.331	7.572	7.433	7.581	7.631	7.684	7.377	7.408	7.437	7.524	7.497	7.538	7.614	7.704
0.06	4.514	4.689	4.578	4.701	4.641	4.704	4.765	4.771	4.611	4.651	4.649	4.772	4.686	4.784	4.759	4.771
0.08	2.170	2.198	2.200	2.201	2.230	2.235	2.288	2.290	2.223	2.230	2.241	2.251	2.258	2.256	2.292	2.295
0.1	3.752	3.772	3.748	3.775	3.744	3.778	3.736	3.751	4.335	4.338	4.330	4.358	4.325	4.379	4.315	4.401
0.15	1.378	1.380	1.376	1.377	1.374	1.381	1.371	1.384	1.587	1.593	1.585	1.604	1.583	1.612	1.579	1.615
0.2	0.699	0.703	0.698	0.701	0.697	0.703	0.695	0.702	0.800	0.804	0.799	0.807	0.798	0.810	0.795	0.813
0.3	0.299	0.302	0.299	0.300	0.299	0.302	0.298	0.305	0.336	0.338	0.335	0.341	0.335	0.345	0.334	0.347
0.4	0.183	0.185	0.183	0.185	0.183	0.185	0.182	0.185	0.201	0.203	0.201	0.203	0.200	0.204	0.200	0.205
0.5	0.134	0.136	0.134	0.136	0.134	0.136	0.133	0.136	0.144	0.145	0.144	0.145	0.144	0.145	0.144	0.144
0.6	0.108	0.110	0.108	0.110	0.108	0.110	0.107	0.110	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114
0.8	0.081	0.095	0.081	0.095	0.081	0.095	0.081	0.095	0.084	0.084	0.084	0.084	0.084	0.084	0.084	0.084
1	0.067	0.071	0.067	0.071	0.067	0.071	0.067	0.071	0.069	0.070	0.069	0.070	0.069	0.070	0.069	0.069
1.5	0.051	0.053	0.051	0.053	0.051	0.053	0.051	0.053	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.053
2	0.045	0.048	0.045	0.048	0.045	0.048	0.045	0.048	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
3	0.040	0.041	0.040	0.041	0.040	0.041	0.040	0.041	0.041	0.042	0.041	0.042	0.041	0.042	0.041	0.042
4	0.038	0.040	0.038	0.040	0.038	0.040	0.038	0.040	0.040	0.040	0.040	0.040	0.041	0.042	0.040	0.040
5	0.038	0.040	0.038	0.040	0.038	0.040	0.038	0.040	0.039	0.040	0.039	0.040	0.039	0.040	0.039	0.040
6	0.038	0.042	0.038	0.042	0.038	0.042	0.038	0.042	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
8	0.040	0.042	0.040	0.042	0.040	0.042	0.040	0.042	0.042	0.043	0.042	0.043	0.042	0.043	0.042	0.043
10	0.041	0.044	0.041	0.044	0.041	0.044	0.042	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
15	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.049	0.050	0.049	0.050	0.049	0.050	0.049	0.051

Figure 2. Variation of linear attenuation coefficients (μ) against photon energy for all glasses.

Figure 3. Variation of mass attenuation coefficient (μ_m) against photon energy for (a) LPb50BEu and (b) LBi50BEu glasses.

Half-value layers ($T_{1/2}$) of the LPb50BEu and LBi50BEu glasses are almost zero in the 0.015–0.1 MeV range. After 0.1 MeV, secondary scattering enhances with the effect of CS, while the $T_{1/2}$ values increase quickly. Beyond 3 MeV, the $T_{1/2}$ values reduce with the annihilation of photons in the PP process. The densities of LPb50BEu and LBi50BEu glasses are reduced in the range of 5.39–5.04 g/cm³ and 6.81–5.94 g/cm³ with the addition of Eu₂O₃. Therefore, it is seen that the $T_{1/2}$ values increase with the insertion of Eu₂O₃. The maximum $T_{1/2}$ values for LPb50BEu and LBi50BEu glasses were obtained as 3.60 cm and 2.95 cm, respectively. These results are quite satisfactory for a good shield material for gamma rays. Moreover, the mean free path values (λ) of proposed glasses in comparison with some commercial SCHOTT [17] glasses, RS-253-G18, RS-360, RS-520, and concrete types, barite, ferrite, chromite [18], are given in Figure 4.

Figure 4. Variation of half-value layer ($T_{1/2}$) against photon energy for (a) LPb50BEu and (b) LBi50BEu glasses.

The λ values of LPb50BEu and LBi50BEu glasses are thinner than other shielding materials. The LBi50BEu2 glass had the smallest λ values, while the RS-213-G18 glass presented the largest MFP values, as seen in Figure 5. In order to express a composite material with a single atomic number, an effective atomic number (Z_{eff}) is needed, which shows the shielding capacity of the shielding material well [19]. Figure 6 presents the change of Z_{eff} values of L (Bi/Pb)50BEu2 glasses versus photon energy. For LPb50BEu and LBi50BEu glasses, the Z_{eff} takes values in the range of 76.72–23.15, 75.73–23.84, and 79.64–27.71, 79.38–28.18, respectively. The largest values of Z_{eff} are at low energies below 0.1 MeV. A few sudden peaks occur on the absorption edge of K and L shells of Pb (L:15.86 keV, K:88.00 keV) and Bi (L:16.38 keV, K: 90.52 keV), and K shell of La (38.92 keV) by the effect of PEA. Between 0.1–1 MeV, the Z_{eff} values rapidly decrease and, beyond 1 MeV, the Z_{eff} values increased due to the Z^2 -dependent change of the PP cross section. While the addition of Eu_2O_3 in the high energy region increased the Z_{eff} values of the glasses, the Z_{eff} values declined at medium and low energy levels. It is noted from Figure 6 that the Z_{eff} values of LBi50BEu glasses prepared with Bi_2O_3 are higher than LPb50BEu glasses. Perfect geometry is not possible in real radiation applications. For this reason, the correction factor B (build-up factor) is needed to account for scattering in the material and in the air in the Lambert–Beer law [20]. Energy absorption and exposure build-up factors (EABF and EBF) for L(Pb/Bi)50BEu glasses were generated using Phy-X/PSD software in photon energies of 0.015–15 MeV for several λ values.

Figures 7 and 8 visualise the trend of change of the EBF and EABF values of the glasses versus the photon energy and Tables 3–10 presented G–P fitting coefficients, respectively. In the low energy range (0.015–0.1 MeV), it is seen that there are very sharp peaks around 0.02 MeV, 0.04 MeV, and 0.1 MeV, which are the L and K absorption edges of the Pb and Bi elements and the K shell absorption edge of La. The high Z values of the relevant elements increase the possibility of PEA interaction and cause the photons to become built up. The EBF and EABF values of LBi50BEu glasses are considerably lower than those of LPb50BEu glasses at lower energies. Since the Z_{eff} values of the glasses are very large, the EBF and EABF values for all glasses possess the smallest values (nearly zero) in the CS process proportional to Z. In the range of 1–15 MeV, since the PP interaction cross-section is dependent on Z^2 , especially when the depth of penetration increases, photon build-up enhances with secondary scatterings. As a result, the EBF and EABF values for all glasses start to boost again at high energies. It is clear from Figures 7 and 8 that the EBFs of the glasses are higher than the EABFs.

Figure 5. Variation of mean free path (λ) against photon energy for LPb50BEu and LBi50BEu glasses, and some commercial shielding materials.

Figure 6. Variation of effective atomic number (Z_{eff}) against photon energy for (a) LPb50BEu and (b) LBi50BEu glasses.

When all gamma-shielding parameters are evaluated together, the LBi50BEu glasses show a superior performance compared to LPb50BEu glasses in reducing photons. Besides, the protection capability of L(Pb/Bi)50BEu glasses against uncharged (fast neutrons) and charged particles (alpha and protons) was also evaluated. For this purpose, the macroscopic removal cross-section (Σ_R) of glasses for fast neutrons was calculated firstly.

Figure 7. Variation of exposure build-up factor (EBF) against photon energy for (a) LPb50BEu and (b) LBi50BEu glasses.

Figure 8. Variation of energy absorption build-up factor (EABF) against photon energy for (a) LPb50BEu and (b) LBi50BEu glasses.

Table 3. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LPb50B glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	74.15	0.205	1.003	1.713	0.181	11.440	−0.210	1.003	1.716	0.186	11.783
0.020	76.73	0.278	2.024	1.365	−0.373	12.434	0.165	1.151	1.421	−0.181	16.239
0.030	76.09	0.138	2.850	0.870	−0.167	26.054	0.149	1.364	0.879	−0.137	22.948
0.040	69.07	0.089	3.918	0.379	−0.038	23.557	0.106	1.500	0.380	−0.044	22.592
0.050	67.75	−0.246	3.154	0.092	0.021	12.536	−0.102	1.413	0.104	0.079	9.298
0.060	66.10	0.917	2.496	0.042	−0.133	15.462	0.655	1.367	0.061	−0.151	15.939
0.080	62.03	0.777	1.695	0.029	−0.232	14.645	0.610	1.322	0.070	−0.228	14.087
0.100	71.70	0.052	1.669	0.463	−0.009	18.106	0.055	1.695	0.449	−0.013	17.643
0.150	63.95	0.415	1.225	0.147	−0.175	14.453	0.502	1.528	0.083	−0.170	18.968
0.200	55.65	0.294	1.157	0.312	−0.163	13.906	0.565	1.505	0.106	−0.286	13.864
0.300	42.79	0.159	1.194	0.509	−0.075	13.692	0.366	1.596	0.235	−0.203	13.337
0.400	35.31	0.115	1.263	0.624	−0.061	14.170	0.276	1.746	0.355	−0.175	13.734
0.500	31.03	0.091	1.324	0.694	−0.051	14.136	0.220	1.864	0.447	−0.145	13.774
0.600	28.46	0.074	1.368	0.745	−0.041	13.708	0.158	1.791	0.559	−0.103	13.603
0.800	25.68	0.052	1.430	0.817	−0.032	13.705	0.120	1.896	0.650	−0.083	13.585
1.000	24.29	0.037	1.460	0.873	−0.027	13.388	0.098	1.924	0.713	−0.074	13.525
1.500	23.15	0.010	1.445	0.992	−0.020	14.204	0.055	1.823	0.858	−0.055	13.794
2.000	23.49	0.004	1.465	1.028	−0.020	13.264	0.062	1.829	0.855	−0.069	13.402
3.000	25.18	0.018	1.491	1.014	−0.044	13.268	0.093	1.792	0.801	−0.111	13.528
4.000	27.12	0.035	1.494	0.979	−0.059	13.740	0.107	1.722	0.778	−0.125	13.860
5.000	29.00	0.068	1.594	0.894	−0.088	13.964	0.143	1.813	0.706	−0.157	14.119
6.000	30.73	0.076	1.646	0.886	−0.092	14.188	0.144	1.813	0.712	−0.157	14.272
8.000	33.72	0.073	1.801	0.927	−0.092	14.177	0.127	1.845	0.782	−0.143	14.289
10.000	36.15	0.038	1.816	1.081	−0.061	14.089	0.087	1.772	0.926	−0.109	14.116
15.000	40.46	0.014	1.972	1.277	−0.046	13.761	0.053	1.784	1.127	−0.086	13.883

Table 4. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LPb50Eu0.5 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	74.02	0.203	1.003	1.707	0.180	11.445	0.208	1.003	1.710	0.185	11.794
0.020	76.62	0.278	2.024	1.365	−0.373	12.433	0.165	1.151	1.420	−0.181	16.237
0.030	76.00	0.138	2.847	0.870	−0.167	26.036	0.149	1.363	0.879	−0.137	22.933
0.040	69.04	0.089	3.920	0.374	−0.037	23.539	0.106	1.499	0.374	−0.044	22.651
0.050	67.64	−0.227	3.166	0.106	0.012	12.690	−0.089	1.422	0.118	0.068	9.564
0.060	66.05	0.881	2.513	0.049	−0.130	15.065	0.627	1.374	0.069	−0.143	16.138
0.080	62.08	0.779	1.700	0.029	−0.229	14.677	0.615	1.325	0.069	−0.228	14.093
0.100	71.66	0.052	1.669	0.462	−0.009	18.112	0.055	1.695	0.448	−0.013	17.647
0.150	63.99	0.415	1.224	0.147	−0.176	14.450	0.503	1.528	0.083	−0.171	18.939
0.200	55.75	0.293	1.157	0.312	−0.163	13.908	0.565	1.505	0.106	−0.286	13.863
0.300	42.95	0.158	1.194	0.509	−0.075	13.693	0.365	1.597	0.235	−0.203	13.337
0.400	35.48	0.115	1.264	0.624	−0.061	14.171	0.276	1.747	0.355	−0.175	13.734
0.500	31.21	0.091	1.325	0.695	−0.051	14.136	0.220	1.865	0.447	−0.145	13.775
0.600	28.64	0.073	1.369	0.745	−0.041	13.708	0.157	1.792	0.560	−0.103	13.604
0.800	25.86	0.052	1.431	0.818	−0.032	13.704	0.120	1.897	0.650	−0.083	13.586
1.000	24.46	0.037	1.461	0.873	−0.027	13.388	0.098	1.925	0.714	−0.074	13.525
1.500	23.33	0.010	1.446	0.992	−0.020	14.203	0.055	1.824	0.858	−0.055	13.793
2.000	23.67	0.004	1.465	1.028	−0.020	13.263	0.062	1.830	0.855	−0.069	13.402
3.000	25.37	0.018	1.491	1.014	−0.044	13.267	0.093	1.792	0.801	−0.111	13.528
4.000	27.31	0.035	1.494	0.979	−0.059	13.740	0.107	1.721	0.778	−0.125	13.860
5.000	29.20	0.068	1.593	0.894	−0.088	13.965	0.143	1.811	0.706	−0.157	14.119
6.000	30.93	0.076	1.645	0.886	−0.092	14.188	0.144	1.811	0.712	−0.157	14.272
8.000	33.93	0.073	1.805	0.927	−0.092	14.177	0.127	1.850	0.781	−0.143	14.288
10.000	36.36	0.038	1.822	1.082	−0.061	14.088	0.087	1.779	0.926	−0.109	14.113
15.000	40.66	0.014	1.981	1.279	−0.045	13.758	0.053	1.793	1.128	−0.086	13.878

Table 5. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LPb50Eu1 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	73.90	0.201	1.003	1.701	0.178	11.450	0.206	1.003	1.704	0.183	11.806
0.020	76.52	0.278	2.023	1.364	−0.374	12.432	0.165	1.151	1.420	−0.181	16.235
0.030	75.91	0.138	2.845	0.869	−0.167	26.018	0.149	1.363	0.878	−0.137	22.919
0.040	69.02	0.088	3.922	0.368	−0.037	23.522	0.106	1.498	0.368	−0.044	22.710
0.050	67.55	−0.208	3.178	0.121	0.002	12.842	−0.075	1.430	0.132	0.056	9.827
0.060	66.00	0.847	2.530	0.056	−0.127	14.682	0.600	1.382	0.076	−0.136	16.329
0.080	62.13	0.780	1.704	0.028	−0.226	14.710	0.620	1.327	0.067	−0.228	14.099
0.100	71.61	0.052	1.669	0.461	−0.009	18.118	0.054	1.695	0.447	−0.013	17.650
0.150	64.03	0.416	1.224	0.147	−0.176	14.446	0.504	1.528	0.082	−0.172	18.911
0.200	55.85	0.293	1.157	0.313	−0.162	13.910	0.564	1.504	0.106	−0.286	13.863
0.300	43.11	0.158	1.194	0.509	−0.075	13.693	0.365	1.597	0.235	−0.203	13.337
0.400	35.66	0.115	1.264	0.624	−0.061	14.171	0.275	1.747	0.355	−0.175	13.734
0.500	31.39	0.091	1.325	0.695	−0.050	14.136	0.220	1.866	0.448	−0.144	13.775
0.600	28.81	0.073	1.369	0.745	−0.041	13.708	0.157	1.794	0.560	−0.103	13.604
0.800	26.03	0.052	1.431	0.818	−0.032	13.704	0.120	1.898	0.651	−0.082	13.586
1.000	24.63	0.037	1.461	0.874	−0.027	13.389	0.098	1.925	0.714	−0.074	13.525
1.500	23.50	0.010	1.446	0.993	−0.020	14.202	0.055	1.824	0.858	−0.055	13.792
2.000	23.84	0.004	1.465	1.028	−0.020	13.263	0.062	1.830	0.855	−0.069	13.402
3.000	25.55	0.018	1.491	1.014	−0.044	13.267	0.093	1.792	0.801	−0.111	13.528
4.000	27.50	0.035	1.493	0.979	−0.059	13.740	0.107	1.720	0.778	−0.125	13.860
5.000	29.39	0.068	1.592	0.895	−0.088	13.965	0.143	1.809	0.707	−0.157	14.120
6.000	31.13	0.075	1.643	0.886	−0.092	14.188	0.144	1.808	0.712	−0.157	14.272
8.000	34.13	0.073	1.809	0.927	−0.091	14.178	0.127	1.856	0.781	−0.143	14.287
10.000	36.56	0.038	1.828	1.083	−0.061	14.086	0.087	1.785	0.927	−0.109	14.110
15.000	40.86	0.014	1.990	1.281	−0.045	13.754	0.053	1.802	1.129	−0.086	13.873

Table 6. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LPb50Eu2 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	73.65	0.197	1.003	1.690	0.176	11.460	0.202	1.003	1.693	0.181	11.828
0.020	76.32	0.279	2.022	1.363	−0.374	12.431	0.166	1.151	1.419	−0.181	16.232
0.030	75.73	0.138	2.841	0.868	−0.167	25.984	0.149	1.362	0.877	−0.137	22.890
0.040	68.98	0.088	3.926	0.358	−0.036	23.488	0.106	1.496	0.358	−0.044	22.825
0.050	67.37	−0.173	3.200	0.147	−0.015	13.130	−0.049	1.445	0.158	0.035	10.325
0.060	65.90	0.781	2.561	0.070	−0.122	13.950	0.549	1.396	0.090	−0.121	16.695
0.080	62.22	0.783	1.713	0.027	−0.219	14.771	0.630	1.333	0.064	−0.228	14.111
0.100	71.52	0.051	1.668	0.459	−0.008	18.130	0.054	1.694	0.445	−0.012	17.657
0.150	64.09	0.416	1.224	0.147	−0.177	14.439	0.506	1.527	0.082	−0.174	18.855
0.200	56.05	0.292	1.157	0.314	−0.162	13.913	0.564	1.504	0.107	−0.285	13.862
0.300	43.44	0.158	1.195	0.509	−0.075	13.695	0.364	1.598	0.236	−0.203	13.338
0.400	36.01	0.115	1.265	0.625	−0.061	14.172	0.275	1.749	0.356	−0.175	13.735
0.500	31.75	0.091	1.326	0.696	−0.050	14.137	0.219	1.868	0.448	−0.144	13.776
0.600	29.17	0.073	1.370	0.746	−0.041	13.709	0.157	1.796	0.561	−0.102	13.605
0.800	26.38	0.051	1.432	0.819	−0.032	13.704	0.120	1.900	0.651	−0.082	13.586
1.000	24.98	0.037	1.462	0.874	−0.027	13.391	0.098	1.927	0.715	−0.074	13.524
1.500	23.84	0.010	1.447	0.993	−0.019	14.199	0.054	1.825	0.858	−0.055	13.791
2.000	24.19	0.004	1.466	1.029	−0.020	13.261	0.062	1.830	0.855	−0.069	13.401
3.000	25.92	0.018	1.491	1.014	−0.044	13.266	0.093	1.791	0.801	−0.111	13.528
4.000	27.88	0.035	1.493	0.979	−0.059	13.740	0.107	1.717	0.779	−0.125	13.861
5.000	29.79	0.068	1.590	0.895	−0.088	13.965	0.142	1.805	0.707	−0.157	14.121
6.000	31.53	0.075	1.641	0.887	−0.091	14.187	0.144	1.804	0.713	−0.157	14.273
8.000	34.54	0.073	1.818	0.928	−0.091	14.178	0.127	1.867	0.780	−0.143	14.285
10.000	36.96	0.037	1.839	1.085	−0.061	14.083	0.087	1.798	0.927	−0.109	14.104
15.000	41.24	0.013	2.008	1.284	−0.045	13.747	0.053	1.819	1.131	−0.086	13.864

Table 7. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LBi50B glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	77.82	0.109	1.004	1.411	0.116	11.705	0.118	1.004	1.416	0.125	12.362
0.020	79.65	0.112	2.370	1.795	−0.139	12.997	0.071	1.200	1.826	−0.069	17.474
0.030	79.20	0.119	3.365	1.015	−0.200	30.012	0.121	1.461	1.023	−0.125	26.240
0.040	74.03	0.089	3.880	0.472	−0.048	23.861	0.104	1.517	0.477	−0.042	21.572
0.050	72.84	−0.192	3.188	0.132	−0.005	12.970	−0.063	1.436	0.144	0.047	10.048
0.060	71.36	0.826	2.540	0.060	−0.125	14.454	0.584	1.386	0.080	−0.131	16.443
0.080	67.62	0.780	1.706	0.028	−0.224	14.721	0.622	1.328	0.067	−0.228	14.101
0.100	75.96	0.124	1.732	0.732	−0.094	16.627	0.130	1.758	0.706	−0.097	16.777
0.150	69.75	0.367	1.247	0.145	−0.104	14.974	0.354	1.580	0.102	−0.052	23.100
0.200	62.62	0.340	1.155	0.256	−0.192	13.709	0.623	1.519	0.078	−0.300	13.939
0.300	50.33	0.168	1.170	0.487	−0.081	13.619	0.396	1.559	0.203	−0.218	13.310
0.400	42.34	0.124	1.231	0.599	−0.065	14.143	0.297	1.673	0.322	−0.187	13.704
0.500	37.45	0.099	1.288	0.669	−0.053	14.136	0.238	1.783	0.412	−0.155	13.734
0.600	34.39	0.081	1.331	0.718	−0.044	13.699	0.168	1.698	0.533	−0.106	13.577
0.800	30.97	0.058	1.393	0.792	−0.033	13.707	0.131	1.815	0.620	−0.086	13.574
1.000	29.20	0.043	1.426	0.847	−0.028	13.385	0.108	1.854	0.684	−0.077	13.527
1.500	27.72	0.013	1.417	0.975	−0.021	14.325	0.060	1.779	0.837	−0.057	13.860
2.000	28.10	0.006	1.435	1.015	−0.020	13.373	0.064	1.777	0.844	−0.069	13.432
3.000	30.09	0.016	1.446	1.019	−0.041	13.341	0.090	1.721	0.807	−0.107	13.535
4.000	32.34	0.030	1.444	0.998	−0.054	13.736	0.103	1.627	0.791	−0.121	13.866
5.000	34.48	0.063	1.529	0.916	−0.083	13.979	0.135	1.663	0.728	−0.150	14.150
6.000	36.43	0.070	1.573	0.911	−0.088	14.164	0.136	1.654	0.736	−0.150	14.296
8.000	39.73	0.068	1.763	0.955	−0.087	14.145	0.122	1.727	0.803	−0.139	14.280
10.000	42.34	0.034	1.845	1.115	−0.058	14.001	0.081	1.710	0.957	−0.105	14.107
15.000	46.86	0.007	2.095	1.336	−0.038	13.694	0.030	2.079	1.229	−0.063	13.727

Table 8. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LBi50Eu0.5 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	77.72	0.108	1.004	1.408	0.115	11.707	0.117	1.004	1.414	0.125	12.366
0.020	79.58	0.113	2.368	1.793	−0.140	12.994	0.071	1.200	1.825	−0.069	17.468
0.030	79.14	0.119	3.362	1.014	−0.200	29.987	0.121	1.461	1.022	−0.125	26.220
0.040	74.00	0.089	3.881	0.468	−0.047	23.849	0.104	1.517	0.473	−0.042	21.611
0.050	72.71	−0.182	3.195	0.141	−0.011	13.058	−0.056	1.441	0.152	0.040	10.201
0.060	71.25	0.806	2.549	0.064	−0.124	14.230	0.569	1.390	0.084	−0.127	16.555
0.080	67.58	0.781	1.709	0.028	−0.222	14.740	0.625	1.330	0.066	−0.228	14.105
0.100	75.91	0.123	1.732	0.730	−0.093	16.636	0.130	1.758	0.705	−0.096	16.783
0.150	69.75	0.367	1.247	0.145	−0.105	14.970	0.355	1.579	0.102	−0.052	23.068
0.200	62.66	0.340	1.155	0.257	−0.192	13.710	0.622	1.519	0.078	−0.299	13.938
0.300	50.41	0.168	1.170	0.487	−0.081	13.620	0.396	1.559	0.203	−0.218	13.310
0.400	42.44	0.124	1.232	0.599	−0.065	14.142	0.297	1.674	0.323	−0.186	13.705
0.500	37.57	0.099	1.288	0.669	−0.053	14.136	0.238	1.783	0.413	−0.155	13.734
0.600	34.51	0.081	1.331	0.718	−0.044	13.699	0.167	1.699	0.533	−0.106	13.577
0.800	31.08	0.058	1.393	0.792	−0.033	13.708	0.131	1.816	0.620	−0.086	13.574
1.000	29.31	0.043	1.427	0.847	−0.028	13.384	0.108	1.855	0.684	−0.077	13.527
1.500	27.84	0.013	1.418	0.975	−0.021	14.323	0.060	1.780	0.837	−0.056	13.859
2.000	28.22	0.006	1.436	1.015	−0.020	13.372	0.064	1.777	0.845	−0.069	13.432
3.000	30.21	0.016	1.446	1.019	−0.041	13.341	0.090	1.721	0.807	−0.107	13.535
4.000	32.46	0.030	1.444	0.998	−0.054	13.736	0.103	1.626	0.791	−0.121	13.866
5.000	34.61	0.063	1.529	0.916	−0.083	13.979	0.135	1.663	0.728	−0.150	14.150
6.000	36.56	0.070	1.573	0.911	−0.088	14.163	0.136	1.653	0.737	−0.150	14.297
8.000	39.86	0.068	1.763	0.955	−0.087	14.145	0.122	1.726	0.803	−0.139	14.280
10.000	42.46	0.034	1.844	1.115	−0.058	14.001	0.081	1.709	0.957	−0.105	14.107
15.000	46.97	0.007	2.094	1.336	−0.038	13.694	0.030	2.080	1.230	−0.063	13.727

Table 9. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LBi50Eu1 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	77.63	0.107	1.004	1.406	0.115	11.709	0.116	1.004	1.412	0.125	12.370
0.020	79.52	0.114	2.367	1.791	−0.141	12.991	0.072	1.200	1.823	−0.070	17.463
0.030	79.08	0.119	3.359	1.013	−0.200	29.963	0.121	1.460	1.021	−0.125	26.199
0.040	73.97	0.089	3.883	0.465	−0.047	23.838	0.104	1.516	0.469	−0.042	21.650
0.050	72.57	−0.171	3.202	0.149	−0.016	13.144	−0.048	1.446	0.160	0.034	10.351
0.060	71.14	0.786	2.559	0.069	−0.122	14.007	0.553	1.395	0.089	−0.122	16.666
0.080	67.54	0.782	1.711	0.028	−0.221	14.759	0.628	1.332	0.065	−0.228	14.108
0.100	75.87	0.123	1.731	0.728	−0.093	16.645	0.129	1.757	0.703	−0.096	16.788
0.150	69.75	0.367	1.246	0.145	−0.105	14.966	0.357	1.579	0.101	−0.053	23.036
0.200	62.70	0.339	1.155	0.257	−0.192	13.712	0.622	1.519	0.078	−0.299	13.938
0.300	50.50	0.168	1.170	0.487	−0.081	13.621	0.396	1.559	0.203	−0.218	13.310
0.400	42.55	0.124	1.232	0.599	−0.065	14.142	0.296	1.674	0.323	−0.186	13.705
0.500	37.68	0.099	1.289	0.669	−0.053	14.135	0.238	1.784	0.413	−0.155	13.735
0.600	34.62	0.081	1.331	0.718	−0.044	13.699	0.167	1.700	0.533	−0.106	13.577
0.800	31.20	0.058	1.393	0.793	−0.033	13.708	0.130	1.816	0.620	−0.086	13.574
1.000	29.43	0.043	1.427	0.848	−0.028	13.382	0.107	1.855	0.685	−0.077	13.527
1.500	27.95	0.013	1.418	0.975	−0.021	14.321	0.060	1.780	0.838	−0.056	13.858
2.000	28.34	0.006	1.436	1.015	−0.020	13.371	0.064	1.778	0.845	−0.069	13.432
3.000	30.33	0.016	1.446	1.019	−0.041	13.341	0.090	1.721	0.807	−0.107	13.535
4.000	32.59	0.030	1.443	0.998	−0.054	13.736	0.103	1.626	0.791	−0.121	13.866
5.000	34.74	0.063	1.529	0.916	−0.083	13.979	0.135	1.663	0.728	−0.150	14.150
6.000	36.68	0.070	1.573	0.912	−0.088	14.163	0.136	1.653	0.737	−0.150	14.297
8.000	39.98	0.068	1.762	0.955	−0.087	14.145	0.122	1.725	0.803	−0.139	14.280
10.000	42.58	0.034	1.843	1.115	−0.058	14.000	0.081	1.707	0.958	−0.105	14.108
15.000	47.08	0.007	2.093	1.336	−0.038	13.695	0.030	2.081	1.231	−0.063	13.726

Table 10. (EBF and EABF) G–P fitting coefficients (b, c, a, X_k and d) of LBi50Eu2 glass sample.

Energy (MeV)	Z _{eq}	G-P Fitting Parameters for EBF					G-P Fitting Parameters for EABF				
		a	b	c	d	X _k	a	b	c	d	X _k
0.015	77.45	0.106	1.004	1.402	0.114	11.712	0.115	1.004	1.408	0.124	12.378
0.020	79.39	0.115	2.364	1.788	−0.143	12.987	0.072	1.200	1.819	−0.071	17.452
0.030	78.96	0.120	3.352	1.011	−0.199	29.915	0.122	1.459	1.019	−0.126	26.159
0.040	73.91	0.089	3.886	0.457	−0.046	23.815	0.104	1.515	0.462	−0.042	21.728
0.050	72.32	−0.150	3.215	0.165	−0.026	13.313	−0.033	1.455	0.175	0.021	10.643
0.060	70.94	0.746	2.577	0.077	−0.119	13.573	0.523	1.403	0.097	−0.114	16.884
0.080	67.46	0.784	1.716	0.027	−0.217	14.795	0.633	1.335	0.063	−0.228	14.115
0.100	75.79	0.122	1.731	0.725	−0.092	16.663	0.128	1.757	0.700	−0.095	16.799
0.150	69.75	0.368	1.246	0.146	−0.107	14.958	0.359	1.578	0.101	−0.055	22.973
0.200	62.78	0.339	1.155	0.258	−0.191	13.715	0.621	1.518	0.079	−0.299	13.937
0.300	50.67	0.168	1.171	0.488	−0.081	13.622	0.395	1.560	0.204	−0.218	13.311
0.400	42.76	0.123	1.232	0.600	−0.065	14.142	0.296	1.675	0.324	−0.186	13.706
0.500	37.90	0.099	1.289	0.670	−0.053	14.134	0.238	1.785	0.414	−0.154	13.736
0.600	34.85	0.081	1.332	0.719	−0.044	13.698	0.167	1.702	0.534	−0.106	13.577
0.800	31.43	0.058	1.394	0.793	−0.033	13.708	0.130	1.818	0.621	−0.086	13.575
1.000	29.66	0.043	1.428	0.848	−0.028	13.378	0.107	1.857	0.685	−0.077	13.528
1.500	28.19	0.013	1.418	0.975	−0.021	14.317	0.060	1.781	0.838	−0.056	13.857
2.000	28.58	0.006	1.436	1.016	−0.020	13.370	0.064	1.778	0.845	−0.069	13.432
3.000	30.58	0.016	1.447	1.019	−0.041	13.341	0.090	1.721	0.807	−0.107	13.535
4.000	32.83	0.030	1.443	0.998	−0.054	13.736	0.103	1.626	0.791	−0.121	13.866
5.000	34.99	0.063	1.528	0.917	−0.083	13.979	0.135	1.662	0.728	−0.150	14.150
6.000	36.94	0.070	1.572	0.912	−0.088	14.163	0.136	1.651	0.737	−0.150	14.297
8.000	40.22	0.068	1.761	0.955	−0.087	14.144	0.122	1.723	0.803	−0.139	14.280
10.000	42.82	0.034	1.842	1.115	−0.059	13.999	0.081	1.704	0.958	−0.105	14.109
15.000	47.29	0.007	2.091	1.337	−0.038	13.695	0.029	2.083	1.233	−0.062	13.725

In Figure 9, Σ_R values of both groups of glasses are established. In both glass systems, the Σ_R values decreased as the density decreased with the addition of Eu_2O_3 . The Σ_R values of LPb50BEu glasses were 0.10106 cm^{-1} , 0.09999 cm^{-1} , 0.09478 cm^{-1} , and 0.09286 cm^{-1} , respectively, while, for LBi50BEu glasses, they were found to be 0.11484 cm^{-1} , 0.11428 cm^{-1} , 0.09745 cm^{-1} , and 0.09921 cm^{-1} . It appears that the LBi50BEu glass system is more effective at capturing neutrons than others. It is clear that selected glass systems are also successful at reducing neutrons when compared to water and paraffin ($\Sigma_R = 0.101 \text{ cm}^{-1}$), which are traditional neutron moderators. As the charged particle moves through the material, it interacts with the atomic electrons in the material and its energy decreases. However, during this time, the stopping power increases because the kinetic energy of the particle is inversely proportional to the stopping power. The change of the mass stopping power (AMSP and PMSP) of L(Pb/Bi)50BEu glasses versus the photon energy for alpha and proton particles is given in Figure 10. While the charged particles move in the glass in the form of a Bragg curve, and the curve increases proportionally with $1/E$, there is a sharp decrease in the curve at the end of the path where the particle travels through the matter. Since alpha particles are heavier than protons, they have reached the maximum MSP at higher energies. Since the stopping power of the material is proportional to the square of the atomic number, LBi50BEu glasses with larger Z_{eff} values have higher MSP values. The furthest distance that the charged particles can travel through the material is expressed as the projected range (PR). Figure 11 presents the change of APR and PPR values of L(Pb/Bi)50BEu glasses in response to kinetic energy. Since the addition of Eu_2O_3 reduces the Z_{eff} values, PR is larger in glasses with 2 mol% Eu_2O_3 added. Since protons are smaller in mass, they move faster and have a longer range inside the glass (PPR > APR). The PRs of alpha and proton particles are shorter in LBi50BEu glasses.

Figure 9. Effective removal cross-sections for fast neutrons (Σ_R) for (a) LPb50BEu and (b) LBi50BEu glasses.

Figure 10. Proton (PMSP) and alpha (AMSP) mass stopping as a function of kinetic energy for (a) LPb50BEu and (b) LBi50BEu glasses.

Finally, it is worth noting that the linear attenuation coefficients determined using Phy-X/PSD and MCNPX (2.7.0) were very consistent. Figure 12 depicts a comparison of obtained linear attenuation coefficients from MCNPX Monte Carlo code and Phy-X/PSD for the LBi50B sample. A relative difference of 2% was reported at 0.02 MeV photon energy. Overall, our findings showed that relative differences were varied from 1.15% to 2.6% at all photon energies. Both outcomes were reported in comparable linear attenuation coefficient values, based on our results. However, minor variations in certain energy areas were discovered. This is closely linked to the tools employed, since MCNPX is a Monte-Carlo-based technique for radiation transport that needs user specification at different stages of the process described before. By contrast, Phy-X/PSD is a web-based tool that requires just the material composition, density, and energy quantities. As a result, some differences are almost certainly due to a variety of variables, including the number of dispersed gamma rays entering the detecting field, the narrow beam shape, the cross-section libraries and physics lists, the hardware performance, and the CPU characteristics of the computers used.

Figure 11. Proton (PPR) and alpha (APR) projected range as a function of kinetic energy for (a) LPb50BEu and (b) LBi50BEu glasses.

Figure 12. Comparison of obtained linear attenuation coefficients from MCNPX Monte Carlo code and Phy-X/PSD.

4. Conclusions

In this study, the nuclear radiation shielding capabilities were thoroughly examined for eight borate glasses of Eu_2O_3 containing high ratios of $\text{PbO}/\text{Bi}_2\text{O}_3$. For this aim, MAC values of the glasses, encoded LPb50BEu and LBi50BEu, in the 0.015–15 MeV photon energy range were acquired by MCNPX simulation codes and Phy-X/PSD online software. While the MAC values for LPb50BEu2 and LBi50Eu2 glasses produced values of between $79.045 \text{ cm}^2/\text{g}$ – $0.045 \text{ cm}^2/\text{g}$ and $89.442 \text{ cm}^2/\text{g}$ – $0.048 \text{ cm}^2/\text{g}$, the MAC values of LPb50B and LBi50B glasses change between $78.429 \text{ cm}^2/\text{g}$ – $0.045 \text{ cm}^2/\text{g}$ and $89.281 \text{ cm}^2/\text{g}$ – $0.048 \text{ cm}^2/\text{g}$. Based on the MAC values, other vital photon-shielding parameters, $T_{1/2}$, λ , Z_{eff} , EABF, and EBF, were also found for LPb50BEu and LBi50BEu glasses. When all parameters were evaluated, it was revealed that the LBi50BEu glass system was more effective than LPb50BEu in shielding gamma radiation. It was seen that the Σ_R values of both glass systems were greater than conventional neutron moderators. LBi50BEu2 glass was also found to be superior to LPb50BEu2 glass in stopping charged particle radiation, as in gamma radiation.

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