Research Article

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A detailed investigation on highly dense CuZr bulk metallic glasses for shielding purposes

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Abstract: Gamma-ray shielding properties of eight different metallic glasses based on $\text{Cu}_x\text{Zr}_{100-x}$: $x = 35$ ($\text{Cu}_{35}\text{Zr}_{65}$) – 70 ($\text{Cu}_{70}\text{Zr}_{30}$) were determined using Monte Carlo simulations and Phy-X/PSD software. A typical gamma-ray transmission setup has been modeled in MCNPX Monte Carlo code. The general trend of the linear attenuation coefficients (μ) was reported as $(\mu)_{\text{Cu}_{35}\text{Zr}_{65}} < (\mu)_{\text{Cu}_{40}\text{Zr}_{60}} < (\mu)_{\text{Cu}_{45}\text{Zr}_{55}} < (\mu)_{\text{Cu}_{50}\text{Zr}_{50}} < (\mu)_{\text{Cu}_{55}\text{Zr}_{45}} < (\mu)_{\text{Cu}_{60}\text{Zr}_{40}} < (\mu)_{\text{Cu}_{65}\text{Zr}_{35}} < (\mu)_{\text{Cu}_{70}\text{Zr}_{30}}$. In terms of half value layer (HVL) values, the $\text{Cu}_{35}\text{Zr}_{65}$ sample has the highest value (2.984 cm) and the $\text{Cu}_{70}\text{Zr}_{30}$ sample has the lowest value (2.769 cm) at 8 MeV photon

energy. The mean free path (MFP) values were 4.305 and 3.995 cm for $\text{Cu}_{35}\text{Zr}_{65}$ and $\text{Cu}_{70}\text{Zr}_{30}$ samples, respectively. Generally, MFP and HVL values of the studied glasses were reported as $(\text{MFP}, \text{HVL})_{\text{Cu}_{35}\text{Zr}_{65}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{40}\text{Zr}_{60}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{45}\text{Zr}_{55}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{50}\text{Zr}_{50}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{55}\text{Zr}_{45}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{60}\text{Zr}_{40}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{65}\text{Zr}_{35}} > (\text{MFP}, \text{HVL})_{\text{Cu}_{70}\text{Zr}_{30}}$ for all photon energy range. The $\text{Cu}_{70}\text{Zr}_{30}$ sample showed maximum values of both the effective conductivity (C_{eff}) and effective electron density (N_{eff}). In addition, the $\text{Cu}_{70}\text{Zr}_{30}$ sample has minimum exposure and energy absorption buildup factor (EBF and EABF) values at all studied gamma-ray energies. The results revealed that the $\text{Cu}_{70}\text{Zr}_{30}$ sample has superior attenuation properties among all studied samples.

Keywords: metallic glasses, radiation shielding, Phy-X PSD, buildup factors

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1 Introduction

Bulk metallic glasses (BMGs), also known as amorphous metals, have been studied since they were first produced in the 1960s. Since then, different types of research on their physical and structural characteristics, as well as production changes, have been conducted. In comparison to traditional metals, where atoms are arranged in a repeated pattern of crystals or grains of various sizes and shapes, BMGs have a random and disordered atomic structure. BMG's competitive physical characteristics such as strength, durability, hardness, elasticity, corrosion and wear resistance are enhanced by this amorphous structure, which is free of grain defects [1]. After a breakthrough at the end of the 1980s and the beginning of the 1990s, BMGs drew the attention of the materials science community. Using various casting and water-cooling processes, the high glass-forming ability (GFA) of some alloys permitted the creation of BMGs up to about 80 mm in size. New BMG forming alloys based on Zr, La, Ti, Ni, Pd, Mg, Al, Fe, and Cu have been developed during the

past 15 years. Due to their low critical cooling rates of 102–100 K/s, these multicomponent alloys may be cast in a glassy state (in mm or cm) using a copper mold. BMGs enable researchers to study the peculiar features of metallic glasses. GFA is associated with a highly reduced glass transition temperature T_{rg} (the ratio of the glass transition temperature T_g to the liquid temperature T_l), a favorable negative enthalpy of mixing of the constituents, and small enthalpy variations between the undercooled liquid and competing crystalline phases. On the other hand, BMGs have sparked interest due to the lack of a crystalline lattice and defects such as dislocations. These materials show a peculiar deformation mechanism, resulting in high strength, extreme stiffness, robust wear resistance, and large elastic deformation [2–5]. Structural applications of BMGs are severely constrained by their poor ductility and macroscopic strain-softening properties at ambient temperature, particularly under tensile loads. To address this brittleness, BMG composites with a crystalline phase spread across a range of length scales inside the glassy matrix have been created using a variety of glass-forming techniques. With properly adjusted formulations and microstructures, the durability and ductility of some BMG composites can be greatly enhanced even under strain [6,7]. BMGs could recently be made for some specific compositions in the binary Cu–Zr system. CuZr-based BMGs have been extensively studied in recent years due to their improved tensile properties and work-hardening performance. Moreover, for binary and ternary Cu-based BMGs, exceptional plasticity was observed. These discoveries rekindled interest in structural and shielding studies of the Cu–Zr system. Cu–Zr glass can be made in a wide variety of compositions, as previous research has shown. In addition to these studies, the radiation shielding properties of BMGs can be investigated by taking into account their broad range of uses and potential applications [5–7]. The efficacy of atomic shielding systems for gamma rays and high-energy X-rays is well understood to be dependent on the atomic number and density of the shielding material. For high-energy X-rays and gamma-rays, a denser shielding substance with a higher atomic number is preferable. The major drawback of lead-based radiation shielding structures is their toxicity and lack of structural integrity. Other typical shielding materials, such as concrete, have drawbacks, such as cracking over time, and the presence of water in concrete reduces the material's density and structural strength. Additionally, concrete is naturally opaque, making visibility difficult in radiation facilities, where the observation of the patient or source is critical. As a consequence, new radiation shielding systems developed must be corrosion-resistant, biocompatible, and capable of being shaped into

slim, compact designs with excellent structural integrity and endurance. Due to their unique features, BMGs have been suggested for use as radiation shields. BMGs have extremely high densities and high atomic numbers that make them effective in blocking high-energy radiation like gamma and X-rays [7,8]. The radiation attenuation parameters of heavy metallic glasses researched in the literature encouraged us to conduct a study on the subject and to perform a detailed examination of several glass types. The primary objective of this investigation was to observe changes in gamma-ray shielding properties as a function of the amount of heavy metal oxide added to the glass samples and to determine at what additive ratios these changes reached their greatest correspondingly. Accordingly, gamma-ray shielding properties of very high-density $\text{Cu}_x\text{Zr}_{100-x}$ metallic glasses ($x = 35\text{--}70$) were determined using Phy-X/PSD software [9] and MCNPX [10] (version 2.7.0) in a wide range of energies between 0.015 and 15 MeV.

2 Materials and methods

Eight distinct $\text{Cu}_x\text{Zr}_{100-x}$ metallic glass systems [2] were comprehensively investigated in this work in terms of their gamma-ray shielding capabilities, effective conductivity, and buildup factors (BUFs). In the reference study, material densities of glass samples were reported as 7.01, 7.17, 7.26, 7.33, 7.47, 7.53, 7.75, and 7.86 g/cm³ for sample codes Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr35, respectively (see Table 1). The calculated nuclear radiation shielding parameters will be discussed in this section, along with technical information.

2.1 Nuclear radiation shielding properties

To simplify the mass attenuation coefficient, it is essential to understand the Lambert–Beer law [11,12], which is shown in equation (1):

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

where I_0 is the original energy of the beam, μ is the linear attenuation coefficient, t is the absorber thickness, and I is the gamma-ray intensity after transit through the absorber.

The mass attenuation coefficient (μ_m) is the ratio of the linear attenuation coefficient to the density. It is generally represented in cm²/g [13–18] and is computed using the following equation:

$$\mu_m = \frac{\mu}{\rho}, \quad (2)$$

Table 1: Sample codes, composition, elemental weight fractions, and density

Code	Composition wt%		Density (g/cm ³)
	Cu	Zr	
Cu35Zr65	34.77	65.23	7.01
Cu40Zr60	39.88	60.12	7.17
Cu45Zr55	44.94	55.06	7.26
Cu50Zr50	49.86	50.14	7.33
Cu55Zr45	55.14	44.86	7.47
Cu60Zr40	59.92	40.08	7.53
Cu65Zr35	64.92	35.08	7.75
Cu70Zr30	69.93	30.07	7.86

where μ is the linear attenuation coefficient and ρ is the density of the sample.

Equation (3) was used to calculate the values of μ_m using the Py-MLBUF platform:

$$\mu_m = \sum_i w_i \left(\frac{\mu}{\rho} \right)_i, \quad (3)$$

where w_i is the weight fraction of the i th constituent of the element and ρ is the density of the sample.

The mean free path (MFP) is defined as the average distance a photon can travel between two successive interactions within a material [19], and can be calculated using equation (4):

$$\text{MFP} = \frac{1}{\mu}. \quad (4)$$

After traveling 1 MFP through a shielding material in perfect narrow-beam geometry, the power of monoenergetic gamma rays is reduced by about 37%. The optical thickness (OT), a dimensionless quantity, is calculated by multiplying the linear attenuation coefficient by the distance in cm between the point source and the detector. The OT depicts the number of MFP lengths covered by gamma photons as they travel through the shield. The half value layer (HVL) is the thickness of material with a transmitted radiation intensity equal to half that of the incoming radiation, while the tenth value layer (TVL) is the thickness of material with a beam intensity equal to one-tenth of its original value [20]. HVL and TVL may be determined using equations (5) and (6):

$$\text{HVL} = \frac{\ln(2)}{\mu}, \quad (5)$$

$$\text{TVL} = \frac{\ln(10)}{\mu}. \quad (6)$$

Equation (7) relates the effective conductivity C_{eff} (s/m) of a shielding material for attenuation at room temperature (300 K) to the effective number of electrons N_{eff} :

$$C_{\text{eff}} = \left(\frac{N_{\text{eff}} \rho \tau e^2}{m_e} \right) \times 10^3, \quad (7)$$

where ρ , e , and m_e are the density of shielding materials (g/cm³), the charge on an electron (C), and the electron's rest mass (kg), respectively. τ depicts the electron's relaxation time and is calculated using equation (8):

$$\tau = \frac{h}{600\pi k}, \quad (8)$$

where h is the Planck constant and k is the Boltzmann constant.

The effective atomic number (Z_{eff}) is a critical parameter in radiation sciences. It can be utilized to describe how complex shielding materials strengthen their shielding capabilities. The direct method was used in this study to calculate the effective atomic number by comparing the atomic and electronic cross sections:

$$Z_{\text{eff}} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho} \right)_i}{\sum_j f_j \left(\frac{A_j}{Z_j} \right) \left(\frac{\mu}{\rho} \right)_j}, \quad (9)$$

where f_i , A_i , and Z_i are the fractions by mole, atomic weight, and the atomic number of the i th constituent element, respectively.

Incoherent scattering is the only way to determine the equivalent atomic number (Z_{eq}) of the shielding material. Z_{eq} values are used to calculate BUFs.

The Z_{eq} values in this work were obtained using the interpolation method, as displayed in equation (10):

$$Z_{\text{eq}} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1}, \quad (10)$$

where the ratio R is the determining factor for the equivalent atomic number, for particular photon energy,

$$R = \frac{\mu_{\text{m, compton}}}{\mu_{\text{m, total}}}. \quad (11)$$

The atomic numbers Z_1 and Z_2 of the elements correspond to their respective R_1 and R_2 ratios.

The BUF is a multiplier that takes into account the contributions of scattered photons to the corrected response to uncollided photons. In other words, it is the number of incoming photons divided by the total number of photons. The ANS standard was developed for the purpose of calculating gamma-ray BUFs for a point isotropic source

operating at energies ranging from 0.015 to 15 MeV. In the energy absorption buildup factor (EABF), the quantity of interest is the amount of energy absorbed or contained in the interacting substance. Geometric progression (G–P) fitting is often used to record EABFs. After determining the Z_{eq} values, the five G–P fitting parameters for the elements (b , a , c , and d Xk) are retrieved from the ANS-standard database, which contains a variety of elements with energies ranging from 0.015 to 15 MeV and OT of 40 MFP. The G–P fitting parameters for the glass materials were calculated using the interpolation approach. The exposure accumulation factor refers to the amount of radiation in the air after it passes through the shielding material (EBF). EABF and EBF are calculated using equations (12–14) for single-layered gamma-ray shielding enclosures (GSEs) with OT up to 100 MFP and energy between 0.015 and 15 MeV.

$$B(E, X) = 1 + \frac{b-1}{K-1} (K^x - 1) \text{ for } K \neq 1, \quad (12)$$

$$B(E, X) = 1 + (b-1)x \text{ for } K = 1, \quad (13)$$

$$K(E, x) = cx^a + \frac{d \tanh \frac{x}{x_k-2} - \tanh(-2)1 - \tanh(-2)}{1 - \tanh(-2)} \quad (14)$$

for $x \leq 40$ MFP,

where E , x , and B denote incoming photon energy, penetration depth in MFP, and accumulation factor at 1 MFP, respectively, and K denotes the photon-dose multiplication factor.

2.2 Monte Carlo simulations using MCNPX (version 2.7.0)

According to the literature review, the relevance of mathematical tools and simulation techniques in radiation sciences is steadily expanding [21–26]. This is due to various physical constraints and the possibility of adverse consequences in experimental radiation investigations. On the other hand, authorized institutions should accredit radiation facilities in order to comply with safety regulations. As a result, enhanced simulation methods may be a viable option for increasing the consistency of the experimental phase and lowering the total cost of research. As such, many well-known Monte Carlo simulation-based radiation transportation codes, such as MCNP, Geant4, EGSnrc, and FLUKA, provide well-structured platforms for developing various sorts of solutions for radiation transportation-related investigations. Among the above-mentioned codes, MCNPX [12] is well-known for its user-

friendliness and reliability, as well as its promising technological aspects. The mass attenuation coefficients of the BMGs under discussion were determined in this inquiry using version 2.7.0 of the MCNPX general-purpose Monte Carlo method. The first step included the development of a generic gamma-ray transmission system based on experimental research. The two- and three-dimensional representations of the MCNPX code's intended gamma-ray transmission arrangement are shown in Figure 1. In a lead (Pb) block, a point isotropic gamma-ray source has been established. Following that, an attenuator between the point isotropic source and detection field has been established. It is worth noting that the attenuator material was chosen based on the elemental characteristics of the investigated glasses (see Table 1). The BMGs' elemental characteristics have been precisely described in the material (Mn) card of the MCNPX INPUT file. Finally, simulation was initiated for a total of 10^8 particle histories. It should be mentioned that each glass sample was examined for gamma-ray energies ranging from 0.015 to 15 MeV. The simulation results indicated that the relative inaccuracy for each track was less than 1%.

3 Results and discussions

In this study, eight different BMGs were characterized in terms of their gamma-ray attenuation competencies. The densities of Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples are shown in Figure 2. As seen in the figure, the glass density is increased from 7.01 to 7.86 g/cm³. The Cu70Zr30 sample with the greatest content of Cu had the highest glass density. Given that the linear attenuation coefficient is a density-dependent characteristic, it is assumed that a direct relationship exists between the density and the linear attenuation coefficient values, and hence, the amount of Cu contribution. The variation of linear attenuation coefficients (/cm) as a function of incoming photon energy (MeV) is shown in Figure 3. As can be seen, as the photon energy increased, linear attenuation coefficients decreased. The largest linear attenuation coefficients were observed in the low-energy region, where the photoelectric effect dominates the majority of photon–matter interactions [27–32]. However, when the glass densities are changed gradually, no significant variations in the linear attenuation coefficients are seen. We noticed an interesting impact of Cu on the photon resistance of glass samples at varying energies. Our results reveal that the Cu70Zr30 sample, which has the greatest concentration of Cu, has the maximum linear

Figure 1: 3-D model of the modeled MCNPX simulation setup (obtained from VISED_X_22S).

Figure 2: Variation of glass densities (g/cm^3).

Figure 3: Variation of linear attenuation coefficients ($1/\text{cm}$) of investigated glasses as a function of incident photon energy (MeV).

attenuation coefficients for all photon energies entering. This is explained by the Cu70Zr30 sample's glass density, which included the largest quantity of studied glasses. For example, linear attenuation coefficients were reported as 0.409, 0.419, 0.425, 0.429, 0.438, 0.442, 0.455, and 0.462/cm for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 1 MeV photon energy, respectively.

In Figure 3, a closer look on the variation trend of linear attenuation coefficients has also been provided as

0.232, 0.236, 0.238, 0.239, 0.242, 0.243, 0.248, and 0.250/cm for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 8 MeV photon energy, respectively. Meanwhile, another critical statistic for gamma-ray shielding, namely mass attenuation coefficients (μ_m), was calculated. Figure 4 depicts the shifting trend in mass attenuation coefficients as a function of incoming photon energy. In general, it was discovered that mass attenuation coefficients behave differently

Figure 4: Variation of mass attenuation coefficients (cm^2/g) of investigated glasses as a function of incident photon energy (MeV).

from linear attenuation coefficients. This is due to the density-independent character of the mass attenuation coefficient parameter. While increasing the Cu contribution improved the density of BMGs, it also lowered the contribution of Zr with a higher atomic number from Cu35Zr65 to Cu70Zr30. Considering the concept of mass attenuation coefficient, which is density-independent, it can be said that there is an inverse correlation between the linear attenuation coefficients and mass attenuation coefficients of the BMGs at the same energy values. The linear attenuation coefficients of the BMGs at 8 MeV photon energy have been listed above. Our results showed that the mass

attenuation coefficients of the studied BMGs have an inverse trend at the same energy level. For example, the mass attenuation coefficients of the BMGs were reported as 0.0331, 0.0329, 0.0328, 0.0326, 0.0324, 0.0322, 0.0320, and 0.0318 cm^2/g for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 8 MeV photon energy, respectively. The term HVL (also known as $T_{1/2}$) is significant in radiation shielding research since it allows for the quantification of the material thickness required to halve the initial gamma-ray intensity [33–36]. This is because radiation studies necessitate that

Figure 5: Variation of HVL (cm) values of investigated glasses as a function of incident photon energy (MeV).

Figure 6: Variation of TVL (cm) values of investigated glasses as a function of incident photon energy (MeV).

Figure 7: Variation of MFP (cm) values of investigated glasses as a function of incident photon energy (MeV).

shielding needs be determined in advance depending on the kind and energy of the radiation used. As a consequence, the quantity of the HVL required for each kind of prospective shielding material should be determined in terms of a more complete understanding of the gamma-ray attenuation capabilities during the incoming gamma ray's contact with the attenuator specimen. Variation of HVL (cm) values of investigated glasses as a function of incident photon energy (MeV) is shown in Figure 5. As indicated in the Materials and Methods section, the linear attenuation coefficients and HVL quantities have an inverse relationship. As a result, it is reasonable to anticipate that the minimum HVL values would be found in the sample

Figure 8: Variation of effective atomic number (Z_{eff}) values of investigated glasses as a function of incident photon energy (MeV).

Figure 9: Variation of effective electron number (N_{eff}) values of investigated glasses as a function of incident photon energy (MeV).

with the maximum linear attenuation coefficient values. Fortunately, our results indicated that the Cu70Zr30 sample with the highest glass density and linear attenuation coefficients has the minimum HVL values. For example, HVLs were reported to be 2.984, 2.934, 2.914, 2.902, 2.865, 2858, 2.792, and 2.769 cm for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 8 MeV photon energy, respectively. The variations in the TVL (cm) values of the examined glasses as a function of incoming photon energy are shown in Figure 6. Similar to the behavior of the HVLs in BMGs, a direct relationship between the glass density and TVL values has also been reported. In other words, increasing glass density has influenced not only the material thickness needed to halve the incoming radiation intensity but also the material thickness necessary to reduce the incident radiation intensity by

Figure 10: Variation of effective conductivity (C_{eff}) values of investigated glasses as a function of incident photon energy (MeV).

Figure 11: Variation of exposure buildup factor (EBF) values of glasses at different MFP values (from 0.5 to 40 MFP) as a function of incident photon energy (MeV).

Figure 12: Variation of EABF values of glasses at different MFP values (from 0.5 to 40 MFP) as a function of incident photon energy (MeV).

one-tenth. The MFP is the route taken by a photon through a substance without colliding [33,37,38]. Therefore, it can be said that a lower distance in MFP values is a clear indicator for superior attenuation properties. Figure 7 depicts the variation of MFP (cm) values of investigated glasses as a function of incident photon energy (MeV). As mentioned above for previous attenuation properties, the Cu70Zr30 sample with the highest glass density was also reported with its minimum MFP values. For instance, MFP values (cm) were reported as 4.305, 4.233, 4.204, 4.187, 4.133, 4.123, 4.029, and 3.995 for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 8 MeV photon energy, respectively. Figure 8 illustrates the variation of the effective atomic number (Z_{eff}) values of investigated metallic glasses as a function of incident photon energy (MeV). From Figure 8, one can observe that the sample Cu35Zr65 has the maximum values of Z_{eff} , while Cu70Zr30 sample has the minimum values of Z_{eff} . This is due to the fact that with the increasing amount of copper ions ($Z = 29$) and decreasing amount of zirconium ions ($Z = 40$), Z_{eff} will be decreased. Figure 9 shows the variation of the effective electron density (N_{eff}) values of the investigated metallic glasses as a function of incident photon energy (MeV). It is clear that the trend of N_{eff} is inverse for the Z_{eff} , where the Cu35Zr65 sample has the minimum values of N_{eff} , while the Cu70Zr30 sample has the maximum values of N_{eff} . This trend of N_{eff} can be attributed to the PE process. In the photon energy zone from 0.1 to 1 MeV, a quick decrease in the N_{eff} values was observed in all investigated samples, and this trend was related to the CS process, which was dominant in this region. In the energy zone greater than 2 MeV, an increase in the N_{eff} values was observed and attributed to the PP process, which was dominant in this region. Figure 10 depicts the variation of effective conductivity (C_{eff}) values of the investigated glasses as a function of incident photon energy (MeV). As seen in Figure 10, the trend of C_{eff} of all investigated samples is similar to that of N_{eff} , where the C_{eff} is directly proportional to N_{eff} as in equation (7). The BUF is required for an accurate evaluation of gamma attenuation, although it has the potential to degrade the measurement quality. Gamma-ray measurement is required in nuclear technology since it is used in a variety of applications including industry, medicine, agriculture, education, research, and defense applications. It is also required for the building of radiation protective structures to protect human health from radiation exposure. When gamma radiation travels through the shielding material, it generates two forms of radiation that may be found either within or outside the shield: uncollided photons and colliding photons. Uncollided photons are the most common type of radiation

found inside the shield. Consequently, the accumulation factor is an extremely important parameter for gamma-ray measurements. A particle count is defined as the ratio of the total number of particles at a point to the total number of particles that have not collided at that site at a certain time. Figures 11 and 12 show the wide range of EBF and EABF values observed across all glass samples. Gamma rays absorb most of their energy in the low and high energy levels, where the majority of absorption occurs [39–43]. Consequently, the EBF values in the Compton area are among the highest in the low-energy zone. Our results showed that the Cu70Zr30 sample has the minimum EBF and EABF values at all gamma-ray energies studied.

4 Conclusion

In the present research, the nuclear shielding properties including the effective conductivity and BUFs of eight different $\text{Cu}_x\text{Zr}_{100-x}$: $x = 35$ (Cu35Zr65) – 70 (Cu70Zr30) in steps of 5 wt% metallic glass systems have been studied. The density of samples was varied from 7.01 g/cm³ for the Cu35Zr65 sample and 7.86 g/cm³ for the Cu70Zr30 sample. The studied nuclear radiation shielding parameters were calculated via MCNPX simulation code and the Phy-x PSD software. The results reveal that the Cu70Zr30 sample with the greatest Cu concentration and lowest Zr content has the maximum linear attenuation coefficient (μ) for all photon energies entering, while the Cu35Zr65 (low Cu and high Zr) sample has the minimum value. The general trend of the μ value was $(\mu)_{\text{Cu35Zr65}} < (\mu)_{\text{Cu40Zr60}} < (\mu)_{\text{Cu45Zr55}} < (\mu)_{\text{Cu50Zr50}} < (\mu)_{\text{Cu55Zr45}} < (\mu)_{\text{Cu60Zr40}} < (\mu)_{\text{Cu65Zr35}} < (\mu)_{\text{Cu70Zr30}}$. As the mass attenuation coefficient (μ_m) is density-independent, it has the trend $(\mu_m)_{\text{Cu35Zr65}} > (\mu_m)_{\text{Cu40Zr60}} > (\mu_m)_{\text{Cu45Zr55}} > (\mu_m)_{\text{Cu50Zr50}} > (\mu_m)_{\text{Cu55Zr45}} > (\mu_m)_{\text{Cu60Zr40}} > (\mu_m)_{\text{Cu65Zr35}} > (\mu_m)_{\text{Cu70Zr30}}$ for the studied metallic glasses. Our results indicated that the glasses studied reported HVL (in cm) values of 2.984, 2.934, 2.914, 2.902, 2.865, 2.858, 2.792, and 2.769 cm for Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 samples at 8 MeV photon energy, respectively. The MFP (in cm) has the same trend of HVL values of 4.305, 4.233, 4.204, 4.187, 4.133, 4.123, 4.029, and 3.995 cm for all studied samples Cu35Zr65, Cu40Zr60, Cu45Zr55, Cu50Zr50, Cu55Zr45, Cu60Zr40, Cu65Zr35, and Cu70Zr30 at 8 MeV photon energy, respectively. The Cu70Zr30 sample possessed the maximum values of both the effective conductivity (C_{eff}) and effective electron density (N_{eff}). The results showed that the Cu70Zr30 sample has the minimum EBF and EABF values at all gamma-ray energies studied.

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