International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)
Vol. 11-No.1 (2025) pp. 1-9
http://www.ijcesen.com
ISSN: 2149-9144

Research Article

High-Density Lead Germanate Glasses with Enhanced Gamma and Neutron Shielding Performance: Impact of PbO Concentration on Attenuation Properties

Hessa ALKARRANI[1,2], Duygu SEN BAYKAL[3,*], Ghada ALMISNED[4], H.O. TEKIN[5,6]

[1] Research Institute for Medical and Health Sciences, University of Sharjah, Sharjah, 27272, Sharjah, United Arab Emirates
[2] Department of Medical Diagnostic Imaging, College of Health Sciences, University of Sharjah, 27272, Sharjah, United Arab Emirates
Email: halkarrani@sharjah.ac.ae - **ORCID**: 0009-0001-7823-5892

[3] Istanbul Nisantasi University, Faculty of Engineering and Architecture, Mechatronics Engineering, 34398, Istanbul, Türkiye
[*]**Corresponding Author Email**: duygu.senbaykal@nisantasi.edu.tr - **ORCID**: 0000-0001-9833-9392

[4] Department of Physics, College of Science, Princess Nourah Bint Abdulrahman University, P.O. Box 84428, Riyadh, 11671, Saudi Arabia
Email: gaalmisned@pnu.edu.sa - **ORCID**: 0000-0001-9072-4480

[5] Department of Medical Diagnostic Imaging, College of Health Sciences, University of Sharjah, 27272, Sharjah, United Arab Emirates
[6] Istinye University, Faculty of Engineering and Natural Sciences, Computer Engineering Department, Istanbul 34396, Türkiye
Email: htekin@sharjah.ac.ae - **ORCID:** 0000-0002-0997-3488

Article Info:

DOI: 10.22399/ijcesen.635
Received : 15 November 2024
Accepted : 30 December 2024

Keywords :

Lead germanate glass,
Radiation shielding,
Gamma-ray attenuation,
Neutron attenuation,
Lead oxide (PbO) concentration.

Abstract:

Lead germanate glasses, improved with lead oxide (PbO), have emerged as effective materials for radiation shielding due to their increased density and structural robustness. The goal of this study is to find out how well lead germanate glasses with PbO concentrations between 20 and 55 mol% can block gamma rays and neutrons. The Phy-X/PSD software was used to obtain important numbers like the mass attenuation coefficient (MAC), the linear attenuation coefficient (LAC), the half-value layer (HVL), the mean free path (MFP), and the fast neutron removal cross section (FNRCS). The results show that the 55PbGe sample, which has the most PbO, has better gamma-ray attenuation and a low energy absorption buildup factor (EABF). This makes it a good choice option for locations requiring compact but efficient radiation shielding. The 50PbGe sample, on the other hand, demonstrates effective neutron shielding capabilities, suggesting it may be suitable for applications requiring protection against both gamma and neutron exposure. Higher PbO content is linked to better radiation blocking, which supports the idea that lead germanate glasses could be used instead of traditional lead-based shielding materials.

1. Introduction

Lead germanate glasses have garnered significant attention in material science due to their remarkable combination of properties, such as high density, optical clarity, and thermal stability. These characteristics make them highly suitable for applications in radiation shielding, photonics, and optoelectronics [1-2]. The addition of lead oxide (PbO) notably enhances the overall density and refractive index of these glasses, while also improving their thermal stability [3]. Sharma et al. (2024) conducted a comprehensive study on the structural, physical, and thermal properties of lead germanate glasses [4]. Their work explored the influence of Ge-O and Pb-O bond lengths and coordination environments within the glass matrix, revealing a direct correlation between an increase in PbO concentration and improvements in both density and thermal stability. These findings underscore the critical role of PbO not only in enhancing the mechanical and thermal properties of these glasses but also in providing deeper insights into their fundamental structural behavior. Lead's exceptional radiation shielding properties have long been recognized in glass products, primarily due to its high atomic number (Z), which makes lead-containing glasses particularly effective at attenuating gamma and X-rays [5-8]. Traditional lead-based materials, such as leaded glass and lead aprons, have been widely used in radiation protection. However, growing concerns over lead toxicity have spurred research into alternative materials that offer similar protective properties without the associated health risks [9]. Lead germanate glasses, with their high density and PbO content, present a promising alternative due to their structural characteristics and radiation-absorbing capabilities [10-14]. Building on the work of Sharma et al. (2024), the present study seeks to evaluate the radiation shielding effectiveness of the same lead germanate glass samples against neutrons and gamma rays. While previous research examined the glasses' thermal and structural properties, our focus is on assessing their potential use as radiation shielding materials—particularly in environments where traditional lead-based materials may pose health hazards. By investigating how gamma rays and neutrons interact with these glasses, we aim to explore their suitability as alternatives to conventional lead shielding materials [15-21]. Our hypothesis is that the high PbO content, combined with the structural stability observed in earlier studies, will contribute to superior radiation shielding properties. This study has the potential to expand our understanding of germanate glasses in radiation protection and could provide valuable insights for developing safer, more efficient shielding materials.

2. Material and Methods

Sharma et al. (2024) described the synthesis of the lead germanate glass samples used in this investigation. The composition and mass density of these samples are presented in Table 1. To assess their radiation shielding capabilities, we utilized the Phy-X/PSD program, which facilitates the calculation of several radiation-related parameters. This software was employed to determine critical parameters, including the mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), half-value layer (HVL), mean free path (MFP), effective atomic number (Z_{eff}), effective neutron density (N_{eff}), fast neutron removal cross section, and energy absorption buildup factor (EABF) [22-29]. Collectively, these factors are essential for evaluating the potential effectiveness of lead germanate glasses as radiation shielding materials. Our study aims to provide comprehensive insights into the shielding effectiveness of these glasses against gamma rays and neutrons.

Table 1. *Composition and mass density of lead germanate glasses.*

Sample ID	Composition	Density
20PbGe	20PbO-80GeO2	5.043
30PbGe	30PbO-70GeO2	5.651
40PbGe	40PbO-60GeO2	6.277
50PbGe	50PbO-50GeO2	6.791
55PbGe	55PbO-45GeO2	6.981

3. Results and Discussions

According to Table 1, the lead germanate glass samples—identified as 20PbGe, 30PbGe, 40PbGe, 50PbGe, and 55PbGe—exhibit varying PbO and GeO_2 concentrations, with Figure 1 illustrating the resulting density trend. Selecting certain PbO concentrations is a methodical approach to investigating the correlation between lead content and density, two critical elements influencing the material's efficacy in radiation shielding.

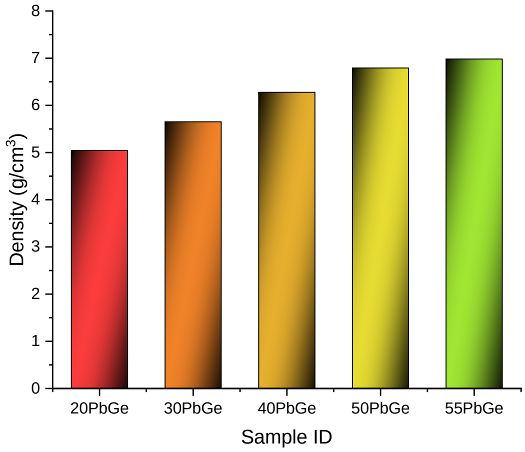


Figure 1. *Density variations of lead germanate glasses (g/cm^3).*

The highest density, found in the 55PbGe sample (6.981 g/cm^3), is linked to its highest PbO concentration (55 mol%). This rise in density can be attributed to lead's (Pb) high atomic mass and number, which directly increase the bulk density of the glass. A high atomic number increases the likelihood of radiation interactions, particularly for photoelectric absorption, hence benefiting denser materials such as 55PbGe for shielding purposes. As Pb concentration increases, so does the effectiveness of radiation shielding. Notably, higher density enhances gamma-ray absorption efficiency, positively influencing key parameters like the linear attenuation coefficient (LAC) and mass attenuation coefficient (MAC). This connection demonstrates that denser materials with higher Pb concentrations may efficiently obstruct damaging gamma radiation, safeguarding sensitive settings and equipment from exposure. Consequently, the shielding performance of lead germanate glasses improves with increasing PbO concentration, demonstrating the direct impact of compositional adjustments on physical properties.

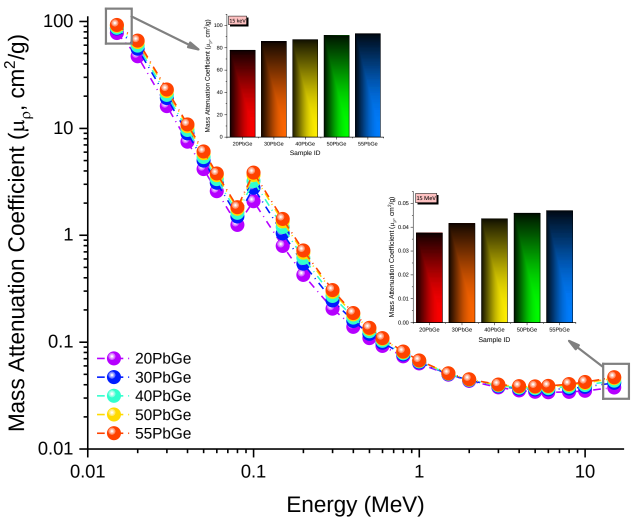


Figure 2. *Mass Attenuation Coefficient variations of lead germanate glasses (cm^2/g).*

Figure 2 illustrates the variation of the mass attenuation coefficient (MAC) for the samples across the energy range of 0.015 MeV to 15 MeV. MAC is an essential, density-dependent parameter that shows how effectively a material attenuates gamma rays. Each sample's density and molar content affect its result. The MAC is higher at lower energies because photoelectric absorption predominates. This is very important in places where low-energy radiation is common, like medical imaging or some industrial settings, where photoelectric interactions are preferred because they are better at stopping low-energy photons. For example, at 0.015 MeV, the 55PbGe sample, with the highest density, exhibits a MAC of approximately 90 cm²/g, compared to 79 cm²/g for the 20PbGe sample, which has the lowest density. The notable disparity between these samples underscores the significance of density and composition in attaining acceptable attenuation levels, with the 55PbGe sample exhibiting a distinct advantage in low-energy settings. MAC values drop as energy increases because photoelectric absorption diminishes, and Compton scattering becomes more pronounced. In contrast to 20PbGe, which has a MAC of 0.037 cm²/g at 15 MeV, 55PbGe maintains a higher MAC of about 0.045 cm²/g. The consistent performance of 55PbGe across various energy levels renders it especially appropriate for situations subjected to both low and high-energy gamma rays, necessitating extensive shielding. Because of its increased density and lead concentration, 55PbGe continuously exhibits superior gamma ray attenuation efficiency, maintaining this density-dependent trend over the energy range. This characteristic positions 55PbGe as a versatile material for a wide spectrum of radiation shielding applications, from healthcare to nuclear industries. This trend continues with the linear attenuation coefficient (LAC), shown in Figure 3, which further confirms the superior shielding efficiency of the 55PbGe sample. LAC, another density-dependent parameter, reflects how well a material absorbs gamma rays per unit length. In addition to having the greatest MAC and density, the 55PbGe glass also had the highest LAC values, which further supports its superior gamma-ray attenuation and general efficacy as a radiation shielding material. The LAC findings indicate that 55PbGe may allow for smaller shielding barriers without compromising their efficacy. This is crucial in scenarios when space is constrained, such as when shielding equipment or medical tools need portability. According to the results, density and PbO concentration are important factors in maximizing radiation shielding effectiveness. The 55PbGe sample, which has the highest linear attenuation coefficient (LAC) and mass attenuation coefficient (MAC), also has the lowest half-value layer (HVL) findings across all energy ranges, as shown in Figure 4. This suggests that the thinnest layer of material may successfully minimize the gamma-ray intensity in half using 55PbGe.

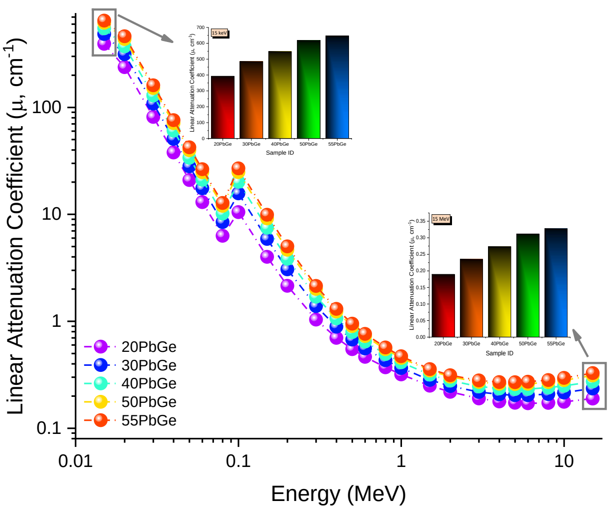


Figure 3. *Linear Attenuation Coefficient variations of lead germanate glasses (cm^{-1}).*

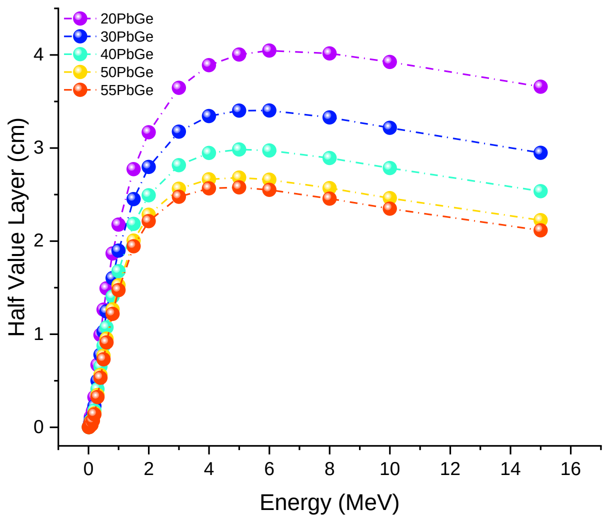


Figure 4. *Half Value Layer variations of lead germanate glasses (cm).*

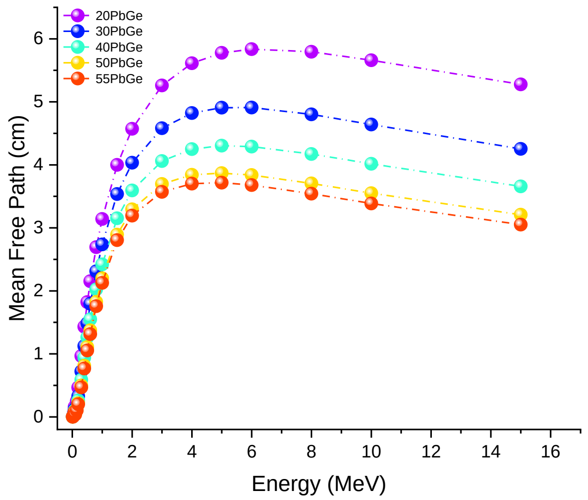


Figure 5. *Mean Free Path variations of lead germanate glasses (cm).*

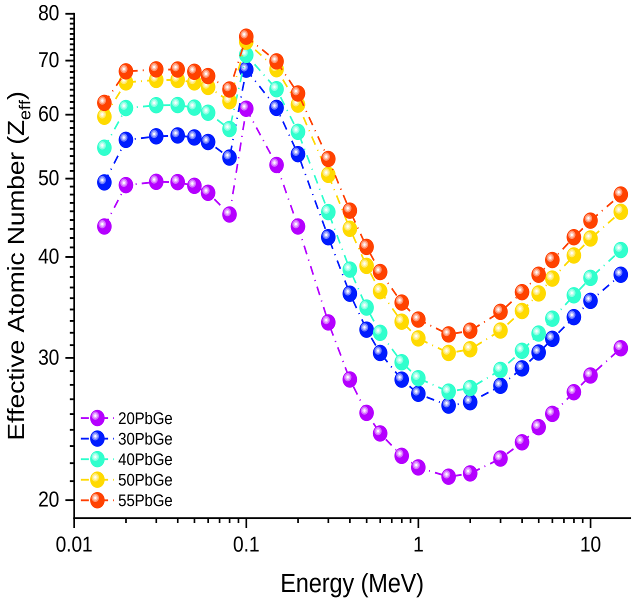


Figure 6. *Effective Atomic Number variations of lead germanate glasses (Z_{eff}).*

A diminished HVL immediately corresponds with efficient space-saving designs, allowing high-performance shielding with minimized material consumption, hence enhancing cost-effectiveness in production. The similar attenuation effect is achieved by the 20PbGe glass, but its larger HVL values indicate that a thicker layer is needed. This comparison illustrates that elevated PbO concentrations provide optimal outcomes since reduced HVL values are often desired for effective tiny shielding solutions.Similarly, Figure 5 depicts the mean free path (mfp) data for the lead germanate samples, showing the typical distance gamma rays travel before interacting with the glass. This trend aligns with the MAC and LAC results, reinforcing that higher density and PbO content improve gamma-ray attenuation efficiency, enhancing the material's effectiveness for radiation shielding. The reduced mean free path in samples with increased Pb indicates a diminished interaction zone. This renders 55PbGe an optimal selection as a high-performance shielding material in gamma-dense situations. Figures 6 and 7 show that the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) generally decrease with increasing photon energy, indicating a reduced likelihood of interactions at higher energies. These characteristics support the higher gamma-ray attenuation efficiency seen in 55PbGe, despite minor variances, and are consistent with the study's overall conclusions. The fact that Z_{eff} and N_{eff} decrease as energy increases supports the idea that the main type of interaction changes, from photoelectric absorption to Compton scattering in high-energy settings. On the other hand, Figure 8 shows the fast neutron removal cross-section (FNRCS) parameter assesses a material's effectiveness in attenuating fast neutrons, which is crucial for radiation shielding evaluation.

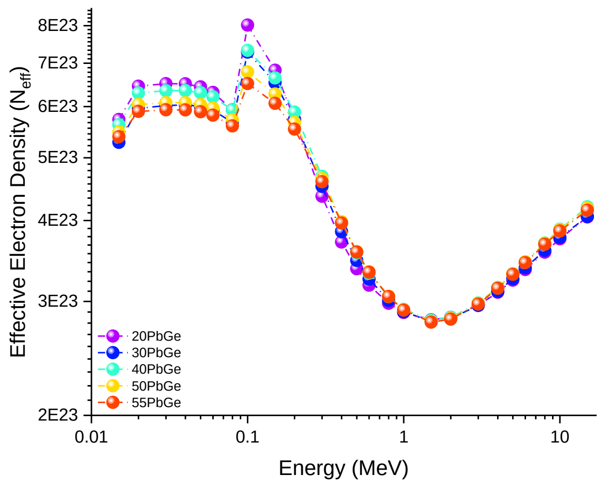


Figure 7. *Effective Electron Density variations of lead germanate glasses (N_{eff}).*

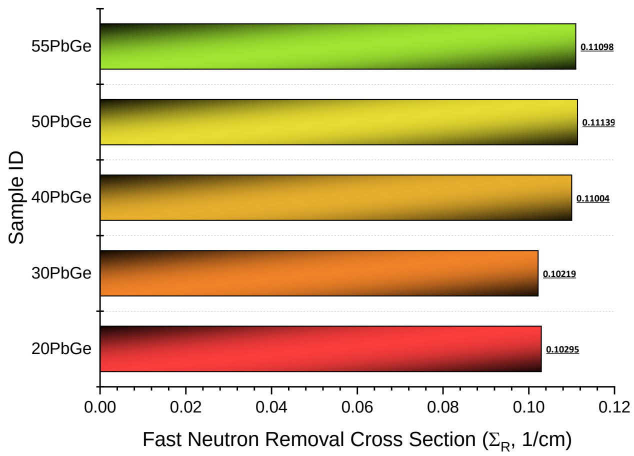
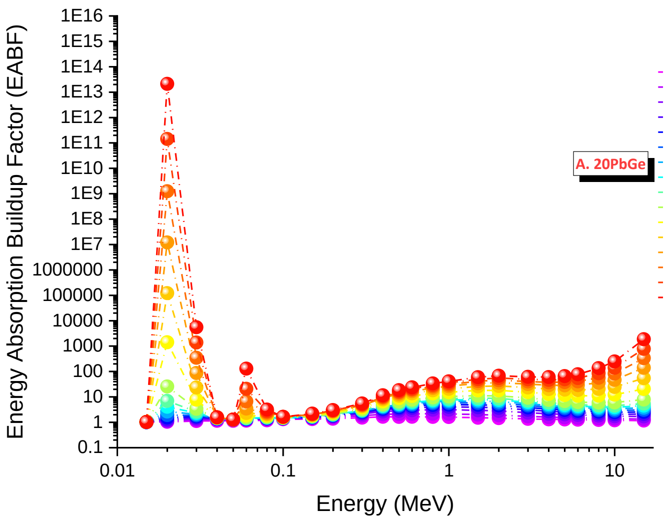


Figure 8. *Fast Neutron Removal Cross Section variations of lead germanate glasses (Σ_R, 1/cm).*

This metric is important because it shows how efficiently a substance can lower neutron flux. Remarkably, the FNRCS of the 50PbGe sample was the highest at 0.11139, although the 55PbGe sample, in spite of its higher gamma-ray shielding, had a near result of 0.11098. This little difference indicates that while 55PbGe has superior overall shielding capabilities, the balanced formulation of 50PbGe makes it a viable option for settings where neutron shielding is paramount. These findings suggest that while 55PbGe's high lead concentration still offers significant shielding against fast neutrons, 50PbGe's balanced composition (50 percent PbO and 50 percent GeO_2) improves its neutron attenuation. Future studies may customize such compositional modifications to enhance glass compositions for settings subjected to gamma and neutron radiation. The last parameter assessed is the energy absorption buildup factor (EABF), illustrated in Figure 9. The results for all investigated samples are relatively close; therefore, a further analysis of EABF was conducted at 5 mean free paths, represented in Figure 10.



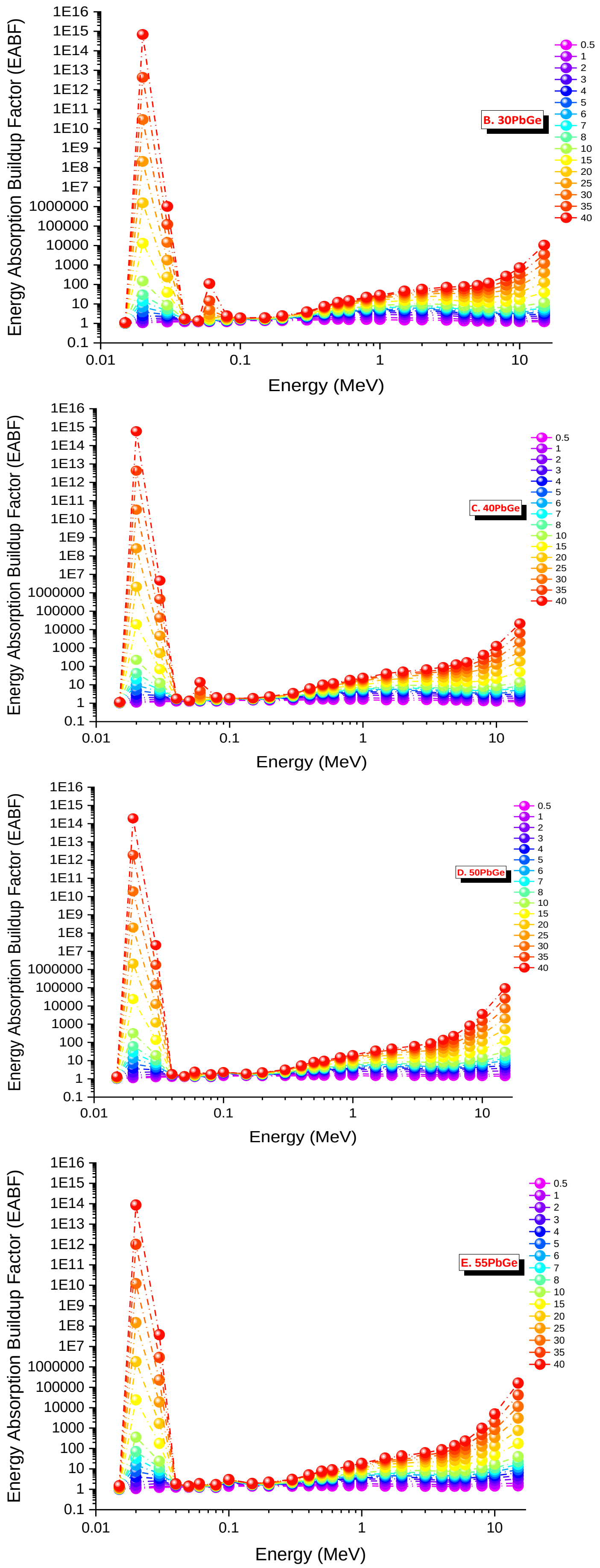


Figure 9. *Energy Absorption Buildup Factor variations of lead germanate glasses.*

Variations in the results across different energies are evident, reflecting changes in interaction mechanisms. The energy dependency of EABF underscores the need for meticulous material selection according to specified energy ranges, since buildup parameters directly affect the deposition of radiation energy inside the shielding material. Notably, 55PbGe demonstrates its superiority with the lowest EABF as energy increases, underscoring its significance in evaluating the practical effectiveness of shielding materials. This highlights 55PbGe's potential for enhanced performance in real-world applications where energy absorption is a critical factor.

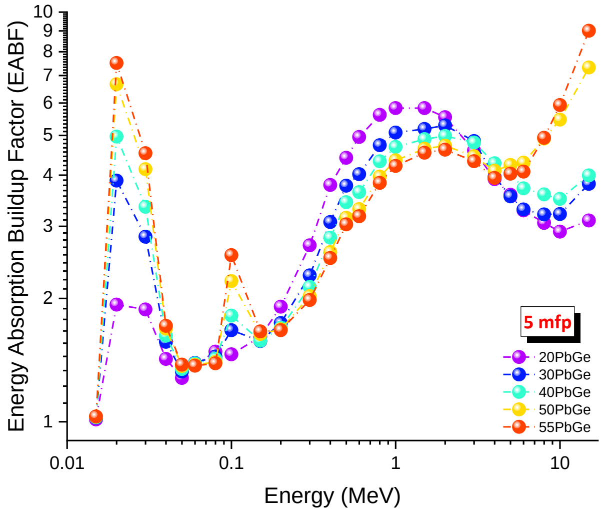


Figure 10. *Benchmarking of Energy Absorption Buildup Factor for lead germanate glasses at 5 mfp.*

In environments where little energy accumulation is essential, such as healthcare facilities requiring management of dispersed radiation, 55PbGe's low EABF makes it an ideal material. The full testing of EABF, MAC, and LAC confirms that the 55PbGe sample is the best choice for complex radiation shielding tasks, especially in dangerous places that need high shielding effectiveness with low thickness.

4. Conclusions

In conclusion, composition and density are important factors in the efficiency of the lead germanate glass samples under investigation, which show great promise as radiation shielding materials. For situations involving gamma rays and fast neutrons, these glasses are very flexible and adaptable. They show that they can be customized by changing the amounts of PbO and GeO_2 present. This flexibility enables the precise adjustment of density, which is closely correlated with shielding qualities. In line with previous research on structural and physical characteristics (Sharma et al., 2024), our results show that density increases with PbO content, which in turn has a favourable effect on important gamma-ray and neutron shielding parameters. Remarkably, because of its maximum density and PbO concentration, the 55PbGe sample continuously exhibits better gamma-ray attenuation, highlighting its effectiveness in radiation shielding devices. The enhanced attenuation performance of the 55PbGe sample makes it an optimal selection for sophisticated radiation shielding applications, particularly in scenarios requiring both high density and minimal material thickness. The 55PbGe sample, due to its high density, may attenuate gamma radiation more efficiently with thinner layers compared to samples of lesser density. This makes it advantageous in scenarios when space is constrained. This mixture had strong neutron attenuation properties and competitive FNRCS values, which shows that it effectively shields against both gamma rays and neutrons. Overall, these insights affirm the suitability of lead germanate glasses, especially high-density compositions, as practical materials for radiation protection. The findings indicate possible benefits compared to conventional materials like lead and borosilicate glass in some environments, especially when neutron radiation is a consideration. Future research could expand on optimizing PbO concentrations to balance structural integrity and enhance gamma-ray and neutron shielding capabilities. Assessing long-term durability, thermal stability, and resistance to radiation-induced deterioration in these materials will be crucial for their extensive use. Experiments with different GeO_2 compositions may also help find the best configurations for different radiation conditions, which would increase the number of uses. These investigations may also examine the lifespan and environmental stability of lead germanate glasses in various radiation conditions, ensuring their practical adaptability and endurance in real-world applications. It can be seen from literatüre that there are many different works done on this inetesting subject [30-45].

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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