Nuclear Materials and Energy 44 (2025) 101971

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

# Neutron shielding and activation estimation of Bismuth doped glasses (60-x) $B_2O_3$–$20SiO_2$–x $Bi_2O_3$–12ZnO–8BaO

Sachin Shet [a], Ashwitha Nancy Dsouza [b], M.I. Sayyed [c,d,h], Aljawhara H. Almuqrin [e], Nagaraj Kamath [f], Srinivas Shenoy Heckadka [g], Sudha Kamath [a,*]

[a] Department of Physics, Manipal Institute of Technology, MAHE, Manipal 576104 Karnataka, India
[b] Department of Physics, Acharya Institute of Graduate Studies, Bangalore, Karnataka, India
[c] Department of Physics, Faculty of Science, Isra University, Amman, Jordan
[d] Renewable Energy and Environmental Technology Center, University of Tabuk, Tabuk, 47913, Saudi Arabia
[e] Department of Physics, College of Science, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia
[f] Department of Humanities and Management, Manipal Institute of Technology, MAHE, Manipal 576104 Karnataka, India
[g] Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, MAHE, Manipal 576104 Karnataka, India
[h] Department of Physics and Technical Sciences, Western Caspian University, Baku, Azerbaijan

ARTICLE INFO

*Keywords:*
Irradiation
Shielding
HVL
TVL
Metal oxides
Rare earth elements

ABSTRACT

Neutron shielding materials play a critical role in nuclear reactors, radiation therapy, and other environments where neutron radiation is present. This study uses theoretical analysis and the Monte Carlo N-Particle (MCNP) simulation tool to investigate the neutron shielding properties of various doped glass materials. In this study, we investigated the neutron shielding properties and activation characteristics of heavy metal oxide glass with the composition (60-x) $B_2O_3$–$20SiO_2$–$xBi_2O_3$–12ZnO–8BaO, where x represents the concentration of $Bi_2O_3$ varied at 0 and 12 mol%. The primary focus was evaluating the neutron shielding performance with the Monte Carlo MCNP tool. MCNP was employed to perform neutron transport simulations to determine shielding properties.

Additionally, we explored neutron activation within the glass matrix to assess its feasibility for neutron shielding applications. The results showed that increasing the $Bi_2O_3$ content reduced the neutron shielding efficiency as it was replaced with a high neutron scattering Boron element. The activation produced in the glass was assessed for thermal neutrons, and the results indicated the glass composite produced a minimal amount of activation. This makes it suitable for the neutron field, considering sufficient cooling time and adequate chemical process needed to eliminate the toxic species produced during irradiation.

## 1. Introduction

Neutron radiation is a significant concern in various fields, such as nuclear reactors, radiation shielding in medical therapy, and space applications [1,2]. The lack of electric charge in neutrons makes them highly penetrating and capable of interacting with atomic nuclei, leading to material damage or radioactive byproducts. Hence, effective neutron shielding is essential to ensure the safety of personnel and equipment. Neutron shielding is necessary in various other research domains, and it has been studied on different kinds of materials, even carbohydrates [3]. Recent studies have explored glass materials doped with elements possessing high neutron and gamma attenuation cross-sections for radiation shielding applications [2,4]. These glasses demonstrate promising capabilities in attenuating pure gamma rays, fast neutrons, slow neutrons, and combined gamma radiation. The attenuation efficiency strongly depends on composition and dopant type [5]. Traditional shielding materials include heavy concretes, borated polymers, and lead. Recently, attention has shifted to doped glass materials, which offer the advantage of being transparent, versatile, and customizable based on the composition. The systematic substitution of $Bi_2O_3$ by $Li_2O$ or other dopants can significantly impact the shielding properties of the glass material [6,7]. This study focuses on the theoretical evaluation of neutron-shielding glasses doped with Bismuth, as this has shown promise in enhancing neutron attenuation. Monte Carlo N-Particle (MCNP) simulation [8,9], a renowned tool for radiation transport analysis, was used to model the interaction between neutrons and

* Corresponding author.
*E-mail address:* sudha.kamath@manipal.edu (S. Kamath).

https://doi.org/10.1016/j.nme.2025.101971
Received 3 April 2025; Received in revised form 13 June 2025; Accepted 17 July 2025
Available online 17 July 2025

various doped glass compositions, analyzing neutron absorption and scattering properties. Several studies utilized the capabilities of the code MCNP for the neutron shielding of glass materials [10]. The increasing demand for effective neutron shielding materials has led to exploring new materials with superior shielding properties. Neutron radiation, being neutral and highly penetrating, poses significant challenges in nuclear reactors, medical facilities, and space applications. Unlike charged particle radiation, neutrons do not ionize directly but can cause substantial damage through secondary reactions such as neutron capture, scattering, and activation [11]. Therefore, materials with high neutron absorption and scattering capabilities are crucial for developing efficient shielding solutions. A preliminary view of the cross-section [12] database also supports the idea that Bismuth-doped glasses can be a good choice for neutron shielding. Heavy metal oxide (HMO) glasses, particularly those containing elements like Bismuth (Bi), Boron (B), and silicon (Si), have gained attention due to their superior shielding properties against both gamma and neutron radiation. The inclusion of bismuth oxide ($Bi_2O_3$) is analyzed in the present study in neutron absorption capacity and shielding applications. The glass system (60-x) $B_2O_3$–20$SiO_2$–x$Bi_2O_3$–12ZnO–8BaO offers a tuneable composition by varying the $Bi_2O_3$ content, which in turn modulates its shielding and activation characteristics. Several attempts have been made to prepare flexible neutron shielding [13] material as they have several applications.

Using glass materials in neutron radiation fields offers advantages like structural integrity, high transparency, and ease of fabrication. Traditional neutron shielding materials like borated polyethene and lead-lined composites are effective but have drawbacks such as toxicity, brittleness, and higher cost. Glasses, particularly heavy metal oxide glasses, address these concerns by offering a non-toxic, flexible, and cost-effective alternative. Apart from doped glasses, surface-modified gadolinium/boron/polyethylene composites show enhanced neutron and gamma shielding and improved interfacial compatibility and dispersion due to filler surface treatment [14]. Apart from the radiation shielding properties, the optical, structural, and mechanical properties of glass composites are of utmost importance as these composites have various applications in various industries [15–20] Some studies have also shown the effectiveness of gallium-doped glasses as well, which have shown good performance in radiation attenuation [21]. Rather than doping with a single dopant, co-doping was found to improve several factors. Co-doping increases density, hardness, and fracture toughness significantly. Mass and linear attenuation coefficients improve while the mean free path decreases, enhancing gamma shielding [22].

Monte Carlo (MC) simulation is a powerful statistical method used to model the interaction of particles with matter and is being used in shielding studies [23]. The Monte Carlo N-Particle code is widely recognized for its ability to simulate complex radiation transport phenomena, including neutron and gamma-ray interactions. By using MCNP simulations, researchers can accurately predict the behaviour of materials under neutron irradiation, calculate the neutron attenuation parameters, and evaluate the activation potential of the material. These tools are also capable of simulating various complex polymer matrix composites [24]. This study leverages MCNP to model the interaction of neutron flux with the HMO glass samples of varying $Bi_2O_3$ content to assess their shielding and activation characteristics. Doped glass materials can be tailored to optimize these two mechanisms. Boron is a crucial dopant for neutron absorption due to its high neutron capture cross-section [12], particularly for thermal neutrons. Heavy elements such as lead and Bismuth contribute to the scattering and absorption of fast neutrons due to their large atomic mass and the higher probability of interaction with neutron radiation. Bismuth borate glass outperformed lead glass and steel-magnetite concrete in total shielding effectiveness. These results suggest Bismuth-doped glasses as promising lead-free alternatives for comprehensive radiation protection [25]. This work explores neutron attenuation and activation properties of (60-x) $B_2O_3$–20$SiO_2$–x $Bi_2O_3$–12ZnO–8BaO (ZBiB) glasses. Fast Neutron Removal Cross section [26] is the essential parameter for the neutron shielding material, and it is being studied in the present work. Like glass composites, polymers are also being used for several radiation shielding applications [27]. Some studies show the doping of CsCl, which raised HVL slightly, and show these glasses outperform commercial glasses and traditional concrete in radiation shielding [28].

## 2. Methodology

### 2.1. MCNP simulation

MCNP is a powerful simulation tool widely used for radiation transport modelling. This study employed the MCNP code to assess the neutron shielding performance of doped glass materials. The simulation environment was set up to model a typical neutron source interacting with glass shields of varying thicknesses and compositions. The F1 tally feature of MCNP is used to account for neutron shielding properties. The neutron activation [29] produced in the sample is accounted for by the tool 'wise-uranium' [30]. The key parameters considered in the simulation were:

- Neutron energy spectrum: The source neutron energy distribution was defined using the SI1 and SP1 cards to simulate a uniform neutron spectrum across the energy range from 0.01 MeV to 10 MeV.
- Glass composition: ZBiB glass matrices with varying percentages of dopants.
- The thickness of glass shields: From 1 cm to 5 cm to assess the dependency of shielding efficiency on material thickness.
- Neutron flux: To evaluate doped glasses' attenuation and scattering behaviour and estimate the activation produced in high neutron flux.
- Neutron source: As the glasses are employed in various neutron energy fields, this study covers the neutron shielding parameters from energy 0.01 MeV to 10 MeV for the simulation.
- Geometry: Glass samples with dimensions of 10 cm × 10 cm × 2 cm and a point source which emits neutrons from 0.01 MeV to 10 MeV in a logarithmic energy bin is defined for the simulations. The geometry of the simulation is shown in Fig. 1.
- Absorbed Dose: Absorbed dose due to neutron irradiation has been calculated for a flux of $10^4$ neutrons/sec, irradiated over an hour period of time.

### 2.2. Output metrics

The neutron shielding performance was evaluated using the following metrics:

- Neutron attenuation coefficient: The reduction in neutron intensity per unit thickness.

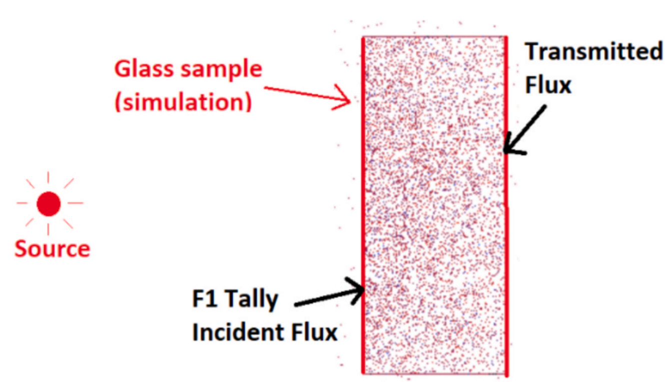


**Fig. 1.** Simulation Geometry.

- Neutron flux reduction: The percentage of neutrons absorbed or scattered.
- Neutron energy spectrum: The change in the energy distribution of neutrons after passing through the shield, providing insights into the effectiveness of the glass at different energy levels.

The shielding effect of materials against neutron rays can be characterized using three key parameters: the macroscopic cross-section ($\sum$), the shielding ratio (SR), and the mean free path (MFP). These parameters are determined by measuring the intensity of neutron rays before ($I_0$) and after (I) passing through the shielding material. The macroscopic cross-section ($\sum$) is calculated using the following formula [31]:

$$I = I_0 exp(-\sum x)$$

Here, x represents the material thickness, and the unit of $\sum$ is $cm^{-1}$. A higher macroscopic cross-section indicates a more effective shielding material. The shielding ratio (SR) quantifies the reduction in neutron intensity and is defined as:

$$SR = \left(1 - \frac{I}{I_0}\right) \times 100\%$$

The mean free path (MFP) represents the average distance between successive interactions of neutron rays with atomic nuclei within the material [32]. A smaller MFP corresponds to better shielding efficiency. It is calculated using the relationship:

$$\mathrm{MFP} = 1/\sum$$

## 3. Results and discussion

### 3.1. Neutron shielding properties of glasses with different amounts of doping materials

The glass composite with the composition (60-x) $B_2O_3$–$20SiO_2$–$xBi_2O_3$–12ZnO–8BaO, where, x varied at 0 and 12 mol%, has promising applications in neutron radiation shielding. This material leverages the high boron oxide ($B_2O_3$) content, which is particularly effective in neutron capture due to boron's high neutron absorption cross-section. Silicon dioxide ($SiO_2$) contributes to the structural integrity and stability of the glass matrix, while zinc oxide (ZnO) enhances the durability and resistance to radiation-induced degradation. Bismuth oxide ($Bi_2O_3$) content, variable with x, provides additional attenuation properties for gamma radiation, which is essential in environments with both neutron and secondary gamma radiation. Barium oxide (BaO) further strengthens the shielding capabilities by adding density to the material, thus improving its performance against high-energy particles. As x increases, the glass becomes more effective in gamma attenuation, making this composite versatile for applications requiring combined neutron and gamma shielding, such as nuclear facilities and medical radiation environments.

The plot shows the Neutron absorbance across different energy levels for two variations of the ZBiB glass composite: one with x = 0 (black squares) and one with x = 12 (red circles). Both compositions exhibit relatively stable attenuation at lower energies, with slight variations between the two, however, at higher energy levels. There is a sharp decline in attenuation for the x = 12 composition compared to x = 0. This suggests that the presence of 12 mol% $Bi_2O_3$ significantly affects the composite's attenuation performance at higher energies. The x = 0 composition maintains a more consistent attenuation across the entire energy range.

The simulation transported $10^8$ neutrons in the geometry. Considering the full energy spectrum,

The peaks in Fig. 2. are because of the neutron cross-section nature of the elements used in preparing the glass samples. Hence, the total neutron absorption of the glass sample depends highly on the neutron cross-section nature of the sample composition. Hence, while evaluating the glass performance, one needs to be very specific on the neutron energy range of interest.

The peaks nearly at 0.8 keV, 20 keV, 400 keV and 1 MeV correspond to the high neutron total cross-section of the Boron and Bismuth isotopes at that energy, which are present in the glass composite. It is clear that the ZBiB with no Bismuth attenuates neutrons best at all energy levels, but as ZBiB with 12 mol% shows a good peak at 0.8 keV, this combination of neutron energy may get attenuated best with ZBiB having 12 mol % of $Bi_2O_3$. Hence, the careful selection of isotopes and neutron spectrum to be shielded must be understood well before the use of such glasses.

### 3.2. Thickness dependence

The thickness of glass shields had a direct influence on neutron attenuation. A general trend was observed where increasing the thickness improved neutron absorption. However, diminishing returns were seen beyond a certain threshold, suggesting an optimal thickness range for different applications.

The total average attenuation of neutrons from energy 1.0E−08 to 1.0E+01 MeV is studied. The sample has varying thicknesses of 1 cm and 5 cm. Simulations have been carried out and show that the ZBiB with 12 mol% is slightly better than the undoped glasses as shown in Fig. 3. Here, as the energy range spans over a wide range, the total absorption/scattering of all energy neutrons is considered.

### 3.3. Fast neutron removal cross-section ($\Sigma_R$)

High atomic number materials on encounter with fast neutrons undergo inelastic scattering and quickly push their energy down below 2 MeV, removing them from the group of highly penetrating/un-collided neutrons and absorbing the secondary ϒ-rays produced during the process [33,34]. The probability of this process is called fast neutron removal cross-section ($\Sigma_R$), and this parameter was investigated for the current ZBiB glasses with the help of theoretical calculations. For multicomponent shielding materials such as glass, the calculation of FNR follows a mixture rule given by the equation:

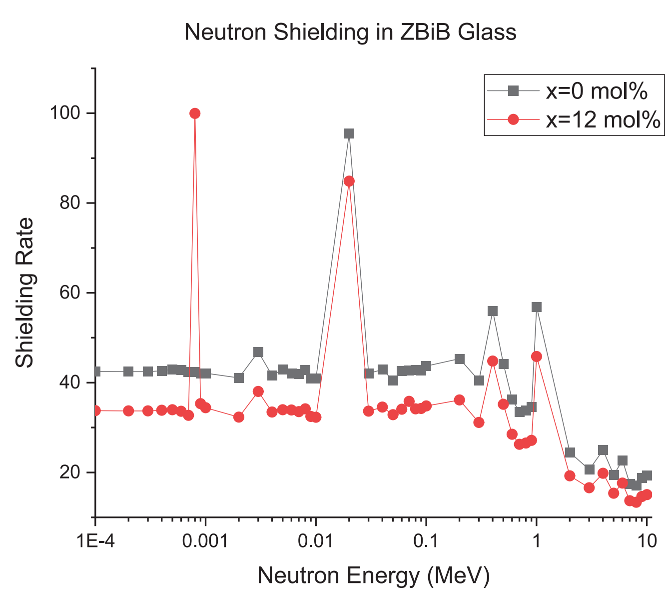


**Fig. 2.** Variation of neutron attenuation with energy.

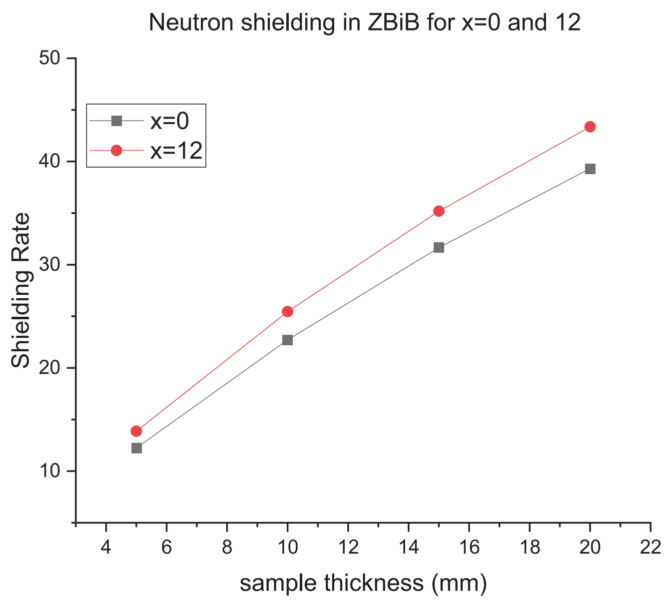


**Fig. 3.** Thickness dependence of ZBiB glass for neutron field.

$$\sum_{R} = \sum_{i=1}^{n} (\rho_x)_i \left(\sum_{r/\rho}\right)_i$$

Here $\rho_x$ denotes partial density, and the parameter $\Sigma_{r/\rho}$ is known as mass removal cross-section, measured in $cm^2/g$. The $\Sigma_{r/\rho}$ value corresponds to constituent elements, and the $\Sigma_{r/\rho}$ values for all elements are compiled in the NCRP-1957 report and other sources [3,32,35,36].

The calculated $\Sigma_R$ values for the ZBiB glass compositions are displayed in Fig. 4 and are found to be comparable and higher than concrete and glasses with similar composition [10,37]. Boron, being a lighter element, has a great mass removal cross-section, and it is a common fact that with the increase in low- Z elements in the composition, the $\Sigma_R$ also increases [38]. Here, the ZBiB–0 composition containing the highest boron content exhibited an FNR value of 0.10006 $cm^{-1}$. However, in the present scenario, the high- Z bismuth element dominated the neutron attenuation property of ZBiB glasses by generating $\Sigma_R$ greater than that of non-bismuth-containing glass. Among the chosen glasses, ZBiB-12 with the lowest boron content (but highest Bi content) produced a $\Sigma_R$ value of 0.1117 $cm^{-1}$ and the maximum $\Sigma_R$ was

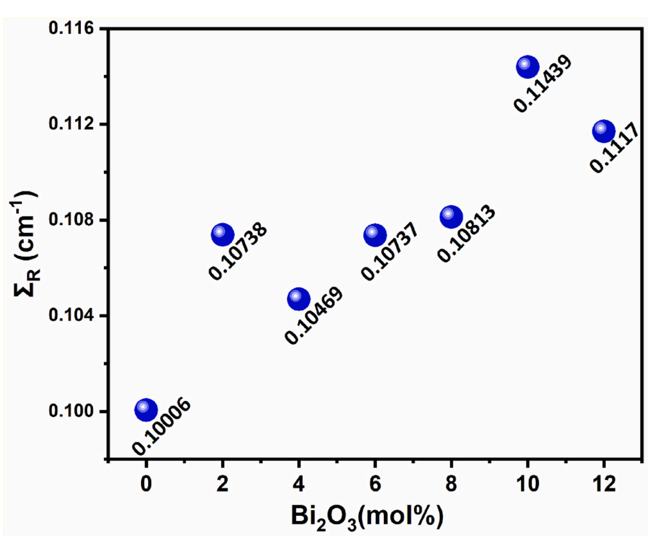


**Fig. 4.** Variation of $\Sigma_R$ with $Bi_2O_3$ content.

observed for ZBiB-10 composition (0.11439 $cm^{-1}$). This clearly justifies the role of HMO $Bi_2O_3$ in absorbing and scattering the fast neutrons [4]. Therefore, it can be interpreted that adding Bismuth was definitely helpful in increasing the neutron shielding ability of the HMO-based borosilicate glasses, which was also evident from the thickness-dependent SR results (Fig. 2).

### 3.4. *Activation-induced in ZBiB glasses*

Activation in ZBiB glasses occurs when the material is exposed to a neutron source, leading to neutron capture reactions within its constituent elements. The resulting nuclear reactions produce radioactive isotopes, with emission characteristics of gamma rays depending on the elements present in the glass matrix, such as zinc, Bismuth, or boron. These glasses are often investigated for their potential in radiation shielding and neutron dosimetry due to their high neutron absorption cross-section, particularly from the boron content. Activation studies are crucial to assess the induced radioactivity, decay pathways, and potential applications or handling safety for these materials in nuclear environments.

The activation details are given in Table 1 for the irradiation of 1 kg of ZBiB glass with $10^9$ neutrons in 1 h. The activity produced in the sample is calculated after the cooling time of 1 hr after the irradiations. The provided data in Table 1. outlines the activation characteristics of isotopes originating from elements such as oxygen, silicon, Bismuth, zinc, and barium. Each nuclide includes the isotope formed after activation, its activity (in becquerels), half-life, and point-source air kerma at a distance of 1 m. Isotopes with high activities, such as Zn and Ba, tend to exhibit significant air kerma values, reflecting their radiation intensity. Additionally, heavier elements like Bismuth produce multiple activation products (e.g., Bi-210 and Po-210) with varying decay chains, showcasing their complexity.

This data is critical for understanding neutron-induced activation, assessing radiation safety, and designing shielding strategies in nuclear applications. Out of all the isotopes produced, Ba-139 produces the maximum radiation from the sample. We can also notice the creation of toxic elements such as Polonium from Bismuth after irradiation, which needs to be taken care of before the use of glasses in neutron irradiations. Activation in ZBiB for x = 12 mol% is given in Table 1.

**Table 1**
Elementwise activation produced per kg of the glass sample.

| Original Nuclide | Isotope | Weight | Act. Product | Activity (Bq)/kg | Half-life | Point source air kerma at 1 m |
|---|---|---|---|---|---|---|
| Oxygen | O-18 | 650 mg | O-19 | 0 | 26 sec | 0 |
| Silicon | Si-30 | 1.88 g | Si-31 | 7.20E+07 | 157 min | 7.817 nGy/h |
| Bismuth | Bi-209 | 305.4 g | Bi-210 | 1.70E+07 | 5.013 day | 935.5e−15 Gy/h |
| | | | Po-210 | 5.34E+03 | 138.3 day | 6.918e−15 Gy/h |
| | | | Tl-206 | 22.44 | 4.200 min | 1.364e−15 Gy/h |
| Zinc | Zn-64 | 56.41 g | Zn-65 | 6.91E+06 | 244.0 day | 504.3 nGy/h |
| | Zn-68 | 23.18 | Zn-69 | 3.69E+08 | 56.40 min | 293.0 pGy/h |
| | Zn-70 | 761 mg | Zn-71 | 2.5 | 2.45 min | 105.8e−15 Gy/h |
| Barium | Ba-130 | 167 mg | Ba-131 | 1.68E+06 | 11.5 day | 130.6 nGy/h |
| | | | Cs-131 | 7.50E+03 | 9.68 day | 116.3 pGy/h |
| | Ba-132 | 161 mg | Ba-133 | 3.60E+03 | 10.5 yr | 257.2 pGy/h |
| | Ba-138 | 120 g | Ba-139 | 5.05E+09 | 83.06 min | 30.30 μGy/h |

### 3.5. Neutron absorbed dose in glasses

In this study, the energy deposition in a ZBiB ($ZnO–Bi_2O_3–B_2O_3$) glass (for x = 0 and x = 12 mol % of Bismuth doped) sample due to neutron irradiation was estimated using MCNP simulations. The goal was to quantify the absorbed dose in grays (Gy) under a defined neutron spectrum and irradiation conditions as a means of assessing the material's neutron interaction behaviour and suitability for radiation shielding or activation studies.

The glass composition used corresponds to the ZBiB series with x = 0 and x = 12 and was modelled in MCNP as a mass mixture defined by the m2 material card. The source neutron energy distribution was defined using the SI1 and SP1 cards to simulate a uniform neutron spectrum across the energy range from 0.01 MeV to 10 MeV. This corresponds to a discretized flat spectrum with equal probability across 28 energy bins, commonly used as a surrogate for broad-spectrum fast neutron fields.

The F6:n tally was used to estimate the energy deposited per unit mass (MeV/g) by neutrons in the glass. For the current composition and neutron source, the simulated output reported a tally value of:

Energy deposition = $1.17618 \times 10^{-4} \pm 0.0002$ MeV/g per source neutron for x = 0

Energy deposition = $8.08295E^{-05} \pm 0.0002$ MeV/g per source neutron for x = 12

Scaling for an irradiation scenario with 10,000 neutrons/sec for 1 h (3600 s) yields: Dose = 0.679 μGy (for, x = 0), 0.466 μGy (for, x = 12). It is clear from the above results that the replacement of Boron with Bismuth considerably decreases the dose absorption capabilities of the glass matrix.

## 4. Conclusion

Theoretical studies using MCNP demonstrate that doped glass materials, particularly those with Boron and Bismuth, have promising neutron shielding properties. Bismuth-doped glass excels in thermal neutron absorption, and it has also been shown that the attenuation mainly depends on the nature of the cross-section of isotopes present in the glass material. The overall attenuation is found to be better in 12 mol % doped glass, whereas it has also been observed that at certain energies, the attenuation varies highly as per the nature of the total cross-section of the isotopes present. Fast neutron removal cross-section improved significantly with the addition of $Bi_2O_3$ to the undoped ZBiB-0 glass; 10 mol% Bi-doped glass generated maximum cross-section value. The practical applications of neutron shielding glasses are extensive, with significant potential for improving safety in nuclear, medical, and industrial environments. The neutron activation studies have shown the air dose at 1 m and also the activation produced in the glass material, which is essential before deploying the ZBiB glass for any practical application. The dose absorbed in the glass matrix gives a clear picture that the addition of Bismuth decreased the neutron absorption capabilities. Future work will involve experimental validation of the simulation results and exploring new dopants for further optimization.

## CRediT authorship contribution statement

**Sachin Shet:** Writing – original draft, Conceptualization, Writing – review & editing, Data curation, Resources, Validation. **Ashwitha Nancy Dsouza:** Validation, Visualization, Resources, Software. **M.I. Sayyed:** Visualization, Software, Validation. **Aljawhara H. Almuqrin:** Formal analysis, Data curation. **Nagaraj Kamath:** Software, Validation, Visualization. **Srinivas Shenoy Heckadka:** Resources, Validation, Visualization. **Sudha Kamath:** Resources, Funding acquisition, Supervision, Investigation, Visualization, Methodology, Writing – original draft, Project administration.

## Declaration of competing 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.

## Acknowledgements

The authors acknowledge the financial support from the Manipal Academy of Higher Education. The authors express their gratitude to Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2025R2), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

## Data availability

The authors do not have permission to share data.

## References

[1] Handbook, Protection against neutron radiation up to 30 million electron volts.
[2] A.H. Almuqrin, M. Rashad, C.V. More, M.I. Sayyed, M. Elsafi, An experimental and theoretical study to evaluate Al2O3–PbO–B2O3–SiO2–BaO radiation shielding properties, Radiat. Phys. Chem. 222 (2024) 111824, https://doi.org/10.1016/j.radphyschem.2024.111824.
[3] H. Akyildirim, Calculation of fast neutron shielding parameters for some essential carbohydrates, Erzincan Üniversitesi Fen Bilimleri Enstitüsü Dergisi 12 (2) (2019) 1141–1148, https://doi.org/10.18185/erzifbed.587514.
[4] M.I. Sayyed, D. Hamad, M. Rashad, The role of ZnO in the radiation shielding performance of newly developed B2O3–PbO–ZnO–CaO glass systems, Radiat. Phys. Chem. 223 (2024) 111896, https://doi.org/10.1016/j.radphyschem.2024.111896.
[5] A. Saeed, et al., Glass materials in nuclear technology for gamma ray and neutron radiation shielding: a review, Nonlinear Opt. Quantum Opt. 53 (2021) 107–159 [Online]. Available: https://www.researchgate.net/publication/376409782.
[6] Y.S. Alajerami, M.H.A. Mhareb, M.I. Sayyed, M.Kh. Hamad, F. Kodeh, M. Rashad, M. Mitwalli, Comprehensive study for radiation shielding features for -Bi2O3–B2O3–ZnO composite using computational radioanalytical Phy-X/PSD, MCNP5, and SRIM software, Scientifc Reports 14 (2024) 17700, https://doi.org/10.1038/s41598-024-67571-z.
[7] F.M.A. Alzahrani, Kheir S. Albarkaty, F. Çalişkan, I.O. Olarinoye, M.S. Al-Buriahi, Physical, microstructural, and radiation energy absorption properties of recycled CRT-screen glass doped with Bi2O3, J. Radiat. Res, Appl. Sci. 16 (4) (2023) 100727, https://doi.org/10.1016/J.JRRAS.2023.100727.
[8] F. Judith, MCNP|A General Monte Carlo N-Particle Transport Code Version 4B.
[9] J.K. Shultis, R.E. Faw, An MCNP primer, Structure 66506 (c) (2006).
[10] M.G. Dong, et al., Investigation of gamma radiation shielding properties of lithium zinc bismuth borate glasses using XCOM program and MCNP5 code, J. Non Cryst. Solids 468 (2017) 12–16, https://doi.org/10.1016/j.jnoncrysol.2017.04.018.
[11] G.F. Knoll, Radiation Detection and Measurement, third ed., 2000.
[12] M.B. Chadwick, et al., ENDF/B-VII.1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data, Nucl. Data Sheets 112 (12) (2011) 2887–2996, https://doi.org/10.1016/j.nds.2011.11.002.
[13] T. Özdemir, A. Güngör, A. Reyhancan, Flexible neutron shielding composite material of EPDM rubber with boron trioxide: Mechanical, thermal investigations and neutron shielding tests, Radiat. Phys. Chem. 131 (2017) 7–12, https://doi.org/10.1016/J.RADPHYSCHEM.2016.10.012.
[14] Z. Huo, S. Zhao, G. Zhong, H. Zhang, L. Hu, Surface modified-gadolinium/boron/polyethylene composite with high shielding performance for neutron and gamma-ray, Nucl. Mater. Energy 29 (2021) 101095, https://doi.org/10.1016/J.NME.2021.101095.
[15] K.C. Sekhar, et al., Synthesis, optical, structural, and radiation transmission properties of $PbO/Bi_2O_3/B_2O_3/Fe_2O_3$ glasses: an experimental and in silico study, Opt. Mater. (Amst.) 117 (2021), https://doi.org/10.1016/J.OPTMAT.2021.111173.
[16] N. Alomayrah, M.S. Al-Buriahi, Optical properties, gamma attenuation and fast neutrons moderating performance of V2O5–Bi2O3–B2O3–PbO glasses, J. Aust. Ceram. Soc. 61 (2) (2024) 517–527, https://doi.org/10.1007/S41779-024-01122-7/FIGURES/9.
[17] A. Edukondalu, S. Stalin, M.S. Reddy, C. Eke, Z.A. Alrowaili, M.S. Al-Buriahi, Synthesis, thermal, optical, mechanical and radiation-attenuation characteristics of borate glass system modified by Bi2O3/MgO, Appl. Phys. A Mater. Sci. Process. 128 (4) (2022) 1–12, https://doi.org/10.1007/S00339-022-05475-3/FIGURES/12.
[18] M.S. Al-Buriahi, et al., Impact of calcium content on optical properties and radiation shielding performance of lithium antimony borate glasses, J. Radiat. Res. Appl. Sci. 17 (4) (2024) 101124, https://doi.org/10.1016/J.JRRAS.2024.101124.
[19] Z.A. Alrowaili, et al., Gamma attenuation, buildup factors, and radiation shielding performance of CaO-borosilicate glasses, J. Radiat. Res. Appl. Sci. 18 (1) (2025) 101221, https://doi.org/10.1016/J.JRRAS.2024.101221.
[20] Z.M. Elqahtani, Z.A. Alrowaili, N.S. Alsaiari, M.M. Alnairi, I.O. Olarinoye, M.S. Al-Buriahi, Gamma absorption and radiation shielding properties of apatite-

wollastonite containing SiO2, Fe2O3, and TiO2, Radiat. Phys. Chem. 226 (2025) 112282, https://doi.org/10.1016/J.RADPHYSCHEM.2024.112282.
[21] N.S. Alsaiari, S.J. Alsufyani, Z.A. Alrowaili, C. Eke, C. Sriwunkum, M.S. Al-Buriahi, Radiation attenuation, dose rate and buildup factors of gallium silicate glass system for nuclear shielding applications, Radiat. Phys. Chem. 229 (2025) 112500, https://doi.org/10.1016/J.RADPHYSCHEM.2024.112500.
[22] N.S. Alsaiari, U. Iliyasu, E. Ibrahimoglu, M.S. Al-Buriahi, Influence of Bi2O3 and Y2O3 co-doping on the structural and nuclear shielding properties of multi-elemental based glass-ceramics, Ceram. Int. 51 (13) (2025) 17993–18002, https://doi.org/10.1016/J.CERAMINT.2025.01.574.
[23] I. Akkurt, R. Boodaghi Malidarre, I. Kartal, K. Gunoglu, Monte Carlo simulations study on gamma ray-neutron shielding characteristics for vinyl ester composites, 2021. doi: 10.1002/pc.26185.
[24] Y. Gaylan, A. Bozkurt, B. Avar, Investigating thermal and fast neutron shielding properties of B4C, B2O3, Sm2O3, and Gd2O3 doped polymer matrix composites using Monte Carlo simulations, Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi 16 (2) (2021) 490–499, https://doi.org/10.29233/sdufeffd.933338.
[25] M. Kurudirek, Heavy metal borate glasses: potential use for radiation shielding, J. Alloys Compd. 727 (2017) 1227–1236, https://doi.org/10.1016/J.JALLCOM.2017.08.237.
[26] M.F. Kaplan, Concrete radiation shielding, (1989) 457. Accessed: May 29, 2025. [Online]. Available: https://inis.iaea.org/records/j5fxa-fb602.
[27] E.O. Echeweozo, S. Alomairy, N.S. Alsaiari, M.S. Al-Buriahi, Effect of lead oxide addition on gamma radiation shielding properties of newly developed geopolymers: theoretical and simulation studies, Sci. Rep. 14 (1) (Dec. 2024) 29968, https://doi.org/10.1038/s41598-024-81186-4.
[28] I. Boukhris, M.S. Al-Buriahi, H. Akyildirim, A. Alalawi, I. Kebaili, M.I. Sayyed, Chalcogenide glass-ceramics for radiation shielding applications, Ceram. Int. 46 (11) (2020) 19385–19392, https://doi.org/10.1016/J.CERAMINT.2020.04.281.
[29] R.R. Greenberg, P. Bode, E.A. De Nadai Fernandes, Neutron activation analysis: a primary method of measurement, 2011, Elsevier B.V. doi: 10.1016/j.sab.2010.12.011.
[30] wise-uranium.
[31] I. Akkurt, R.B. Malidarre, I. Kartal, K. Gunoglu, Monte Carlo simulations study on gamma ray–neutron shielding characteristics for vinyl ester composites, Polym. Compos. 42 (9) (2021) 4764–4774, https://doi.org/10.1002/pc.26185.
[32] A.B., S.J.K., F.R.E. Chilton, Principles of Radiation Shielding. . Prentice Hall, Englewood Cliffs, 1984.
[33] Y. Gaylan, A. Bozkurt, B. Avar, Investigating thermal and fast neutron shielding properties of B4C-,B2O3-,Sm2O3- AND Gd2O3-doped polymer matrix composites using Monte Carlo simulations, Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi (2021), https://doi.org/10.29233/sdufeffd.933338.
[34] Z. Huo, S. Zhao, G. Zhong, H. Zhang, L. Hu, Surface modified-gadolinium/boron/polyethylene composite with high shielding performance for neutron and gamma-ray, Nucl. Mater. Energy 29 (2021), https://doi.org/10.1016/j.nme.2021.101095.
[35] National Bureau of Standards Handbook 63, Protection Against Neutron Radiation Up to 30 million electron volts, 1957.
[36] M.F. Kaplan, Concrete Radiation Shielding, John Wiley & Sons, New York, 1989.
[37] M. Kurudirek, Heavy metal borate glasses: potential use for radiation shielding, J. Alloys Compd. 727 (2017) 1227–1236, https://doi.org/10.1016/j.jallcom.2017.08.237.
[38] T. Özdemir, A. Güngör, İ.A. Reyhancan, Flexible neutron shielding composite material of EPDM rubber with boron trioxide: mechanical, thermal investigations and neutron shielding tests, Radiat. Phys. Chem. 131 (July 2016) (2017) 7–12, https://doi.org/10.1016/j.radphyschem.2016.10.012.