

THE EFFECT OF Nb₂O₅ FOR GAMMA RAYS, FAST AND THERMAL NEUTRONS SHIELDING ON B₂O₃-TeO₂ BASED GLASSES

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Abstract

In this work, the glass system in formula (70-x)B₂O₃-30TeO₂-xNb₂O₅ at x = 0, 10, 20, 30, 40 and 50 mol% were determined gamma rays, fast and thermal neutrons shielding properties. The gamma-ray shielding properties have been explained for some parameters such as mass attenuation coefficients (μ_m), effective atomic number (Z_{eff}), and half value layer (HVL). These parameters were evaluated by the WinXCom software program at energies of 10⁻³-10⁵ MeV. While fast and thermal neutrons were calculated based on the macroscopic neutron capture cross-section. The results found that the addition of Nb₂O₅ by replacing B₂O₃ improved gamma ray shielding characteristics. This event also improved fast neutron shielding. Whereas, the thermal neutron found that the low Nb₂O₅ content was superb. These results reflected that the glass sample with high Nb₂O₅ content is excellent for gamma rays and fast neutron attenuation while low Nb₂O₅ content is excellent thermal neutron shielding glass. The results of this study are useful in enhancing the efficiency of materials for shielding gamma rays, fast and thermal neutrons.

Keywords: Fast and Thermal Neutrons Shielding; Gamma Rays Shielding; Glasses

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Introduction

Nowadays, oxide glasses are a favored and interesting material that can be found in many fields such as super-capacitors, oxide fuel cells, electrochemical equipment and radiation shielding materials (Shen *et al.*, 2019; Aboalatta *et al.*, 2021; Kaur *et al.*, 2022; Zou *et al.*, 2022). As well known, the oxide groups of compounds used to prepare glass can be separated into three types: 1) network formers such as SiO₂, B₂O₃, P₂O₅, GeO₂, Sb₂O₃ and TeO₂ 2) network modifiers such as SrO, CaO and CaF₂ and 3) network intermediate such as Nb₂O₅ which glass preparation should have at least one network former (Glumglomchit *et al.*, 2018; Mhareb *et al.*, 2021; Madhavi *et al.*, 2021; Ravangvong *et al.*, 2022). B₂O and TeO₂ are widely used for forming glass because B₂O₃ is environmentally friendly, low melting point, transparency to visible light, easy to prepare, chemical stability, cheap and higher sensitivity (El-Bayoumi *et al.*, 2021; Goma *et al.*, 2021) while TeO₂ has a low melting point, also has a high density, including thermal stability, transparency, electrical conductivity and refractive index (RI) (Al-Hadeethi and Sayyed, 2020; Kilic *et al.*, 2021; Sayyed *et al.*, 2022). However, glasses can be improved in efficiency by mixing different compounds depending on their use. Nb₂O₅ is a compound that improves glass structure and directly affects RI, absorption and transparency in visible light and NIR, stability in air and water, resistance to acid and base, and widely used in intelligent windows (Xiao *et al.*, 2008; Guedes *et al.*, 2020; Goma *et al.*, 2021; Madhavi *et al.*, 2021).

In the field of radiation shielding, important parameters such as mass attenuation (μ_m), effective atomic number (Z_{eff}) and half value layer (HVL) are values used for discussion of medium efficiency. In addition, there are important radiation interactions with the medium such as the photoelectric effect (PE), Compton Scattering (CS) and pair production (PP). While radiation shielding is better when the medium has high density and high atomic number (Sayyed and Ramana, 2018; Agar and Kurtulus, 2019; Sayyed *et al.*, 2021).

In this context, the effects of variation Nb₂O₅ for gamma rays, fast and thermal neutrons shielding properties on (70-x)B₂O₃-30TeO₂-xNb₂O₅ at x = 0,

10, 20, 30, 40, and 50 mol% glass system were determined. The parameters for gamma rays such as attenuation coefficients (μ_m), effective atomic number (Z_{eff}) and half value layer (HVL) were evaluated by the WinXCom software program at energies of 10⁻³-10⁵ MeV. Fast and thermal neutrons were calculated based on the macroscopic neutron capture cross-section. The results of this research were used to shield gamma-rays, fast and thermal neutrons to replace existing lead glass systems.

Material and Methods

Glasses Description

The Nb₂O₅ based on TeO₂-B₂O₃ glass system in this research adjusted Nb₂O₅ contents in formula (70-x)B₂O₃-30TeO₂-xNb₂O₅ at x = 0, 10, 20, 30, 40, and 50 mol%. The evaluation of these glass systems has been displayed in Table 1.

Density (ρ), Mass Attenuation Coefficients (μ_m), Effective Atomic Number (Z_{eff}) and Half-value layer (HVL)

The density (ρ ; g/cm³) is an important basic value for the determination of the other values. The glass density can be calculated as shown in Eq. (1). The density values were brought to calculate the molar volume (V_m) of glasses as shown in Eq. (2) (Limkitjaroenporn *et al.*, 2011; Kurtulus *et al.*, 2021):

$$\rho = (0.53) \frac{\left(\sum M_i x_i\right)}{\left(\sum V_i x_i\right)} \quad (1)$$

here M_i , V_i and x_i are molecular weight, packing density factor, and molar fraction of i^{th} component, respectively.

$$V_m = \frac{M_T}{\rho} \quad (2)$$

here M_T is the total molecular weight of the glass composition.

The mass Attenuation Coefficient (μ_m) is a quantity used to explain the sum of partial

Table 1. Chemical composition and abbreviation of glass system (mol%)

Compound	Glass abbreviation and composition (mol%)					
	TBN1	TBN2	TBN3	TBN4	TBN5	TBN6
TeO ₂	30	30	30	30	30	30
B ₂ O ₃	70	60	50	40	30	20
Nb ₂ O ₅	0	10	20	30	40	50

interactions such as PE, CS and PP (Al-Buriah *et al.*, 2020). The theoretical value of the μ_m is given by the mixture rule and displayed in Eq. (3) (Limkitjaroenporn *et al.*, 2011):

$$\mu_m = \sum w_i (\mu_m)_i \quad (3)$$

here w_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of glass sample, respectively, of i^{th} constituent elements.

The effective atomic number (Z_{eff}) is the parameter used to explain the probability of interaction with the medium which high Z_{eff} indicates a superb reduction of radiation intensity and according to the following Eq. (4) (Çaglar *et al.*, 2021; Kamislioglu, 2021):

$$Z_{\text{eff}} = \frac{\sum f_i A_i (\mu_m)_i}{\sum f_i \frac{A_i}{Z_i} (\mu_m)_i} \quad (4)$$

here f_i , Z_i and A_i are mole fractions, atomic number and atomic weight, respectively, of i^{th} constituent elements.

The half-value layer (HVL) is the value to discuss the thickness of the medium which deduces radiation intensity 50%. This value is low exhibit excellent radiation shielding medium and following Eq. (5) (Kilicoglu *et al.*, 2019; Çaglar *et al.*, 2021):

$$\text{HVL} = \frac{0.693}{\mu} \quad (5)$$

here μ (cm^{-1}) is the linear attenuation coefficient.

Fast and thermal neutrons

Neutrons can be divided into different types depending on their energy range such as fast neutron (> 0.1 MeV), intermediate neutron (0.1-100 keV), epithermal neutron (0.1-100 eV) and thermal neutron (0.015 eV). The interaction of neutrons with the medium can be separated into transmission, absorption and scatter neutrons. The possibility of these processes is determined by the microscopic cross section of reaction (Rammah and Elshafie, 2021; Lakshminarayana *et al.*, 2022).

The fast neutrons removal cross section (Σ_R) and the thermal neutrons have been evaluated in Eq. (6) and Eq. (7), respectively.

$$\Sigma_R = \sum_i w_i \left(\Sigma_R / \rho \right)_i \quad (6)$$

$$\Sigma(E) = N_A \rho \sum_i \frac{W_i}{M_i} \sigma_i(E) \quad (7)$$

here $W_i = \rho w_i$ is partial density, w_i and ρ are referred fractions by weight of element i^{th} and the total density of the medium, respectively. $\sigma_i(E)$ (in barn units), W_i and M_i are the microscopic cross section, the mass fraction and atomic mass of i^{th} element in medium, respectively, while $\Sigma(E)$ (cm^{-1}) and N_A are medium's macroscopic cross section and Avogadro's number, respectively (Rammah *et al.*, 2020; Lakshminarayana *et al.*, 2021; Rammah and Elshafie, 2021; Lakshminarayana *et al.*, 2022).

In addition, both values (Σ_R and $\Sigma(E)$) are fundamental quantities using simulated the other quantities such as the transmission factors (TF), the neutrons shielding percentage (SP) and the relaxation lengths for neutrons.

Results

Density (ρ), Mass Attenuation Coefficients (μ_m), Effective Atomic Number (Z_{eff}) and Half value layer (HVL)

The density of glass is the parameter to be discussed as the degree adjustment in formation units in the glass composition. The density of this glass system has been exhibited in Figure 1. It found that the density of glass samples increased with increasing Nb_2O_5 content because of molecular weight and density of Nb_2O_5 (265.81 g/mol and 4.60 g/cm^3) had higher compared with B_2O_3 (69.63 g/mol and 2.46 g/cm^3). In addition, the increasing of molar volume with increasing Nb_2O_5 content for the glass system as exhibited in Figure 1, indicated that the non-bridging oxygen (NBO) atoms were increased (Limkitjaroenporn *et al.*, 2011; Halimah and Zulkifli, 2019).

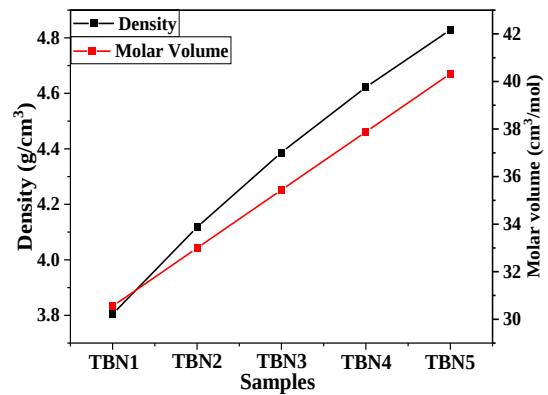


Figure 1. The density and molar volume of glass system

The theoretical value of μ_m with energy ranging 1 keV- 100 GeV is displayed in Figure 2. It found that the μ_m increased with increasing Nb₂O₅ content according to density and chemical composition in glass samples, which TBN6 had the highest μ_m (Lakshminarayana *et al.*, 2021). In addition, the μ_m values were high and decreased rapidly at low energy ranging ($E < 0.1$ MeV) and then gradually decreased at intermediate energy ranging ($0.1 < E < 5$ MeV) after that increased until nearly constant at high energy ranging ($E > 5$ MeV). These events are because of the main interaction: PE ($\alpha E^{-3.5}$), CS (αE^{-1}), and PP ($\alpha \log E$) dominated at each energy range, respectively. Also, at low energy ranging, graphs were not continuous due to M-, L- and K-absorption edges of Nb and Te in selected glasses (Ravangvong and Phan, 2022).

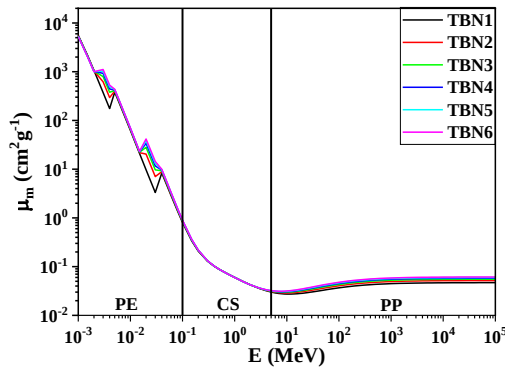


Figure 2. The μ_m versus energies for glass system

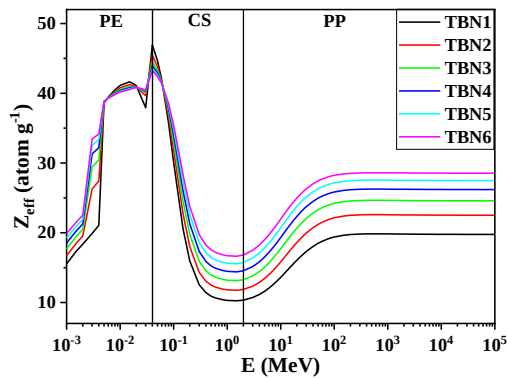


Figure 3. The Z_{eff} versus energies for glass system

Figure 3 shows Z_{eff} versus energy ranging from 10^{-3} - 10^5 MeV of glass system. The graphs displayed that Z_{eff} values increased at an energy ranging less than 40 keV because PE ($\alpha Z^{4.5}$) is the main process and in this energy range Z_{eff} value had peaked ($E = 15$ and 40 keV) due to absorption edges of Nb and Te, respectively. After that Z_{eff} values decreased quickly with increased energy ($40 \text{ keV} < E < 2$

MeV). These because CS (αZ) is the main process. Finally, at high energy ranging, the Z_{eff} value became increased with increasing energy until 80 MeV and then Z_{eff} was nearly constant due to PP (αZ^2) being the main process. Among selected glass systems, Z_{eff} for the TBN6 glass sample was the highest value according to density and chemical composition in the glass sample (Singh *et al.*, 2018; Ravangvong *et al.*, 2022).

The HVL values of glass system with energy were visualized in Figure 4. Due to the inverse proportion of HVL with μ_m ($1/E^{3.5}$), so, the HVL value was nearly zero at low energy ranges. The highest density of the TBN6 glass sample had a lower HVL value. It indicated that the density of the glass system was effective on HVL results. While, at high energy ranging, it needed to increase the glass sample thickness so that photons can penetrate more into glass samples (Perişanoğlu and Yavuz, 2020).

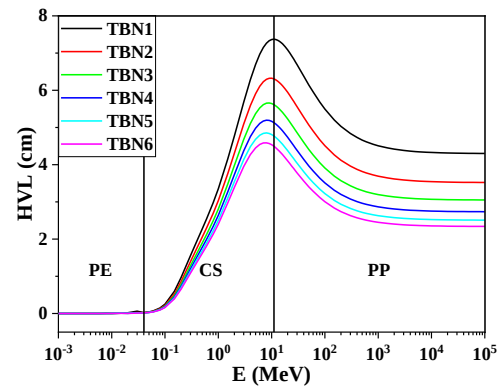


Figure 4. The HVL versus energies for glass system

Fast neutrons

The fast neutrons shielding properties for glass system were explained on fast neutrons removal cross sections (Σ_R). Figure 5 shows the Σ_R values for glass samples. It found that Σ_R increased with increasing Nb₂O₅ content. This event indicated that Nb which is a heavy element can improve fast neutrons shielding glass system (Perişanoğlu and Yavuz, 2020; Issa and Sayed, 2020).

Figure 6 exhibited the transmission factor (TF) of fast neutrons of glass systems with different thicknesses. It found that all graphs of the glass system quickly decreased with increasing medium thickness and the TBN6 glass sample had the lowest TF at the same thickness. It demonstrated TBN6 sample had the highest attenuation efficiency. In addition, it indicated that TF value depends on the heavy chemical content and density of glass (Sathiyapriya and Kumar, 2019; Kamislioglu, 2021).

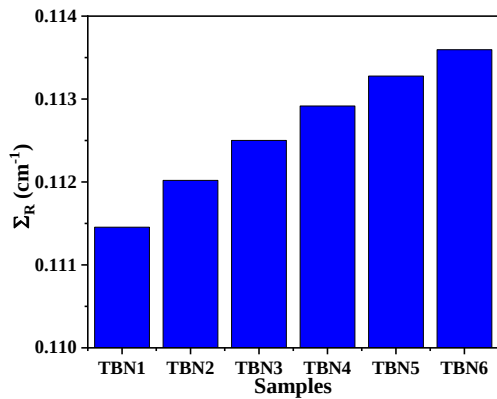


Figure 5. The fast neutrons removal cross sections (Σ_R) for glass system

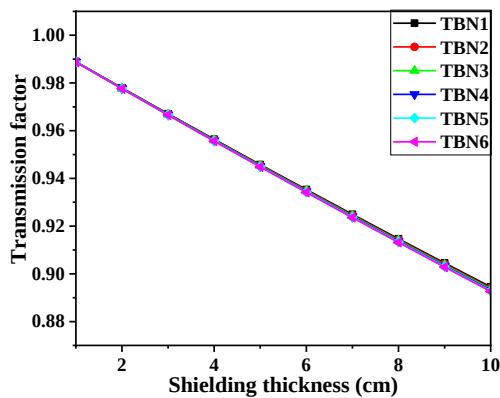


Figure 6. The transmission factor (TF) of fast neutrons for glass system versus thickness

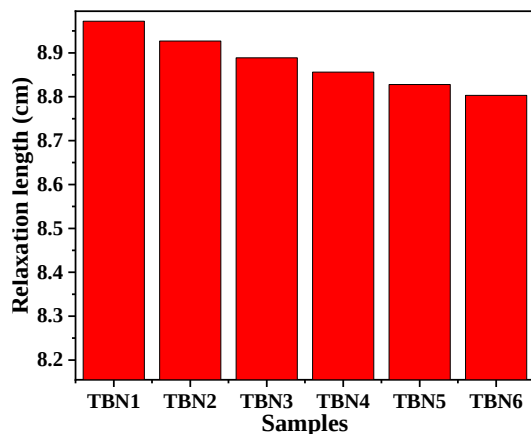


Figure 7. The relaxation length for fast neutrons of glass system

The relaxation length for fast neutrons values as illustrated in Figure 7, it found that TBN6 glass samples had this value the lowest while Σ_R the highest. Because of the content of Nb which heavy element in this sample had the largest so, it will be

more effective in shielding photons caused by inelastic scattering reactions and nucleated neutrons (Sahadath and Alam, 2017).

Thermal neutrons

The thermal neutrons shielding properties for the glass system were calculated on macroscopic cross sections $\Sigma(E)$. Figure 8 exhibited $\Sigma(E)$ values for glass samples. It found that $\Sigma(E)$ decreased with increasing Nb_2O_5 content. This event is because boron (B) is excellent thermal neutron shielding so, the decreasing B_2O_3 content results in a decrease in thermal neutrons shielding (Rammah and Elshafie, 2021).

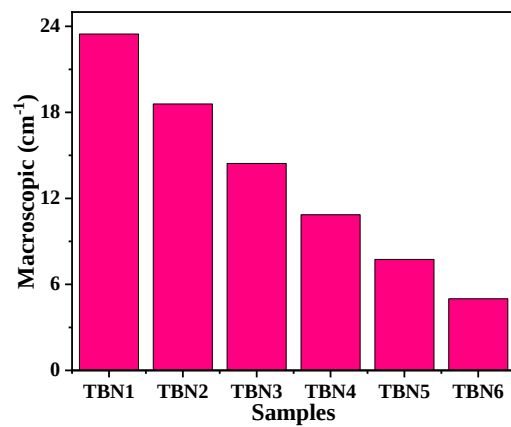


Figure 8. The thermal neutrons cross sections (ΣE) for glass system

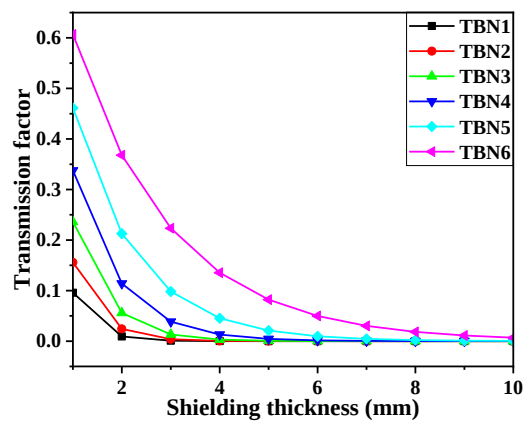


Figure 9. The transmission factor (TF) of thermal neutrons for glass system versus thickness

The transmission factors (TF) of thermal neutrons for TBN glass system with thickness (mm) was exhibited in Figure 9. It found that TBN1 sample had TF lowest value at same thickness and all samples decreased with increasing thickness. Lastly, the thermal neutrons shielding percentage (SP) of the TBN glass system with the thickness

(t: mm) as illustrated in Figure 10. It found that TBN1 had SP highest and SP of all samples rapidly increased at first t region and then almost 100% with increasing t while SP of glass system decreased with increasing Nb content and density. These indicated that the B element had a relatively higher micro cross-section than Nb (Lakshminarayana and Bhagat, 2021; Rammah and Elshafie, 2021).

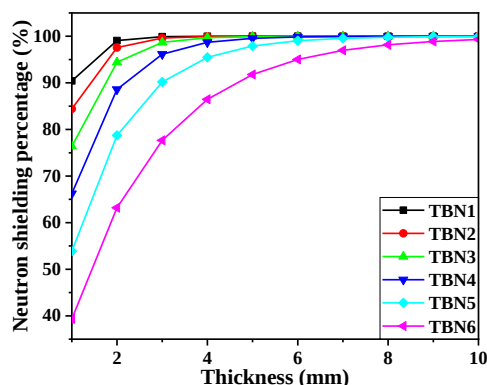


Figure 10. The thermal neutrons shielding percentage (SP) for glass system versus thickness

Conclusion

In this work, glass system in formula $(70-x)\text{B}_2\text{O}_3-30\text{TeO}_2-x\text{Nb}_2\text{O}_5$ at $x = 0, 10, 20, 30, 40$ and 50 mol% were explained gamma rays, fast and thermal neutrons shielding properties. The properties of gamma rays shielding which were simulated using the WinXCom program at an energy ranging 10^{-3} - 10^5 MeV were discussed on mass attenuation coefficients (μ_m), effective atomic number (Z_{eff}) and half value layer (HVL). While fast and thermal neutron shielding properties were calculated using the macroscopic neutron cross-section. The results found that the Nb₂O₅ compounds improved gamma rays and fast neutron shielding behavior. Whereas these results opposite effect on the thermal neutron. These results indicated that glass sample with high Nb₂O₅ content is excellent for gamma rays and fast neutron attenuation while low Nb₂O₅ content is superb thermal neutron shielding glass. The results of this study are useful in enhancing the efficiency of materials for shielding gamma rays, fast and thermal neutrons.

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