Fabrication, physical, structure characteristics, neutron and radiation shielding capacity of high-density neodymium-cadmium lead-borate glasses: Nd$_2$O$_3$/CdO/PbO/B$_2$O$_3$/Na$_2$O

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Abstract
High-density glasses of neodymium-cadmium lead borate of chemical composition xNd$_2$O$_3$/20CdO/20PbO/(57-x)B$_2$O$_3$/3Na$_2$O, where (0 ≤ x ≤ 5) wt% have been fabricated by a melt quenching process. Physical, structure properties as well as gamma-radiation and neutron shielding effectiveness in wide photon energy range 0.015–15 MeV have been examined. The amorphous nature of xNd-glasses was confirmed, where there was a lack of their crystallinity. Density was gradually increased from 5.006 g/cm$^3$ for 0Nd-glass sample to 5.245 g/cm$^3$ for 5Nd-glass sample. In terms of the mass attenuation coefficient (MAC), introducing Nd$^{3+}$ ions in the glass matrix has a direct constructive influence on the obtained values of MAC. Generally, the MAC trend follows the order (MAC)$_{5Nd}$ > (MAC)$_{4Nd}$ > (MAC)$_{3Nd}$ > (MAC)$_{2Nd}$ > (MAC)$_{1Nd}$ > (MAC)$_{0Nd}$. The linear attenuation coefficient (LAC) has a similar trend as MAC for all xNd-glasses. In terms of the half-value layer ($T_{1/2}$), the 5Nd-glasses possessed the minimum $T_{1/2}$ values (0.004 cm at 15 keV to 4.301 cm at 15 MeV). Therefore, the $T_{1/2}$ of the fabricated xNd-glasses has an inverse behavior of the MAC and LAC. Thus, ($T_{1/2}$)$_{5Nd}$ > ($T_{1/2}$)$_{4Nd}$ > ($T_{1/2}$)$_{3Nd}$ > ($T_{1/2}$)$_{2Nd}$ > ($T_{1/2}$)$_{3Nd}$ > ($T_{1/2}$)$_{1Nd}$ > ($T_{1/2}$)$_{0Nd}$. The effective atomic number ($Z_{\text{eff}}$) parameter follows the order ($Z_{\text{eff}}$)$_{5Nd}$ > ($Z_{\text{eff}}$)$_{4Nd}$ > ($Z_{\text{eff}}$)$_{3Nd}$ > ($Z_{\text{eff}}$)$_{2Nd}$ > ($Z_{\text{eff}}$)$_{1Nd}$ > ($Z_{\text{eff}}$)$_{0Nd}$. In the energies preferred for radiation applications, 5Nd-glasses possess very low exposure (EBF) and energy absorption (EABF) buildup factor values. The fast neutron removal cross-section (FNRC) of the fabricated glasses is improved as the Nd$^{3+}$ content increases in the glass matrix.

Keywords Glasses · Photon · Neutron · Mass attenuation coefficient · Radiation shielding

1 Introduction

Due to the fact that glasses are transparent materials, low in price, ease in fabrication, light in weight, tough, non-toxic, and radiation resistant, the use of different glasses for radiation shielding applications has more attention from several researchers and engineers [1–9]. In addition, the interesting physical, mechanical, thermal characteristics of glasses, several glass compositions have been suggested and investigated for their optical, mechanical, thermal, electrical, and radiation shielding capacity through different experimental and theoretical treatments [10–16].

The most common oxide that can act as a glass base is boron oxide (B$_2$O$_3$). Borate-based glasses are particularly advantageous due to their physical and chemical properties, which include a low melting point and good transparency [17, 18]. To make a series of glasses with promising optical and radiation shielding properties, the chemical structure of the glasses must be flexible, allowing for doping with
new elements or radicals, and changing the stoichiometry of atomic components of glasses. This has necessitated a large number of glass series, each with its own set of properties. A large number of studies have investigated the ability of various metal oxides (B, Li, Cd, Zn, Ca, and others) and rare earth elements (Gd₂O₃, Sm₂O₃, Y₂O₃, La₂O₃, Nd₂O₃, and others) in the glass matrix, such as to improve photon and charged particle radiation shielding coefficients [19, 20]. Kilic [21] studied the influence of Nd³⁺ ions on structural, optical, and thermal characterization of V₂O₅–TeO₂–(B₂O₃/Nd₂O₃) glasses and concluded that Nd³⁺ ions makes changing in the glass network and acts as a modifier leads to improve the optical and thermal properties. Rammah et al. [22] investigated the optical features of the prepared bismuth borotellurite glasses doped with NdCl₃. They reported that the optical properties were enhanced as NdCl₃ content increases. Abdel-Aziz et al. [23] reported that Nd³⁺ and Er³⁺ ions enhanced the physical, structure, mechanical, and dielectric characteristics of calcium lead-borate glasses. In terms of radiation shielding field, Mahmoud et al. [24] investigated the gamma-ray shielding capacity of glasses doped with Nd³⁺ ions rare earth using MCNP-5 code, they claimed that the insertion of Nd³⁺ ions in the glass matrix leads to enrich their radiation shielding capacity. Hegazy et al. [25] studied the nuclear shielding properties of borate glasses modified with Nd³⁺ ions; they reported that increasing Nd³⁺ ions content in the glass matrix helps to enhance the radiation attenuation capacity. Recently, Rammah et al. [26] and Zakaly et al. [27] reported that the insertion of Nd³⁺ ions in the fabricated cadmium lead-borate glasses has a direct improvement in their physical, structural, and optical features.

This paper reports about:

(i) Fabrication of high-density neodymio-cadmium leads borate glasses.
(ii) XRD patterns and physical properties of the fabricated glasses have been measured.
(iii) Investigating the significant role of neodymium (Nd³⁺) ions content in the fabricated glasses on the photon and neutron shielding efficacy.
(iv) Comparing between our findings and that of some commercial radiation shielding materials such as concrete and glasses.

2 Materials and methods

2.1 Preparation of xNd-glasses

A series of high-density neodymio-cadmium lead-borate glasses of chemical composition xNd₂O₃/20CdO/20PbO/(57-x)B₂O₃/3Na₂O, where (0 ≤ x ≤ 5 wt%) have been fabricated by a melt quenching process. The fabricated process was achieved using high purity (99%) for all oxides which supplied from Strem chemicals and Riedel-De Haën Company. Precursors were weighed and thoroughly mixed to obtain a homogeneous composite mixture and finely divided additions, which were then placed in porcelain crucibles and stored inside an electric melting furnace at temperature 1050 °C for about 25 min. Then, the prepared glasses quickly pressed with a steel plate to place in a preheated oven at 250 °C and leave to cool to room temperature inside the oven. The code of the fabricated glasses is abbreviated as xNd-glasses: 0 (0Nd), 1 (1Nd), 2 (2Nd), 3 (3Nd), 4 (4Nd), and 5 (5Nd). A photo of the fabricated glasses is shown in (Fig. 1).

The amorphous state of the fabricated xNd-glasses was examined using X-ray diffraction (XRD) technique with Cu Kα radiation source (λ = 1.54 nm), Philips model (PW-1729) step size 0.02 °C; time per step: 21 s.

Density (ρglass) of the fabricated xNd-glasses was measured experimentally by Archimedes’ principle with Xylene as an immersion liquid medium with density (ρXylene = 0.863 g/cm³). Weigh each glass sample in air (WAir) and in Xylene (WXylene) and the density of every xNd-glass samples was calculated using the next relation:

\[ \text{Density (ρglass)} = \frac{W_{\text{Air}} - W_{\text{Xylene}}}{V_{\text{displaced}}} \]

\[ V_{\text{displaced}} = \frac{W_{\text{Air}} - W_{\text{Xylene}}}{\rho_{\text{Xylene}}} \]

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Fig. 1 X-ray diffraction patterns of glasses with different Nd₂O₃ content
\[ \rho_{\text{glass}} = \frac{W_{\text{Air}}}{(W_{\text{Air}} - W_{\text{Xylene}}) \times \rho_{\text{Xylene}}} \]  

(1)

Table 1 shows codes, chemical compositions, and density of the xNd-glasses.

### 2.2 XCOM software and FLUKA code for γ-photons

In the current work, FLUKA simulation code was used to examine the gamma-ray shielding characteristics of the prepared xNd-glasses [28]. Figure 2 displays the needed geometry for investigating γ-ray transmission via the prepared glasses. A mono-energetic gamma source emits an initial number of γ-photons about \(10^6\) photons to incident directly on the glass sample. The ratio of initial and passed photons used to evaluate the linear attenuation coefficient \(\text{LAC} = \mu\) for each glass sample. Then, the mass attenuation coefficients \(\text{MAC} = \mu/\rho = \mu_m\) (\(\rho\) is the glass density) based on the following expression [29–34]:

\[ \frac{\mu}{\rho} = \frac{\mu_m}{\rho} = \sum W_i \left( \frac{\mu}{\rho} \right)_i \]  

(1)

The obtained results of FLUKA code were compared with the theoretical values obtained via XCOM platform [35]. Furthermore, the values \(\mu\) and \(\mu/\rho\) were used to examine the half-value layer (HVL, \(T_{1/2}\)), mean free path (MFP, \(\lambda\)), and effective atomic number \(Z_{\text{eff}}\) as follows [29–34, 36]:

\[ T_{1/2} = \frac{0.693}{\mu}, \quad \lambda = \frac{\mu}{\rho}^{-1} \]  

(2)

\[ Z_{\text{eff}} = \frac{\sum f_i A_i \left( \frac{\mu}{\rho} \right)_i}{\sum \left( \frac{A_i}{Z_i} \right)} \]  

(3)

where \(A_i\) and \(f_i\) are the atomic mass and molar fraction of ith constituent pure element in the glass. The exposure buildup factor (EBF) and energy absorption buildup factor (EABF) of the fabricated xNd-glasses also examined using the G–P fitting coefficients (b, c, a, Xk and d) as in Ref. [37].

### 2.3 Calculation of fast neutron removal cross section

Inelastic collisions occur when a fissile/fast neutron collides with any non-hydrogenous material. The fast neutron removal cross-section is the statistical probability that a fast neutron interacts in such a way that it is no longer categorized as fast \((FNRC - \Sigma_R)\). For fast neutrons with energy ranging from 2 to 12 MeV, this is the macroscopic cross-section. The \((FNRC)\) may be calculated for materials (xNd-glasses) according to the following expression [38]:

\[ \sum R = \rho \sum w_i (MRCS)_i \]  

(4)

where \(\rho\), \((MRCS)_i\), and \(w_i\) are the mass density of the interacting medium, mass removal cross-section, and weight fraction of the \(i^{th}\) element.

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**Table 1** Codes, chemical compositions, and density of the xNd-glasses: \(x=0, 1, 2, 3, 4,\) and \(5\) wt%

| Code | Chemical compositions (Wt %) | Density, \(\rho_{\text{glass}}\) (g/cm³) ± 0.001 |
|------|-------------------------------|-----------------------------------------------|
| 0Nd  | \(0\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/57\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.006                                         |
| 1Nd  | \(1\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/56\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.054                                         |
| 2Nd  | \(2\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/55\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.101                                         |
| 3Nd  | \(3\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/54\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.150                                         |
| 4Nd  | \(4\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/53\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.200                                         |
| 5Nd  | \(5\text{Nd}_2\text{O}_3/20\text{CdO}/20\text{PbO}/52\text{B}_2\text{O}_3/3\text{Na}_2\text{O}\) | 5.245                                         |

**Fig. 2** A demonstration of simulation setup for mass attenuation coefficients calculation.
3 Results and discussion

3.1 Density property and XRD analysis

Through relation (1), the densities of the fabricated xNd-glasses were measured and listed in Table 1. Results of densities showed a gradual slightly increase in the sample’s density with Nd2O3 addition. This trend may be attributed to the systematic increase in the molecular mass of the glass samples due to the addition of the higher molecular weight Nd2O3 (336.48 g/mol) at the expense of the lighter molecular weight B2O3 (69.6 g/mol). Another equally valid interpretation is that the density of xNd-glasses increased as the gradual replacement of the lower density B2O3 (2.46 g/cm³) by the higher density Nd2O3 (7.24 g/cm³).

Figure 1 illustrates the XRD patterns of the fabricated xNd-glasses. As shown in (Fig. 1), the XRD patterns confirm the amorphous phase for all fabricated glasses. Furthermore, the characteristic diffraction peak was defined and sharp at around 29°, confirming the amorphous state. In addition, the absence of strong diffraction peaks and the presence of hump can be seen in all XRD patterns for all samples.

3.2 γ-radiation shielding characteristics

The ionizing radiation shielding effectiveness of the fabricated xNd-glasses is controlled, governed, and examined using the linear (LAC = µ) and mass attenuation coefficient (MAC = µm). The LAC and MAC mainly depends on both the nature of glasses (compositions) and incident photon energy and not depends on thickness of glasses. Physically, the MAC is considered as the sum of the probability of photons interaction mechanism with the material (i.e. photoelectric effect (PE), Compton scattering (CS), and pair production (PP) processes).

In the current work, the MAC of the fabricated xNd-glasses with their elemental compositions and density is estimated as a function of the photon energy (E) in the range 0.015–15 MeV via XCOM programs [35] and simulated via FLUKA code [28]. The obtained values of 0Nd, 1Nd, 2Nd, and 2Nd glasses are listed in Table 2 and for 3Nd, 4Nd, and 5Nd glasses are listed in Table 3. The variation of mass attenuation coefficient (MAC = µm) values as a function of photon energy (E) of xNd-glasses is illustrated in (Fig. 3). The relative deviation between the computed and simulated values has been calculated and depicted in (Fig. 4), it was in the range from –8 to 8% for 0Nd-glasses, while in the range of –7 to 8% for 5Nd-glasses. Therefore, the simulated and computed values were in well agreement.

As shown in (Fig. 3), introducing Nd³⁺ ions in the glass matrix has a direct constructive influence on the obtained values of MAC. It is observed that the MAC enriched with the increase of the Nd³⁺ ions content in the fabricated glasses. Therefore, the 5Nd-glasses possess the highest MAC and the 0Nd-glasses possess the lowest values. The minimum MAC at 15 MeV were 0.027 cm²/g, 0.027 cm²/g, 0.030 cm²/g, 0.030 cm²/g, and 0.030 cm²/g for 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses, respectively. The maximum of MAC at 0.015 MeV were 25.780 cm²/g, 26.051 cm²/g, 26.177 cm²/g, 26.737 cm²/g, 26.963 cm²/g, and 30.322 cm²/g for 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses, respectively. Generally, the MAC trend follows the order (MAC)5Nd > (MAC)4Nd > (MAC)3Nd > (MAC)2Nd > (MAC)1Nd > (MAC)0Nd which confirms the influence of Nd³⁺ ions in glass matrix. The obtained trend of the MAC explained as: in the lowest photon energy, the behavior of the MAC exhibits due to the photoelectric effect (PE) that variation is directly with Z² of absorbing material and inversely with the E⁴ of the photon energy. In the intermediate region, the Compton Scattering (CS) varies directly with (Z/A) and inversely with energy (E). In the highest energy region, pair production (PP) interaction changes with the second power of Z. In conclusion, the MAC has the highest values depending on the higher (Z) and density of the absorber.

In terms of the MAC parameter, the 5Nd-glasses (5 wt% of Nd³⁺ ions) with high density (5.245 g/cm³) possessed the greatest MAC values, while 0Nd-glasses (free of Nd³⁺ ions) with low density (5.006 g/cm³) possessed the minimum MAC values.

Dependence of linear attenuation coefficient (LAC = µ) in cm⁻¹ versus photon energy (E) for the fabricated xNd-glasses is shown in (Fig. 5). As it was observed in (Fig. 5), the LAC has a similar trend of MAC, i.e. the 5Nd-glasses possessed the highest LAC values, while 0Nd-glasses possessed the lowest LAC values. Therefore, the LAC trend follows the order (LAC)5Nd > (LAC)4Nd > (LAC)3Nd > (LAC)2Nd > (LAC)1Nd > (LAC)0Nd.

Dependence of the half-value layer T₁/₂ in cm with photon energy (E) of the fabricated xNd-glasses is depicted in (Fig. 6). The variation of T₁/₂ with low energy region is small and their values tend close together, because of the (PE) cross-section dominance in this region. By increasing of (E), the T₁/₂ improved and values more differ from sample to another due to the dominance of both (CS) and (PP) interactions processes. As 5Nd-glasses with high density (5.245 g/cm³) possessed the minimum T₁/₂ values and it varied from 0.004 cm at 15 keV to 4.301 cm at 15 MeV. Furthermore, 0Nd-glasses with low density (5.006 g/cm³) possessed the maximum T₁/₂ values changes from 0.005 cm at 15 keV to 4.719 cm at 15 MeV. Therefore, the T₁/₂ of the fabricated xNd-glasses has an inverse behavior of the MAC and LAC. Thus, (T₁/₂)5Nd > (T₁/₂)4Nd > (T₁/₂)3Nd > (T₁/₂)2Nd > (T₁/₂)1Nd > (T₁/₂)0Nd. Regarding to the obtained results of MAC, LAC,
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and $T_{1/2}$, one can conclude that 5Nd-glasses can be considered as superior in radiation shielding capacity among all fabricated glasses.

Figure 7 shows a comparison of the HVL of 5Nd sample with some commercial radiation shielding materials such as Ordinary concrete (OC) [39], Hematite-Serpentine concrete (HSC) [39], (ILmenite-Limonite concrete (ILC) [39], Basalt-Magnitite concrete (BMC) [39], Imenite concrete (IC) [39], Steel-Scrap concrete (SSC) [39], and glasses [40]. From (Fig. 7), it was observed that the currently fabricated 5Nd-glasses is superior as radiation shielding material than several commercial ones.

In terms of mean free path (λ), the variations of λ with the incident photon (E) for xNd-samples is depicted in (Fig. 8). As shown in (Fig. 8), there was negative effect of Nd$^{3+}$ ions content on the trend of λ. Consequently, 5Nd-glass has the lowest values of $\lambda = 0.006$ cm at photon energy 15 keV and 6.205 cm at photon energy 15 MeV, while the 0Nd-glass has the highest values of $\lambda = 0.007$ cm and 6.808 cm at photon energy 15 MeV, respectively.

| Energy (MeV) | 0Nd    | 1Nd    | 2Nd    |
|-------------|--------|--------|--------|
|             | FLUKA µm | XCOM µm | FLUKA µm | XCOM µm | FLUKA µm | XCOM µm |
| 0.015       | 25.78   | 27.96  | 26.05   | 28.61   | 26.18   | 29.26   |
| 0.02        | 18.16   | 19.15  | 18.85   | 19.45   | 18.81   | 19.75   |
| 0.03        | 11.15   | 12.03  | 11.64   | 12.13   | 11.60   | 12.22   |
| 0.04        | 6.00    | 5.67   | 5.81    | 5.71    | 5.88    | 5.75    |
| 0.05        | 3.33    | 3.15   | 3.47    | 3.28    | 3.61    | 3.42    |
| 0.06        | 2.09    | 1.96   | 2.18    | 2.04    | 2.27    | 2.12    |
| 0.07        | 1.42    | 1.32   | 1.47    | 1.38    | 1.54    | 1.43    |
| 0.08        | 1.02    | 0.95   | 1.07    | 0.99    | 1.11    | 1.03    |
| 0.09        | 1.78    | 1.73   | 1.81    | 1.76    | 1.84    | 1.78    |
| 0.10        | 1.39    | 1.33   | 1.41    | 1.36    | 1.44    | 1.38    |
| 0.15        | 0.55    | 0.53   | 0.56    | 0.53    | 0.57    | 0.54    |
| 0.20        | 0.31    | 0.30   | 0.32    | 0.30    | 0.32    | 0.30    |
| 0.30        | 0.17    | 0.16   | 0.17    | 0.16    | 0.17    | 0.16    |
| 0.40        | 0.12    | 0.12   | 0.12    | 0.12    | 0.12    | 0.12    |
| 0.50        | 0.10    | 0.10   | 0.10    | 0.10    | 0.10    | 0.10    |
| 0.60        | 0.09    | 0.09   | 0.09    | 0.09    | 0.09    | 0.09    |
| 0.70        | 0.08    | 0.08   | 0.08    | 0.08    | 0.08    | 0.08    |
| 0.80        | 0.07    | 0.07   | 0.07    | 0.07    | 0.07    | 0.07    |
| 0.90        | 0.07    | 0.07   | 0.07    | 0.07    | 0.07    | 0.07    |
| 1.00        | 0.06    | 0.06   | 0.06    | 0.06    | 0.06    | 0.06    |
| 1.02        | 0.06    | 0.06   | 0.06    | 0.06    | 0.06    | 0.06    |
| 1.50        | 0.05    | 0.05   | 0.05    | 0.05    | 0.05    | 0.05    |
| 2.00        | 0.04    | 0.04   | 0.04    | 0.04    | 0.04    | 0.04    |
| 2.04        | 0.04    | 0.04   | 0.04    | 0.04    | 0.04    | 0.04    |
| 3.00        | 0.04    | 0.04   | 0.04    | 0.04    | 0.04    | 0.04    |
| 4.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 5.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 6.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 7.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 8.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 9.00        | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 10.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 11.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 12.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 13.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 14.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
| 15.00       | 0.03    | 0.03   | 0.03    | 0.03    | 0.03    | 0.03    |
energy 0.015 MeV and 15 MeV, respectively. Therefore, $(\lambda)_{3\text{Nd}} > (\lambda)_{1\text{Nd}} > (\lambda)_{2\text{Nd}} > (\lambda)_{3\text{Nd}} > (\lambda)_{4\text{Nd}} > (\lambda)_{5\text{Nd}}$. Results of the $\lambda$ confirm that the 5Nd-glasses have the best shielding capacity among all xNd-glasses.

Figure 9 depicts the dependence of the effective atomic number ($Z_{\text{eff}}$) on photon energy (E) for all xNd-glasses. According to (Fig. 9), the increasing of the Nd$_2$O$_3$ content in the fabricated glass matrix has a positive influence for

| Energy (MeV) | 3Nd FLUKA | 3Nd XCOM | $\Delta$ | 4Nd FLUKA | 4Nd XCOM | $\Delta$ | 5Nd FLUKA | 5Nd XCOM | $\Delta$
|---|---|---|---|---|---|---|---|---|---|
| 0.015 | 26.74 | 29.91 | -0.11 | 27.96 | 30.56 | -0.08 | 30.32 | 31.21 | -0.03 |
| 0.02 | 18.49 | 20.95 | -0.08 | 20.03 | 20.96 | -0.02 | 19.97 | 20.63 | -0.07 |
| 0.03 | 11.43 | 12.32 | -0.07 | 12.08 | 12.42 | -0.03 | 12.09 | 12.51 | -0.03 |
| 0.04 | 6.00 | 5.79 | 0.04 | 6.06 | 5.84 | -0.04 | 6.15 | 5.88 | 0.05 |
| 0.05 | 3.77 | 3.56 | 0.06 | 3.91 | 3.69 | 0.06 | 4.09 | 3.83 | 0.07 |
| 0.06 | 2.35 | 2.21 | 0.06 | 2.44 | 2.29 | 0.06 | 2.52 | 2.38 | 0.06 |
| 0.07 | 1.59 | 1.49 | 0.07 | 1.65 | 1.54 | 0.07 | 1.71 | 1.60 | 0.07 |
| 0.08 | 1.14 | 1.06 | 0.08 | 1.19 | 1.10 | 0.08 | 1.23 | 1.14 | 0.08 |
| 0.09 | 1.87 | 1.81 | -0.03 | 1.90 | 1.84 | -0.03 | 1.93 | 1.87 | -0.04 |
| 0.10 | 1.46 | 1.40 | -0.04 | 1.48 | 1.42 | -0.04 | 1.50 | 1.44 | -0.05 |
| 0.15 | 0.57 | 0.55 | -0.05 | 0.58 | 0.55 | -0.05 | 0.59 | 0.56 | -0.05 |
| 0.20 | 0.32 | 0.31 | -0.05 | 0.33 | 0.31 | -0.05 | 0.33 | 0.31 | -0.06 |
| 0.30 | 0.17 | 0.16 | -0.04 | 0.17 | 0.16 | -0.04 | 0.17 | 0.17 | -0.05 |
| 0.40 | 0.12 | 0.12 | -0.03 | 0.12 | 0.12 | -0.03 | 0.12 | 0.12 | -0.04 |
| 0.50 | 0.10 | 0.10 | -0.02 | 0.10 | 0.10 | -0.03 | 0.10 | 0.10 | -0.02 |
| 0.60 | 0.09 | 0.09 | -0.02 | 0.09 | 0.09 | -0.02 | 0.09 | 0.09 | -0.01 |
| 0.70 | 0.08 | 0.08 | -0.02 | 0.08 | 0.08 | -0.01 | 0.08 | 0.08 | -0.02 |
| 0.80 | 0.07 | 0.07 | -0.00 | 0.07 | 0.07 | -0.00 | 0.07 | 0.07 | -0.01 |
| 0.90 | 0.07 | 0.07 | -0.01 | 0.07 | 0.07 | -0.00 | 0.07 | 0.07 | -0.00 |
| 1.00 | 0.06 | 0.06 | -0.01 | 0.06 | 0.06 | -0.01 | 0.06 | 0.06 | -0.00 |
| 1.02 | 0.06 | 0.06 | 0.00 | 0.06 | 0.06 | 0.01 | 0.06 | 0.06 | 0.00 |
| 1.50 | 0.05 | 0.05 | 0.00 | 0.05 | 0.05 | 0.01 | 0.05 | 0.05 | 0.00 |
| 2.00 | 0.04 | 0.04 | -0.01 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 | 0.00 |
| 2.04 | 0.04 | 0.04 | -0.00 | 0.04 | 0.04 | 0.01 | 0.04 | 0.04 | 0.00 |
| 3.00 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 | 0.00 |
| 4.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 5.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 6.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 7.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 8.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 9.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 10.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 11.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 12.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 13.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 14.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
| 15.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 | 0.03 | 0.03 | 0.00 |
enriching the $Z_{\text{eff}}$. The $Z_{\text{eff}}$ is strongly dependent on the glass density. Results confirm that the $Z_{\text{eff}}$ parameter follows the order $(Z_{\text{eff}})^{5\text{Nd}} > (Z_{\text{eff}})^{4\text{Nd}} > (Z_{\text{eff}})^{3\text{Nd}} > (Z_{\text{eff}})^{2\text{Nd}} > (Z_{\text{eff}})^{1\text{Nd}} > (Z_{\text{eff}})^{0\text{Nd}}$.

For radiation shielding evaluating, exposure and energy absorption buildup factors (EBF and EABF) are urgent. They are considered as parameters to study the effect of multiple scatterings in the construction of new shielding...
glasses. Figures 10, 11a–f) present the variation of the EBF and EABF as a function of photon energy (E) at distinct mean free paths (0.5–40 mfp) for xNd-glasses, respectively. The EBF and EABF G–P fitting coefficients (b, c, a, Xk and d) of the fabricated 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses are tabulated in (Tables 4, 5, 6, 7, 8, 9). As shown in (Figs. 11, 12), at low penetration depths, EBFs and EABFs are small. Secondary scatterings take place as the depth of penetration increases, thus the photon buildup becomes greater at 10–40 mfp. At higher energies, both EBFs and EABFs begin to enhance due to the possibility of photons interacting with the glasses in this energy region changes with $Z^2$ (where PP interaction is dominant in this energy zone). In the energies preferred for radiation applications, 5Nd-glasses possess very low EBF and EABF values. This ensures that 5Nd-glasses have more effectiveness among all other glasses in absorbing photons.
Fig. 10 (a–f) Variation of exposure buildup factor (EBF) against Photon energy for all studied materials
Fig. 11 (a–f) Variation of energy absorption buildup factor (EABF) against Photon energy for all studied materials.
3.3 Fast neutron removal cross-section (FNRC)

The fast neutron shielding capacity of the fabricated xNd-glasses is evaluated by their fast neutron removal cross-section (FNRC). The obtained values of FNRC of the xNd-glasses are presented in (Fig. 12). Values of the FNRC were 0.1684, 0.1686, 0.1687, 0.1688, 0.1689, and 0.1690 cm⁻¹ for 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses, respectively. The result reveals that 0Nd-glasses (free with Nd³⁺ ions) include the optimum content of glass constituents that achieves the best neutron shielding ability. Compared to recently studied glass, graphite (FNRC = 0.077 cm⁻¹), S30 (FNRC = 0.0506) [40], and OC (FNRC = 0.094 cm⁻¹) [39], the fast neutron absorbing capacity of xNd-glasses is superior to that of other materials.

4 Conclusion

A series of six samples with high density of neodymium-cadmium lead-borate glasses of chemical composition xNd₂O₃/20CdO/20PbO/(57-x)B₂O₃/3Na₂O, where (0 ≤ x ≤ 5) wt% have been fabricated by a melt quenching process. Physical, structure characteristics as well as gamma-radiation and neutron shielding effectiveness in wide photon energy range 0.015–15 MeV have been examined. The amorphous nature of xNd-glasses was confirmed, where there was a lack of their crystallinity. Density of the fabricated xNd-glasses was gradually increased from 5.006 g/cm³ for 0Nd-glass sample with free of Nd³⁺ ions to 5.245 g/cm³ for 5Nd-glass sample enrich with Nd³⁺ ions. In terms of the MAC, introducing Nd³⁺ ions in the glass matrix has a direct constructive influence on the
obtained values of MAC. The minimum MAC at 15 MeV were 0.027 cm²/g, 0.027 cm²/g, 0.030 cm²/g, 0.030 cm²/g, and 0.030 cm²/g for 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses, respectively. The maximum of MAC at 0.015 MeV were 25.780 cm²/g, 26.051 cm²/g, 26.177 cm²/g, 26.737 cm²/g, 26.963 cm²/g, and 30.322 cm²/g for 0Nd, 1Nd, 2Nd, 3Nd, 4Nd, and 5Nd glasses, respectively. Generally, the MAC trend follows the order (MAC)_{5Nd} > (MAC)_{4Nd} > (MAC)_{3Nd} > (MAC)_{2Nd} > (MAC)_{1Nd} > (MAC)_{0Nd}. The LAC has a similar trend as MAC for all xNd-glasses. In terms of the $T_{1/2}$, the 5Nd-glasses with high density (5.245 g/cm³) possessed the minimum $T_{1/2}$ values and it varied from 0.004 cm at 15 keV to 4.301 cm at 15 MeV. Furthermore, 0Nd-glasses with low density (5.006 g/cm³) possessed the maximum $T_{1/2}$ values changes from 0.005 cm at 15 keV to 4.719 cm at 15 MeV. Therefore, the $T_{1/2}$ of the fabricated

| Energy (MeV) | Z_{eq} | G-P fitting parameters for EBF | G-P fitting parameters for EABF |
|-------------|-------|-------------------------------|-------------------------------|
|             |       | a    | b    | c    | d    | X_k   | a    | b    | c    | d    | X_k   |
| 0.015       | 6.47  | 0.158 | 1.312 | 0.508 | −0.079 | 14.290 | 0.158 | 1.319 | 0.506 | −0.078 | 14.493 |
| 0.020       | 6.49  | 0.105 | 1.708 | 0.658 | −0.051 | 15.775 | 0.105 | 1.727 | 0.658 | −0.051 | 15.670 |
| 0.030       | 6.49  | 0.014 | 3.054 | 0.993 | −0.016 | 14.305 | 0.014 | 3.205 | 0.994 | −0.015 | 14.358 |
| 0.040       | 6.50  | 0.090 | 4.580 | 1.504 | 0.037  | 13.739 | −0.088 | 4.507 | 1.495 | 0.036  | 13.945 |
| 0.050       | 6.50  | −0.140 | 5.838 | 1.864 | 0.061  | 14.085 | −0.136 | 5.229 | 1.839 | 0.058  | 14.209 |
| 0.060       | 6.51  | −0.175 | 6.318 | 2.149 | 0.079  | 14.084 | −0.168 | 5.277 | 2.094 | 0.074  | 14.193 |
| 0.080       | 6.51  | −0.210 | 6.058 | 2.475 | 0.094  | 13.836 | −0.194 | 4.889 | 2.349 | 0.083  | 14.078 |
| 0.100       | 6.52  | −0.213 | 5.525 | 2.550 | 0.093  | 14.395 | −0.195 | 4.495 | 2.388 | 0.080  | 14.666 |
| 0.150       | 6.52  | −0.226 | 4.159 | 2.643 | 0.100  | 14.124 | −0.196 | 3.645 | 2.387 | 0.078  | 14.663 |
| 0.200       | 6.52  | −0.219 | 3.558 | 2.541 | 0.097  | 14.126 | −0.187 | 3.277 | 2.273 | 0.076  | 14.786 |
| 0.300       | 6.53  | −0.194 | 3.046 | 2.265 | 0.084  | 14.219 | −0.171 | 2.821 | 2.089 | 0.068  | 14.550 |
| 0.400       | 6.53  | −0.176 | 2.765 | 2.076 | 0.074  | 13.788 | −0.152 | 2.624 | 1.910 | 0.062  | 14.494 |
| 0.500       | 6.53  | −0.157 | 2.592 | 1.914 | 0.069  | 14.157 | −0.138 | 2.459 | 1.792 | 0.058  | 14.989 |
| 0.600       | 6.53  | −0.142 | 2.468 | 1.788 | 0.059  | 13.881 | −0.122 | 2.379 | 1.672 | 0.048  | 14.573 |
| 0.800       | 6.53  | −0.121 | 2.273 | 1.630 | 0.056  | 13.927 | −0.107 | 2.200 | 1.553 | 0.045  | 14.151 |
| 1.000       | 6.53  | −0.102 | 2.154 | 1.505 | 0.047  | 13.885 | −0.089 | 2.099 | 1.443 | 0.038  | 14.486 |
| 1.500       | 5.79  | −0.072 | 2.023 | 1.323 | 0.036  | 13.707 | −0.060 | 1.940 | 1.277 | 0.027  | 14.302 |
| 2.000       | 5.76  | −0.045 | 1.911 | 1.197 | 0.022  | 14.089 | −0.038 | 1.841 | 1.171 | 0.015  | 14.442 |
| 3.000       | 5.76  | −0.015 | 1.760 | 1.061 | 0.007  | 12.153 | −0.011 | 1.715 | 1.051 | 0.003  | 14.154 |
| 4.000       | 5.75  | 0.004  | 1.660 | 0.984 | −0.007 | 23.669 | 0.003  | 1.627 | 0.989 | −0.002 | 13.315 |
| 5.000       | 5.75  | 0.017  | 1.581 | 0.938 | −0.011 | 14.604 | 0.015  | 1.566 | 0.945 | −0.008 | 14.767 |
| 6.000       | 5.75  | 0.026  | 1.529 | 0.907 | −0.015 | 14.490 | 0.029  | 1.520 | 0.901 | −0.018 | 12.541 |
| 8.000       | 5.75  | 0.037  | 1.442 | 0.869 | −0.032 | 16.393 | 0.035  | 1.435 | 0.877 | −0.017 | 11.884 |
| 10.000      | 5.75  | 0.042  | 1.375 | 0.855 | −0.020 | 12.606 | 0.040  | 1.381 | 0.858 | −0.022 | 14.365 |
| 15.000      | 5.75  | 0.046  | 1.278 | 0.838 | −0.028 | 14.969 | 0.047  | 1.286 | 0.837 | −0.031 | 15.470 |
Fabrication, physical, structure characteristics, neutron and radiation shielding capacity...

The \((T_{1/2})^0_{\text{Nd}} > (T_{1/2})^1_{\text{Nd}} > (T_{1/2})^2_{\text{Nd}} > (T_{1/2})^3_{\text{Nd}} > (T_{1/2})^4_{\text{Nd}} > (T_{1/2})^5_{\text{Nd}}\), the \(Z_{\text{eff}}\) parameter follows the order \((Z_{\text{eff}})_{5\text{Nd}} > (Z_{\text{eff}})_{4\text{Nd}} > (Z_{\text{eff}})_{3\text{Nd}} > (Z_{\text{eff}})_{2\text{Nd}} > (Z_{\text{eff}})_{1\text{Nd}} > (Z_{\text{eff}})_{0\text{Nd}}\). In the energies preferred for radiation applications, \(5\text{Nd}-\text{glasses}\) possess very low EBF and EABF values. This ensures that \(5\text{Nd}-\text{glasses}\) have more effectiveness among all other glasses in absorbing photons. The FNRC of the fabricated glasses is improved as the \(\text{Nd}^{3+}\) content increases in the glass matrix. The obtained results confirm that the \(5\text{Nd}-\text{glasses}\) have more capacity compared to other proposed glasses in absorbing photons.

| Energy (MeV) | \(Z_{\text{eq}}\) | G-P fitting parameters for EBF | G-P fitting parameters for EABF |
|-------------|----------------|-------------------------------|-----------------------------|
|              | \(a\) | \(b\) | \(c\) | \(d\) | \(X_k\) | \(a\) | \(b\) | \(c\) | \(d\) | \(X_k\) |
| 0.015        | 6.25 | 0.153 | 1.346 | 0.522 | −0.075 | 14.299 | 0.156 | 1.355 | 0.515 | −0.078 | 14.459 |
| 0.020        | 6.26 | 0.093 | 1.784 | 0.692 | −0.046 | 16.135 | 0.092 | 1.805 | 0.694 | −0.045 | 16.027 |
| 0.030        | 6.27 | −0.004 | 3.260 | 1.065 | −0.005 | 13.637 | −0.005 | 3.439 | 1.065 | −0.004 | 13.553 |
| 0.040        | 6.27 | −0.107 | 4.886 | 1.612 | 0.046 | 13.816 | −0.105 | 4.759 | 1.603 | 0.044 | 14.015 |
| 0.050        | 6.27 | −0.154 | 6.227 | 1.974 | 0.066 | 14.199 | −0.149 | 5.393 | 1.941 | 0.063 | 14.331 |
| 0.060        | 6.27 | −0.185 | 6.717 | 2.254 | 0.083 | 14.284 | −0.176 | 5.343 | 2.180 | 0.076 | 14.402 |
| 0.080        | 6.28 | −0.217 | 6.373 | 2.571 | 0.097 | 14.105 | −0.199 | 4.877 | 2.411 | 0.083 | 14.404 |
| 0.100        | 6.28 | −0.225 | 5.687 | 2.671 | 0.098 | 14.397 | −0.201 | 4.411 | 2.459 | 0.081 | 14.761 |
| 0.150        | 6.29 | −0.235 | 4.257 | 2.741 | 0.103 | 14.131 | −0.200 | 3.591 | 2.433 | 0.079 | 14.794 |
| 0.200        | 6.29 | −0.225 | 3.642 | 2.610 | 0.101 | 14.547 | −0.191 | 3.231 | 2.313 | 0.076 | 14.779 |
| 0.300        | 6.29 | −0.201 | 3.090 | 2.330 | 0.089 | 14.303 | −0.173 | 2.811 | 2.107 | 0.069 | 14.730 |
| 0.400        | 6.29 | −0.183 | 2.799 | 2.129 | 0.077 | 13.649 | −0.152 | 2.626 | 1.917 | 0.062 | 14.646 |
| 0.500        | 6.29 | −0.163 | 2.620 | 1.957 | 0.074 | 14.171 | −0.138 | 2.458 | 1.796 | 0.060 | 15.453 |
| 0.600        | 6.29 | −0.146 | 2.501 | 1.816 | 0.060 | 13.758 | −0.121 | 2.388 | 1.668 | 0.047 | 14.751 |
| 0.800        | 6.29 | −0.126 | 2.290 | 1.657 | 0.059 | 13.871 | −0.108 | 2.199 | 1.557 | 0.045 | 14.124 |
| 1.000        | 6.29 | −0.106 | 2.171 | 1.522 | 0.050 | 13.839 | −0.091 | 2.094 | 1.451 | 0.039 | 14.361 |
| 1.500        | 5.71 | −0.073 | 2.028 | 1.328 | 0.037 | 13.714 | −0.061 | 1.939 | 1.278 | 0.027 | 14.306 |
| 2.000        | 5.69 | −0.046 | 1.915 | 1.198 | 0.023 | 14.120 | −0.038 | 1.840 | 1.172 | 0.016 | 14.414 |
| 3.000        | 5.69 | −0.015 | 1.762 | 1.061 | 0.007 | 12.204 | −0.012 | 1.715 | 1.051 | 0.003 | 14.046 |
| 4.000        | 5.68 | 0.005 | 1.662 | 0.984 | −0.007 | 23.109 | 0.003 | 1.627 | 0.989 | −0.002 | 13.456 |
| 5.000        | 5.68 | 0.017 | 1.582 | 0.937 | −0.011 | 14.634 | 0.015 | 1.566 | 0.944 | −0.008 | 14.687 |
| 6.000        | 5.68 | 0.026 | 1.530 | 0.907 | −0.015 | 14.527 | 0.029 | 1.521 | 0.901 | −0.017 | 12.594 |
| 8.000        | 5.68 | 0.037 | 1.442 | 0.869 | −0.031 | 16.206 | 0.036 | 1.436 | 0.876 | −0.018 | 11.823 |
| 10.000       | 5.68 | 0.042 | 1.376 | 0.854 | −0.020 | 12.674 | 0.040 | 1.381 | 0.858 | −0.022 | 14.377 |
| 15.000       | 5.68 | 0.047 | 1.279 | 0.838 | −0.028 | 14.889 | 0.047 | 1.287 | 0.837 | −0.031 | 15.352 |
| Energy (MeV) | \( Z_{eq} \) | G-P fitting parameters for EBF | G-P fitting parameters for EABF |
|-------------|----------------|--------------------------------|--------------------------------|
|             | \( a \) | \( b \) | \( c \) | \( d \) | \( X_k \) | \( a \) | \( b \) | \( c \) | \( d \) | \( X_k \) |
| 0.015       | 6.57  | 0.161 | 1.297 | 0.502 | −0.080 | 14.287 | 0.159 | 1.303 | 0.502 | −0.078 | 14.508 |
| 0.020       | 6.57  | 0.109 | 1.679 | 0.645 | −0.054 | 15.639 | 0.110 | 1.698 | 0.644 | −0.054 | 15.535 |
| 0.030       | 6.57  | 0.020 | 2.984 | 0.969 | −0.020 | 14.532 | 0.020 | 3.125 | 0.969 | −0.019 | 14.632 |
| 0.040       | 6.57  | −0.084 | 4.481 | 1.469 | 0.035 | 13.715 | −0.082 | 4.426 | 1.461 | 0.033 | 13.922 |
| 0.050       | 6.57  | −0.136 | 5.716 | 1.830 | 0.059 | 14.049 | −0.133 | 5.178 | 1.807 | 0.056 | 14.171 |
| 0.060       | 6.58  | −0.172 | 6.197 | 2.117 | 0.078 | 14.024 | −0.165 | 5.257 | 2.068 | 0.073 | 14.130 |
| 0.080       | 6.58  | −0.207 | 5.966 | 2.446 | 0.093 | 13.757 | −0.193 | 4.893 | 2.330 | 0.083 | 13.983 |
| 0.100       | 6.58  | −0.210 | 5.497 | 2.515 | 0.091 | 14.394 | −0.193 | 4.519 | 2.367 | 0.080 | 14.639 |
| 0.150       | 6.59  | −0.224 | 4.132 | 2.615 | 0.099 | 14.122 | −0.195 | 3.660 | 2.374 | 0.078 | 14.626 |
| 0.200       | 6.59  | −0.218 | 3.534 | 2.522 | 0.096 | 14.010 | −0.186 | 3.290 | 2.262 | 0.076 | 14.788 |
| 0.300       | 6.59  | −0.192 | 3.034 | 2.247 | 0.083 | 14.196 | −0.171 | 2.824 | 2.084 | 0.068 | 14.501 |
| 0.400       | 6.59  | −0.174 | 2.755 | 2.062 | 0.073 | 13.825 | −0.152 | 2.623 | 1.908 | 0.061 | 14.454 |
| 0.500       | 6.60  | −0.156 | 2.584 | 1.903 | 0.068 | 14.153 | −0.138 | 2.460 | 1.791 | 0.058 | 14.866 |
| 0.600       | 6.60  | −0.141 | 2.459 | 1.781 | 0.059 | 13.913 | −0.122 | 2.377 | 1.673 | 0.048 | 14.526 |
| 0.800       | 6.60  | −0.120 | 2.268 | 1.623 | 0.055 | 13.941 | −0.107 | 2.200 | 1.551 | 0.044 | 14.158 |
| 1.000       | 6.60  | −0.101 | 2.150 | 1.501 | 0.047 | 13.897 | −0.089 | 2.100 | 1.441 | 0.037 | 14.519 |
| 1.500       | 6.08  | −0.068 | 2.007 | 1.307 | 0.032 | 13.790 | −0.060 | 1.940 | 1.275 | 0.027 | 14.298 |
| 2.000       | 6.06  | −0.044 | 1.895 | 1.191 | 0.020 | 13.987 | −0.037 | 1.842 | 1.168 | 0.014 | 14.492 |
| 3.000       | 6.05  | −0.014 | 1.750 | 1.058 | 0.006 | 12.996 | −0.011 | 1.715 | 1.050 | 0.003 | 14.401 |
| 4.000       | 6.05  | −0.004 | 1.652 | 0.986 | −0.008 | 25.086 | 0.003 | 1.626 | 0.989 | −0.002 | 12.903 |
| 5.000       | 6.05  | 0.017  | 1.574 | 0.939 | −0.011 | 14.450 | 0.014 | 1.564 | 0.946 | −0.007 | 14.966 |
| 6.000       | 6.05  | 0.026  | 1.525 | 0.908 | −0.015 | 14.258 | 0.029 | 1.518 | 0.902 | −0.018 | 12.607 |
| 8.000       | 6.05  | 0.038  | 1.439 | 0.869 | −0.034 | 16.805 | 0.033 | 1.430 | 0.883 | −0.016 | 12.106 |
| 10.000      | 6.04  | 0.042  | 1.372 | 0.856 | −0.021 | 12.440 | 0.040 | 1.377 | 0.860 | −0.022 | 14.320 |
| 15.000      | 6.05  | 0.046  | 1.276 | 0.841 | −0.030 | 15.259 | 0.047 | 1.282 | 0.838 | −0.033 | 15.865 |

Table 7 (EBF and EABF) G–P fitting coefficients \((b, c, a, X_k, d)\) of 4Nd sample
Table 9 (EBF and EABF) G–P fitting coefficients (b, c, a, Xk and d) of 5Nd sample

| Energy (MeV) | Z_{eq} | G-P Fitting Parameters for EBF | G-P Fitting Parameters for EABF |
|-------------|--------|-------------------------------|-------------------------------|
|             |        | a   | b    | c     | d    | Xk       | a   | b    | c     | d    | Xk       |
| 0.015       | 6.61   | 0.162 | 1.290 | 0.499 | -0.081 | 14.285   | 0.159 | 1.296 | 0.500 | -0.078 | 14.515   |
| 0.020       | 6.62   | 0.111 | 1.665 | 0.640 | -0.055 | 15.576   | 0.113 | 1.684 | 0.637 | -0.055 | 15.472   |
| 0.030       | 6.61   | 0.023 | 2.951 | 0.957 | -0.022 | 16.393   | 0.023 | 3.087 | 0.958 | -0.020 | 14.761   |
| 0.040       | 6.61   | -0.081 | 4.434 | 1.452 | 0.033 | 13.703   | -0.079 | 4.387 | 1.444 | 0.031 | 13.911   |
| 0.050       | 6.61   | -0.134 | 5.657 | 1.814 | 0.058 | 14.032   | -0.131 | 5.154 | 1.792 | 0.055 | 14.153   |
| 0.060       | 6.61   | -0.170 | 6.137 | 2.102 | 0.077 | 13.994   | -0.164 | 5.247 | 2.055 | 0.073 | 14.098   |
| 0.080       | 6.62   | -0.206 | 5.920 | 2.432 | 0.093 | 13.717   | -0.193 | 4.894 | 2.321 | 0.083 | 13.935   |
| 0.100       | 6.62   | -0.208 | 5.455 | 2.497 | 0.091 | 14.394   | -0.192 | 4.532 | 2.357 | 0.079 | 14.625   |
| 0.150       | 6.62   | -0.222 | 4.117 | 2.601 | 0.099 | 14.121   | -0.195 | 3.668 | 2.368 | 0.078 | 14.607   |
| 0.200       | 6.62   | -0.217 | 3.522 | 2.512 | 0.095 | 13.950   | -0.185 | 3.296 | 2.256 | 0.076 | 14.789   |
| 0.300       | 6.63   | -0.191 | 3.027 | 2.238 | 0.082 | 14.184   | -0.170 | 2.825 | 2.082 | 0.068 | 14.475   |
| 0.400       | 6.63   | -0.173 | 2.750 | 2.054 | 0.073 | 13.846   | -0.152 | 2.623 | 1.908 | 0.061 | 14.432   |
| 0.500       | 6.63   | -0.155 | 2.580 | 1.897 | 0.068 | 14.151   | -0.138 | 2.460 | 1.791 | 0.058 | 14.798   |
| 0.600       | 6.63   | -0.140 | 2.454 | 1.777 | 0.059 | 13.931   | -0.122 | 2.376 | 1.674 | 0.048 | 14.500   |
| 0.800       | 6.63   | -0.119 | 2.266 | 1.619 | 0.054 | 13.949   | -0.106 | 2.201 | 1.551 | 0.044 | 14.161   |
| 1.000       | 6.63   | -0.101 | 2.147 | 1.499 | 0.046 | 13.903   | -0.088 | 2.101 | 1.440 | 0.037 | 14.538   |
| 1.500       | 6.64   | -0.066 | 2.000 | 1.301 | 0.031 | 13.971   | -0.060 | 1.938 | 1.276 | 0.026 | 14.313   |
| 2.000       | 6.64   | -0.043 | 1.889 | 1.188 | 0.020 | 13.981   | -0.038 | 1.841 | 1.169 | 0.015 | 14.394   |
| 3.000       | 6.64   | -0.014 | 1.744 | 1.059 | 0.006 | 12.436   | -0.011 | 1.713 | 1.052 | 0.003 | 14.052   |
| 4.000       | 6.64   | 0.004 | 1.648 | 0.987 | -0.007 | 23.349   | 0.004 | 1.627 | 0.988 | -0.003 | 13.164   |
| 5.000       | 6.64   | 0.017 | 1.572 | 0.939 | -0.011 | 14.289   | 0.016 | 1.565 | 0.943 | -0.009 | 14.697   |
| 6.000       | 6.65   | 0.027 | 1.523 | 0.906 | -0.016 | 13.926   | 0.027 | 1.514 | 0.908 | -0.018 | 13.443   |
| 8.000       | 6.65   | 0.037 | 1.436 | 0.872 | -0.031 | 15.853   | 0.035 | 1.430 | 0.881 | -0.018 | 12.094   |
| 10.000      | 6.65   | 0.041 | 1.370 | 0.859 | -0.021 | 12.770   | 0.040 | 1.375 | 0.861 | -0.022 | 14.322   |
| 15.000      | 6.65   | 0.046 | 1.275 | 0.841 | -0.031 | 15.218   | 0.047 | 1.281 | 0.838 | -0.033 | 15.705   |

Fig. 12 Variation neutron removal cross section of the prepared xNd-glasses

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

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