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Research Article

Investigation of Gamma and Neutron Shielding Parameters for Borate Glasses Containing NiO and PbO

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The mass attenuation coefficients, μ/ρ, half-value layer, HVL, tenth-value layer, TVL, effective atomic numbers, Z_{PIeff}, and effective electron densities, $N_{e,\mathrm{eff}}$, of borate glass sample systems of (100-x-y) $Na_2B_4O_7 : x$PbO : yNiO (where x and $y = 0, 2, 4, 6, 8$, and 10 weight percentage) containing PbO and NiO, with potential gamma ray and neutron shielding applications, have been investigated. The gamma ray interaction parameters, μ/ρ, HVL, TVL, Z_{PIeff}, and $N_{e,\mathrm{eff}}$, were computed for photon energy range 1 keV–100 GeV. The macroscopic fast neutron removal cross-sections (Σ_R) have also been calculated. Appreciable variations were noted for all the interaction parameters by varying the photon energy and the chemical composition of the glass samples. The better shielding properties of borate glass samples containing PbO were found. These results indicated that borate glass samples are a good radiation shielding material.

1. Introduction

Interaction of energetic radiations X/γ-ray and neutron with the material is essential in radiation technologies, medical, nuclear engineering, agriculture, space technology, industries, and other shielding applications. Transparent radiation shielding materials have been an interesting area in nuclear engineering to provide the adequate radiation protection as well as visibility through it. Glasses are found to perform the double functions of being transparent to visible light and absorbing the radiations, thus providing radiation shielding to the observer. The silicate glasses are found to be the most commonly commercial glasses owning to ease of fabrication and excellent transparency to the visible light [1]. The transparent property of the glass makes it useful for optical windows in nuclear reactors and isotope technology centers. The optical windows play a crucial role in operation and maintenance of nuclear facilities for complete visual inspection without radiation exposure.

Lead and lead glasses are easily available for shielding of the gamma rays and neutrons due to high densities and atomic numbers [2]. The high atomic number (Z) offers large gamma ray interaction cross-section for gamma rays and density plays vital role in neutron interaction. Nowadays, bismuth (Bi) and barium (Ba) are playing an analogous role in radiation shielding by replacing lead. The glasses containing low Z elements (H, Li, B, C, etc.) are another group of the glasses required for neutron radiation shielding produced specially in nuclear reactors and accelerators. It has been found that gamma photon in reactor is in range of 0.10 to 10 MeV and prompt neutron energy spectrum ranges from 0.18 to 12 MeV with average neutron energy 1 to 2 MeV during uranium fission [3]. Therefore boron containing glass materials are found to be a potential candidate for neutron radiation shielding.

The absorption of gamma ray is being represented by the mass attenuation coefficients, atomic cross-sections, effective atomic numbers, and effective electron densities. The attenuation coefficient is defined as the probability of radiation interaction with a material per unit length [4]. The effective atomic number is a convenient parameter for evaluation of gamma ray interaction for a compound or mixtures. The other important parameter for interaction is an electron density which is defined as the electrons per unit mass

Table 1: Borate glass samples containing PbO and NiO for shielding.

Glass sample	Densities ($g\,cm^{-3}$)	Weight percentage		
		$Na_2B_4O_7$	PbO	NiO
S_1	2.64 ± 0.02	100	0	0
S_2	2.67 ± 0.04	90	0	10
S_3	2.67 ± 0.05	90	2	8
S_4	2.71 ± 0.03	90	4	6
S_5	2.73 ± 0.02	90	6	4
S_6	2.75 ± 0.02	90	8	2
S_7	2.78 ± 0.01	90	10	0

of the absorber. Mass attenuation coefficients of elements, compounds, and mixtures are taken from standard tables [5] developed as XCOM program at energies 1 keV to 100 GeV. The XCOM program has been converted to user-friendly windows platform WinXcom [6].

Various investigators have reported gamma ray interaction parameters of phosphate, lead, bismuth, silicate, and fly-ash glasses [2, 7–11]. NiO is being used for making smoky colored glasses and for decolouring lead crystal glasses [12]. The gamma ray attenuation coefficients of borate glasses are found for 1173 and 1332 keV [13]. However detailed study on gamma ray and neutron interaction for the colored borate glasses containing NiO is not found in the literatures. This encouraged us to investigate the gamma and neutron interaction parameters of borate glasses, potential shielding materials. Therefore, we have calculated the mass attenuation coefficients, μ/ρ, half-value layer, HVL, tenth-value layer, TVL, effective atomic numbers, Z_{PIeff}, and effective electron densities, $N_{e,\mathrm{eff}}$, of borate glass samples containing PbO and NiO given in Table 1. The study shall be useful for shielding against gamma ray and neutron applications.

2. Theoretical Background and Computational Work

2.1. Gamma Ray Interaction Parameters. The compositions of borate glass samples containing PbO and NiO are given in Table 1. The transmission of gamma ray is dependent upon the material thickness, t, and linear attenuation coefficient, μ. The μ value is a parameter which is dependent upon the absorber density, its atomic number, and energy of incident photon. The linear attenuation coefficients of the borate glass samples are calculated by multiplication of mass attenuation coefficients, μ/ρ, and density. The μ/ρ values of the borate glasses are calculated by mixture rule ($(\mu/\rho)_{\mathrm{glass}} = \sum_i^n w_i(\mu/\rho)_i$), where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the ith element by using WinXcom [6]. The quantity w_i is given by $w_i = n_i A_i / \sum_j^n n_j A_j$ with condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of the ith element and n_i is the number of formula units in the compounds. The half-value layer, HVL (HVL $= 0.6932/\mu$), and tenth-value layer, TVL (TVL $= 2.303/\mu$), are inversely proportional to μ values.

The effective atomic numbers (Z_{PIeff}) for total photon interaction are given by [14]

$$Z_{PIeff} = \frac{\sum_i f_i\ A_i(\mu/\rho)_i}{\sum_j f_j\left(A_j/Z_j\right)(\mu/\rho)_j}, \tag{1}$$

where f_i is molar fraction in the mixture, μ is linear attenuation coefficient, ρ is density, μ/ρ is mass attenuation coefficient, A is atomic weight, Z is atomic number, and the ratio, A/Z, between the atomic mass and the atomic number is approximately constant. The electron density is given by $N_{e,\mathrm{eff}} = N_A Z/A$ which is generalized as

$$N_{e,\mathrm{eff}} = N_A \frac{nZ_{PIeff}}{\sum_i n_i A_i} = N_A \frac{Z_{PIeff}}{\langle A\rangle}, \tag{2}$$

where n_i is the number of atoms of the ith constituent element, n is the total number of atoms, and $\langle A\rangle$ is average atomic mass of the glass samples.

2.2. Macroscopic Fast Neutron Removal Cross-Sections. The effective removal cross-section of compounds and homogenous mixtures is calculated using the value of Σ_R (cm^{-1}) or Σ_R/ρ (cm^2/g) of the elements in the compounds by mixture rule [4]. The detailed calculation procedure for Σ_R can be found various recent literatures for alloys [15], fly-ash brick materials [16], bismuth borosilicate glasses [17], oxide dispersion strengthened steels [18] and building materials [19]. The Σ_R/ρ values of elements have been taken from Kaplan and Chilton [20, 21].

3. Results and Discussion

In the present investigation, the mass attenuation coefficients, μ/ρ, half-value layer, HVL, tenth-value layer, TVL, effective atomic numbers, Z_{PIeff}, and effective electron densities, $N_{e,\mathrm{eff}}$, of borate glasses containing PbO and NiO were calculated. The variation of μ/ρ, HVL, TVL, Z_{PIeff}, and $N_{e,\mathrm{eff}}$ is shown in Figures 1–5 respectively. The macroscopic fast neutron removal cross section of the borate glasses is given in the Table 5.

3.1. Mass Attenuation Coefficients. The variation of mass attenuation coefficients, μ/ρ, of the borate glass samples with photon energy ranging from 1 keV to 100 GeV is shown in Figure 1. From Figure 1 one can observe that the μ/ρ values of the borate glass samples are very high in photoelectric absorption region, reduce gradually, and become lowest in Compton scattering region. After it again starts increasing and becomes constant at around photon energy of 100 MeV in pair production region, various peaks in μ/ρ values are observed for the glasses in photoelectric absorption region due to K-edge absorption (1.072, 8.333, and 8.8 keV), L-edge absorption (1.008, 1.586, 1.52, and 1.304 keV), and M-edge absorption (3.851, 3.554, 3.066, 2.586, and 2.484 keV). The K, L, and M absorption energy values of the constituent elements (Na, Ni, and Pb) are given in Table 2. The borate glass sample containing maximum PbO composition (S_7) shows

Table 2: Photon energies (in keV) of absorption edges of K, L, and M.

Element	Z	Energy (keV)								
		K	L			M				
			L_1	L_2	L_3	M_1	M_2	M_3	M_4	M_5
B	5	—	—	—	—	—	—	—	—	—
O	8	—	—	—	—	—	—	—	—	—
Na	11	1.072	—	—	—	—	—	—	—	—
Ni	28	8.333	1.008	—	—	—	—	—	—	—
Pb	82	8.800	1.586	1.520	1.304	3.851	3.554	3.066	2.586	2.484

Table 3: Effective atomic numbers (Z_{PIeff}) of borate glasses at different energies (MeV) for total photon interaction.

Glass sample	$\langle Z \rangle$	Z_{PIeff} lower	Z_{PIeff} upper	Z_{PIeff}								
				10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}
S_1	7.47	7.54	9.03	7.69	9.02	7.60	7.54	7.66	7.92	7.95	7.94	7.94
S_2	8.00	7.75	14.31	8.38	14.04	8.20	7.75	7.99	8.49	8.54	8.53	8.53
S_3	8.00	7.84	21.46	8.47	15.25	12.48	7.86	8.24	9.08	9.15	9.14	9.14
S_4	8.02	7.95	27.76	8.56	16.52	16.30	7.96	8.49	9.66	9.75	9.74	9.73
S_5	8.04	8.03	33.30	8.65	17.84	19.71	8.07	8.74	10.23	10.35	10.33	10.32
S_6	8.06	8.12	38.22	8.74	19.22	22.79	8.18	8.99	10.79	10.93	10.91	10.90
S_7	8.08	8.22	42.86	8.85	20.81	25.76	8.29	9.25	11.39	11.55	11.52	11.52

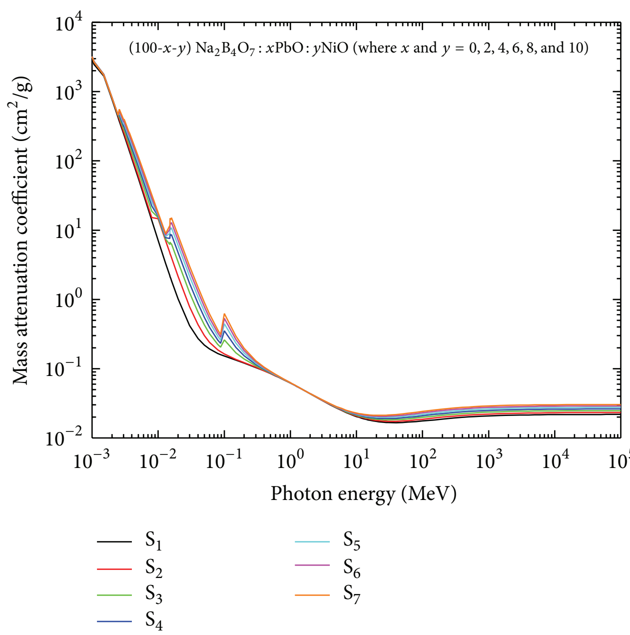


Figure 1: Variation of mass attenuation coefficients of the borate glasses containing PbO and NiO with photon energy for range 1 keV to 100 GeV.

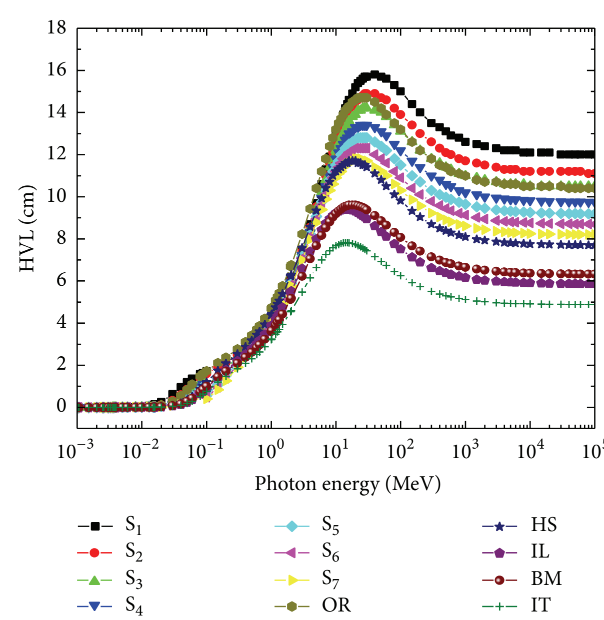


Figure 2: Variation of half-value layer of the borate glasses containing PbO and NiO with photon energy for range 1 keV to 100 GeV.

multiple peaks due to K, L, and M absorption edges whereas borate glass sample without PbO and NiO (S_1) is found to be with single peak due to Na element. These variations can be explained by the partial photon interactions such as photoelectric absorption for low-energy, Compton scattering for intermediate-energy, and pair production (nuclear and electric) for high-energy regions.

Initially at 1 keV energy, the values of μ/ρ are very large (order of 10^3) which decrease sharply. At low-energy range ($0.01\,\text{MeV} < E < 0.1\,\text{MeV}$), the maximum value of μ/ρ was found. The values of μ/ρ of all the borate glass samples become of order of 10^{-1} as photon energy reaches 100 keV. Hence the μ/ρ values decrease rapidly in low-energy region. This shows the dominance of photoelectric absorption in low-photon energy region. It can also be observed that there is

Table 4: Effective electron densities ($N_{e,\mathrm{eff}}$) of borate glasses at different energies (MeV) for total photon interaction.

Glass sample	$\langle N \rangle$	$N_{e,\mathrm{eff}}$ lower	$N_{e,\mathrm{eff}}$ upper	$N_{e,\mathrm{eff}} \times 10^{23}$								
				10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}
S_1	2.92	3.05	3.65	3.11	3.65	3.07	3.05	3.10	3.20	3.21	3.21	3.21
S_2	3.04	3.04	5.61	3.28	5.50	3.21	3.04	3.13	3.33	3.35	3.34	3.34
S_3	3.00	3.04	8.32	3.28	5.91	4.84	3.05	3.20	3.52	3.55	3.54	3.54
S_4	2.97	3.04	10.60	3.28	6.32	6.24	3.05	3.25	3.70	3.73	3.73	3.72
S_5	2.94	3.03	12.58	3.27	6.74	7.45	3.05	3.30	3.86	3.91	3.90	3.90
S_6	2.91	3.03	14.25	3.26	7.16	8.50	3.05	3.35	4.02	4.07	4.07	4.06
S_7	2.88	3.02	15.78	3.25	7.65	9.48	3.05	3.40	4.19	4.25	4.24	4.24

Table 5: Macroscopic fast neutron removal cross-section of the borate glasses.

(a)

Ele.	S_1		S_2		S_3		S_4	
	PD	Σ_R (cm^{-1})	PD	Σ_R (cm^{-1})	PD	Σ_R (cm^{-1})	PD	Σ_R (cm^{-1})
Na	$6.03E-01$	$2.06E-02$	$5.86E-01$	$2.00E-02$	$5.77E-01$	$1.97E-02$	$5.77E-01$	$1.97E-02$
B	$5.67E-01$	$3.26E-02$	$5.51E-01$	$3.17E-02$	$5.43E-01$	$3.12E-02$	$5.42E-01$	$3.12E-02$
O	$1.47E+00$	$6.02E-02$	$1.43E+00$	$5.88E-02$	$1.42E+00$	$5.84E-02$	$1.44E+00$	$5.89E-02$
Ni	$0.00E+00$	$0.00E+00$	$9.81E-02$	$1.86E-03$	$7.73E-02$	$1.47E-03$	$5.79E-02$	$1.10E-03$
Pb	$0.00E+00$	$0.00E+00$	$0.00E+00$	$0.00E+00$	$4.89E-02$	$5.09E-04$	$9.77E-02$	$1.02E-03$
	2.64	**0.1134**	2.67	**0.1124**	2.67	**0.1112**	2.71	**0.1118**

(b)

Ele.	S_5		S_6		S_7	
	PD	Σ_R (cm^{-1})	PD	Σ_R (cm^{-1})	PD	Σ_R (cm^{-1})
Na	$5.72E-01$	$1.95E-02$	$5.68E-01$	$1.94E-02$	$5.73E-01$	$1.95E-02$
B	$5.38E-01$	$3.09E-02$	$5.34E-01$	$3.07E-02$	$5.39E-01$	$3.10E-02$
O	$1.44E+00$	$5.89E-02$	$1.44E+00$	$5.89E-02$	$1.43E+00$	$5.84E-02$
Ni	$3.83E-02$	$7.28E-04$	$1.90E-02$	$3.61E-04$	$0.00E+00$	$0.00E+00$
Pb	$1.45E-01$	$1.51E-03$	$1.92E-01$	$2.00E-03$	$2.43E-01$	$2.53E-03$
	2.73	**0.1116**	2.75	**0.1113**	2.78	**0.1115**

PD: partial density.

slight variation of μ/ρ of all the selected borate glass samples at particular photon energy. It is due to the reason that photoelectric absorption is dependent on photon energy and atomic number as Z of the elements and $Z^{4.5}/E^{3.5}$. All the borate glass samples under investigation contain different constituent elements ($_5$B, $_8$O, $_{11}$Na, $_{28}$Ni, and $_{82}$Pb) with different weight fractions of elements. The slight differences in the weight fraction of elements result in insignificant variation of μ/ρ values in photoelectric absorption region.

With increase in photon energy (above 100 keV), the reduction rate of the μ/ρ is observed to be very slow (10^{-1} to 10^{-2}). It was observed that the variation is negligible between 0.5 and 5 MeV where Compton scattering dominates. It is because the interaction cross-section is linearly dependent on Z. With further increase in photon energy (above 50 MeV), it was found that the μ/ρ values start increasing and become constant at around 100 MeV. This is because the pair production process in nuclear field, $\mu/\rho_{(\mathrm{npp})}$, and electron field, $\mu/\rho_{(\mathrm{epp})}$, starts at threshold energies of 1.022 MeV and 2.044 MeV and thereafter increases with increase in the incident photon energy. In this high-energy region, a slight variation at particular incident photon energy was again observed due to their different chemical compositions. It may be due to the cross-sections for pair production process in nuclear field and for triplet production depending on atomic numbers Z^2 and Z, respectively. It is to be noted that although pair production processes initiate at photon energy 1.022 MeV, they require more incident photon energy to overcome Compton scattering.

3.2. HVL and TVL Values. The variation of half-value layer, HVL, and tenth-value layer, TVL, of the borate glass samples with photon energy ranging from 1 keV to 100 GeV is shown in Figures 2 and 3. We have plotted HVL and TVL of ordinary (OR), hematite-serpentine (HS), ilmenite-limonite (IL), basalt-magnetite (BM), and ilmenite (IT) [22] along with borate glass samples for comparison.

3.3. Effective Atomic Numbers. The variation of effective atomic numbers, $Z_{PI\mathrm{eff}}$, for total photon interaction and

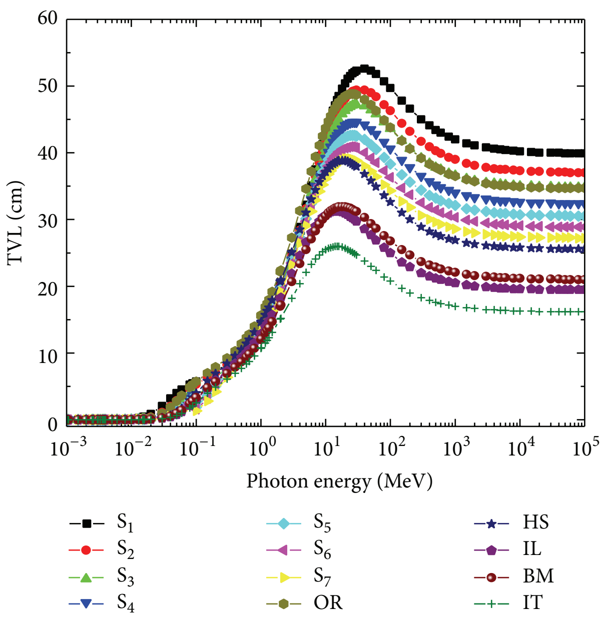
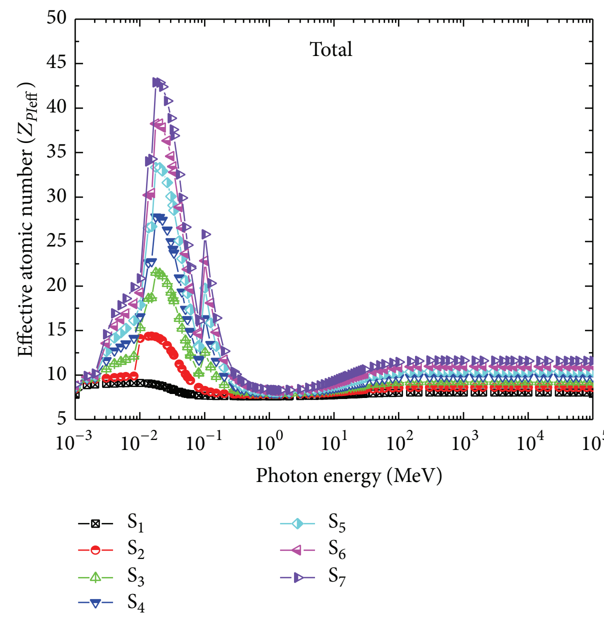
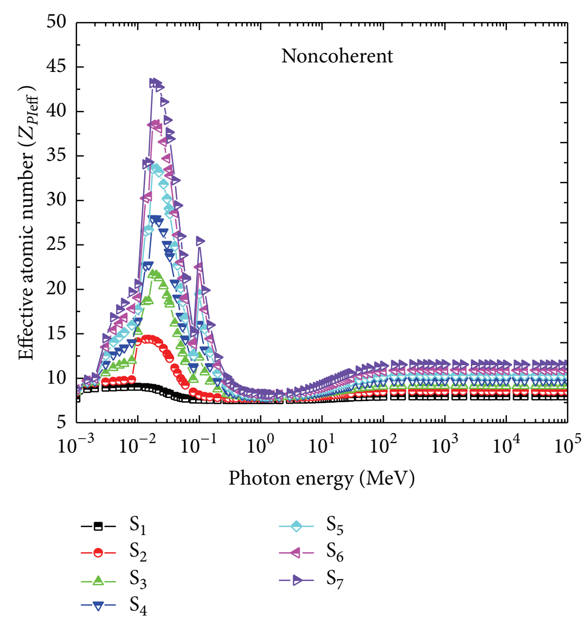


Figure 3: Variation of tenth-value layer of the borate glasses containing PbO and NiO with photon energy for range 1 keV to 100 GeV.



(a)



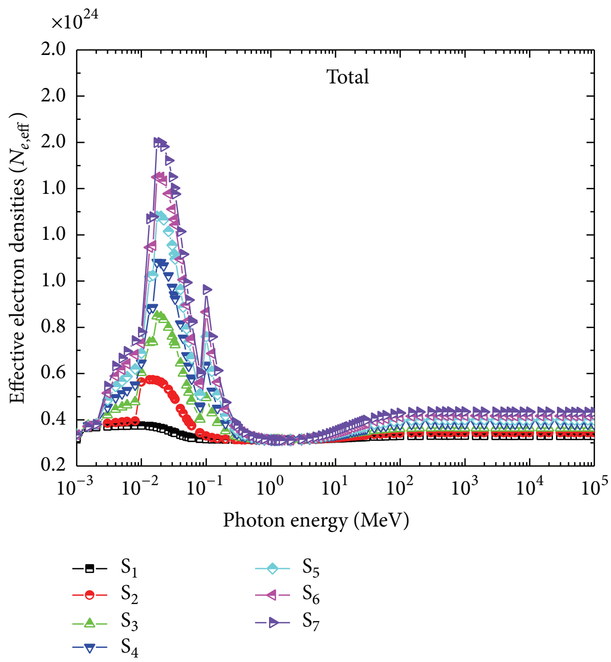
(b)

Figure 4: Variation of effective atomic numbers of the borate glasses containing PbO and NiO with photon energy for range 1 keV to 100 GeV.

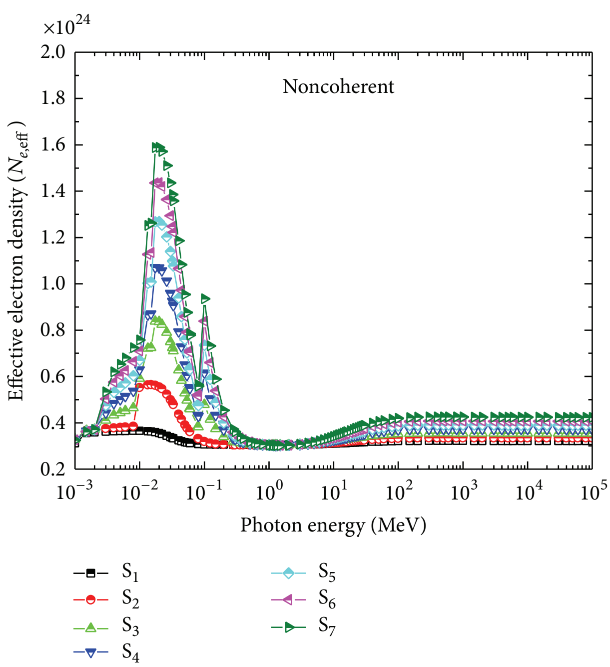
noncoherent interaction of the borate glass samples for photon energy ranging from 1 keV to 100 GeV is shown in Figures 4(a) and 4(b). The average effective atomic numbers, $\langle Z \rangle$, lower and upper values of effective atomic numbers at energies $10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2}, 10^{3}, 10^{4}$, and 10^{5} are given in Table 3. At low-energy range (0.01 MeV < E < 0.05 MeV), the maximum value of Z_{PIeff} was found. At intermediate energies (0.05 MeV < E < 5 MeV), where Compton scattering is the main photon interaction process, Z_{PIeff} is approximately equal to the arithmetic mean of the atomic number calculated from the chemical formula of the glass samples, $\langle Z \rangle = (1/n)\sum_i n_i z_i$. At high energies, ($E$ > 50 MeV), Z_{PIeff} is again constant but smaller than in the low-energy region. It is observed that there is a good agreement between Z_{PIeff} at 10 MeV (Table 3) and the mean atomic number, $\langle Z \rangle$, derived from the chemical composition of the glass samples, where Compton scattering is the main photon interaction process.

3.4. Effective Electron Densities. The variation of effective electron densities, $N_{e,\mathrm{eff}}$, for total interaction and noncoherent interaction of the borate glass samples with photon energy ranging from 1 keV to 100 GeV is shown in Figures 5(a) and 5(b). The average effective electron density, $\langle N_e \rangle$, lower and upper values of effective electron densities at specific energies as 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2}, 10^{3}, 10^{4}, and 10^{5} are given in Table 4. The variations of $N_{e,\mathrm{eff}}$ with photon energy for total interaction processes (Figures 5(a) and 5(b)) were similar to that of Z_{PIeff} and can be explained in similar manner.

3.5. Macroscopic Fast Neutron Removal Cross-Section. The macroscopic fast neutron removal cross-sections Σ_R (cm^{-1}) of the borate glass samples are given in Table 5. It was observed that the Σ_R was highest (0.1134) for S_1 whereas all the remaining borate glasses range from 0.1112 to 0.1118. The highest value of Σ_R for S_1 was observed due to zero contribution of Pb and Ni elements. It can be concluded that borate glass sample (S_1) is a superior neutron shielding material. Moreover, the borate glass alone may not be suitable for gamma ray shielding; therefore borate glasses containing PbO and NiO are suitable glass shielding materials for gamma ray and neutron. Since oxide containing glasses



(a)



(b)

Figure 5: Variation of effective electron densities of the borate glasses containing PbO and NiO with photon energy for range 1 keV to 100 GeV.

are having roughly constant Σ_R, borate glass containing 10% PbO (S_7) would be preferable gamma ray as well as neutron shielding. The Σ_R value of borate glass sample (S_1) was found to be higher than ordinary concrete whereas other borate glass samples ($S_2 \cdots S_7$) were lower than it.

4. Conclusions

In the present investigation, the mass attenuation coefficients, μ/ρ, half-value layer, HVL, tenth-value layer, TVL, effective atomic numbers, $Z_{PI\mathrm{eff}}$, and effective electron densities, $N_{e,\mathrm{eff}}$, of borate glass samples containing PbO and NiO were calculated for photon energy 1 keV to 100 GeV. The macroscopic fast neutron removal cross-sections were calculated for neutron energy 2–12 MeV. These parameters were found to be varying with the photon energy and chemical compositions of the glass samples. These results shall be useful for shielding applications against gamma ray and neutron.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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