Radiation shielding properties of BaO:WO₃:Na₂O:B₂O₃ glass system using WinXCom program in the range of 1 keV to 100 GeV: Theoretical calculation

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Abstract. The research aimed to study the radiation shielding properties of xBaO-5WO₃-15Na₂O-(80-x)B₂O₃ glass system where x = 5, 10, 15, 20, 25, 30 and 35 mol%. The theoretical values calculated using WinXCom program in the range of 1 keV to 100 GeV energy regions. The results of calculation found that the mass attenuation coefficients were increased with increase in BaO concentration and decreased with the increasing energy. Moreover, these glass system at low energies show discontinuities corresponding to photoelectric absorption edges of tungsten and barium. For the partials interaction at the low energies range the photoelectric absorption is the main interaction in these energy regions. At the medium energy regions, the radiation shielding parameters are almost constants dominated by Compton scattering process. In the high energy regions, pair production becomes the main interaction process over the energy. It can also be concluded that the characteristics of radiation shielding parameters for the glasses system depend on different barium in this concentration and the energy regions. The lead equivalent thickness of glass samples show that glass samples increasing trend with increase in concentration of BaO and the experimental are good agreement with theoretical value.

1. Introduction
Glasses have special properties such as transparent, radiation shielding which are not found in other engineering materials. The combination of transparency and hardness at room temperature along with sufficient strength and excellent corrosion resistance to most normal environments make glasses indispensable for many engineering applications. Glass is one of the materials which can be used for radiation shielding materials. This attention of the glass is attributed to their unique properties. It also posses 100% recyclable capability, can be transparent to visible light, and also modified to tailor the properties by adding other the oxides [1-4]. In recent times researchers has investigated that by adding heavy elements in the glass composition their radiation shielding ability can be enhanced. In year 2003, H. Singh.et.al had investigated the gamma-ray shielding parameters, they reveal that the photon mean free path (MFP), the effective atomic number (Zeff) and the electron density (Nel) in ZnO-PbO-B₂O₃ glasses at 511, 662, 1173 and 1332 keV energy range show enhanced radiation shielding properties [5]. N. Sing.et.al (2006), studies show that the gamma-ray attenuation of PbO-BaO-B₂O₃ glasses show enhanced values at 511, 662 and 1274 keV photon energies. Gamma-ray attenuation...
coefficients of the prepared glass samples have been compared with the results of XCOM program software and found that good agreement with experimental and theoretical values. Moreover, radiation shielding properties of the glass system have been compared with some standard radiation shielding concretes with these glasses which are higher than experimental concretes [6]. K.J. Singh and et.al (2008) were also considered the gamma-ray shielding and structural properties of PbO-SiO$_2$ system which illustrate that these glasses at 662, 1,173 and 1,332 keV photon energy show enhanced attenuation values and these values were well agreement with theoretical values compared using the WinXCom software. The results have been utilized to evaluate the gamma-ray shielding properties and can be concluded that adding PbO in the glass composition improves the radiation shielding properties [7]. The research also shows that lead being hazardous material and has disadvantages in both its weight and environmental issues. M.I. Sayyed.et.al (2018) studies show that the addition of Bi$_2$O$_3$ increases the values of MAC, Z$_{eff}$, N$_{el}$, MFP and half value layer (HVL) [8]. N. Chanthima and J. Kaewkhao, (2013) were investigated the radiation shielding parameters of SiO$_2$-B$_2$O$_3$-Al$_2$O$_3$-CaO-Na$_2$O-Bi$_2$O$_3$ glass systems which theoretically calculated by using WinXCom program in the range of the energies from 10 MeV to 100 GeV. The results found that at low-energy region, the radiation shielding parameters show several discontinuous jumps correspond to photoelectric absorption edges. At medium-energy region, the Compton scattering process is main interaction. In high-energy regions, pair production becomes the main interaction process and tends to be constant over energy [9].

The objective of this work is to investigate the mass attenuation coefficient and partial interactions of xBaO-5WO$_3$-15Na$_2$O-(80-x)B$_2$O$_3$ glass system for various concentration of BaO (x = 5, 10, 15, 20, 25, 30 and 35 mol%) using WinXCom program the values were calculated in the energy range from 1 keV to 100 GeV.

2. Theory

2.1. The absorption of gamma-rays with matter

The absorption of gamma-rays intensity decreases with matter interaction as well as the thickness of the material. It can be easily illustrated by using the equation

\[ \frac{I}{I_0} = e^{-\mu x} \]  

(1)

where the proportionality constant $\mu$ is called the linear attenuation coefficient. $I$ is the transmitted intensity of radiation passing through the material. $I_0$ is the incident intensity traversed a thickness $x$ of a given material [10]. A more convenient parameter coefficient characterizing a given material is the density ($\rho$) independent mass attenuation coefficient ($\mu_m$) by the following relation

\[ \mu_m = \mu / \rho \]  

(2)

2.2. The mass attenuation coefficient

The theoretical values of the mass attenuation coefficient of mixture were calculated by WinXCom program which are based on the rule of mixture and followed by equation [11,12]

\[ \mu_m = \sum_i w_i (\mu_m)_i \]  

(3)

where $w_i$ and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of the elements. For weight fraction can be calculated by equation (3).
2.3. The lead equivalent thickness

The lead equivalent thickness is the thickness of lead required to achieve the same shielding effect against radiation, under specified conditions, as that provided by a given material [13].

\[ d_{pb} = \frac{\mu_{glass}}{\mu_{pb}} \times d_{glass} \]  

(4)

Where \( d_{pb} \) represents the lead equivalent thickness of glass sample, \( \mu_{pb} \) is the linear attenuation coefficient of lead, \( \mu_{glass} \) is the linear attenuation coefficient of glass sample, \( \mu_{glass} \) represents the thickness of certain concrete.

3. Measurement of density

Density of each the glass samples were measured by Archimedes’ principle using distilled water as reference liquid and those were calculated by the equation

\[ \rho = \frac{w_a}{w_a - w_b} \times \rho_b \]  

(5)

where \( w_a \) is the weight of each glass samples in air and \( w_b \) is the weight of each glass sample in water, and \( \rho_b \) is density of water is 0.998 g/cm³

4. Results and discussion

![Figure 1](image)

Figure 1. Density and molar volume of the glass samples

Figure 1. shows the density and molar volume of the prepared glass samples. The density of the glass increased with the increase in concentration of BaO. Such trend is due to the BaO replacing the B₂O₃ where the molecular weight of BaO (153.33 g/cc) is higher than B₂O₃ (69.61 g/cc) hence one could expect such increasing trend. The interesting characteristics in the molar volume is visible at 15 mol% concentration of BaO. Initial addition of BaO up to 15 mol% the trigonal borate \([BO_3/2 - B_3]\) units present in the glass network gets converted into tetrahedral \([BO_4/2 - B_4]\) units decreasing their volume and increasing the density. Such decreasing trend is quite observed when the mole fraction of the alkali oxide content is beyond 0.33 which is considered as borate anomaly. Beyond 15 mol% of BaO concentration the molar volume increases with increase in BaO content this is due to B₄ units gets converted to B₃ units suggesting that the network is loosely packed.
From figure 2 it is clear that the coherent scattering interaction with various photon energy ranging from 1 keV to 100 GeV. The coherent scattering decreased rapidly with increase in energy and increased with increase in BaO concentration. However, coherent scattering occurs in lower energy range.

Figure 3. Incoherent scattering

Figure 3. shows incoherent scattering with photon energy ranging from 1 keV to 100 GeV. The results can be concluded that the incoherent scattering was continuously decreased with the increasing of photon energy and found that the energy ranges from $10^{-2}$ MeV to 1 MeV. Incoherent scattering is main interaction in this case.
From figure 4 the results are clear that photoelectric absorption increased with the increasing of BaO content and decreased with increase in energy. Photoelectric absorption occur by interaction of the gamma-ray photon with one of the bound electrons in an atom. This can result in the release of further electrons from the atom which transfers a further fraction of the total gamma-ray energy to the detector. The most likely to be occurred is the K electron. If sufficient energy is not available to interacts with K electron, then L or M electrons will be occurred. The photoelectric absorption edges in this case occurred at K absorption edge of BaO at 3.72 keV and 6.95 keV, L absorption edge at 5.25 keV, 5.62 keV and 5.99 keV, M absorption edge at 1.06 keV, 1.14 keV and 1.29 keV.

Figure 4. Photoelectric absorption

Figure 5. Pair production
From figure 5 the results show that the pair production increased with increase in BaO content and decreased with increase in photon energy. The major interaction of pair production will be happened from 1.02 MeV to 100 GeV in the present case.

Figure 6. Total mass attenuation coefficient

Figure 7. Lead equivalent thickness of glass sample.

Figure 6 shows that the total mass attenuation coefficient were calculated by using WinXCom program for the formula xBaO-5WO3-15Na2O-(80-x)B2O3 glass system where x = 5, 10, 15, 20, 25, 30 and 35 mol%. It can also be concluded that the mass attenuation coefficient showed that the total mass attenuation coefficients were increased with increase in BaO concentration and decreased with increase in energy. The low energy range show several discontinuation in attenuation due to presence of various absorption edges such as K, L and M edges from tungsten (WO3) and barium (BaO) as these elements show different electron energy range interacting with atom, the attenuation coefficient falls in a stepwise manner at the precise energy of the K, L, M and other less tightly bound electrons can be seen at lower energies.
From Figure 7. The lead equivalent thickness of glass samples were calculate by equation (4). The results show that glass samples increasing trend with increase in concentration of BaO and the experimental are good agreement with theoretical value. These results can be applied candidate for glass shielding materials.

5. Conclusions
BaO:WO$_3$:Na$_2$O:B$_2$O$_3$ glass was prepared by melt quench technique. The radiation shielding properties were calculated from WinXCom program and found that when concentration of BaO increased all the interaction, such as coherent, incoherent scattering, photoelectric absorption, pair production and mass attenuation coefficient increases. Boron anomoly was observed in the present glass due to addition alkali oxide more than 0.33 at 15 mol% BaO content. For the partial interactions at lower energy range suggesting that major interaction comes from photoelectric absorption. At the intermediate energy regions, the radiation shielding parameters are almost constants dominated by Compton scattering process. In the high energy regions, pair production becomes the major interaction process at such range. The lead equivalent thickness of glass samples show that glass samples increasing trend with increase in concentration of BaO.

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