The Barium Borosilicate Glass on Neutron/Gamma Rays Shielding from Theoretical Values Computation at 1 keV to 100 GeV of the Energy Range

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Abstract. The inspection of radiation shielding specimens in the composition xBaO : (40-x)SiO2 : 25ZnO : 30B2O3 : 5Al2O3, where x = 10, 15, 20, 25, 30, 35, and 40 mol % of borosilicate glasses went on to radiation shielding parameters, found that the MAC, the $\text{Z}_{\text{eff}}$, the atomic cross-section, and the electronic cross-section have the same trends when added BaO increase, but when the energy increases, all values of the four parameters decreased with increasing of the energy ranges. The result of $N_e$ was described as the atomic radius of BaO that affects the probability of interactions in the Compton scattering ranges. The results of HVL and MFP demonstrated that the lower both parameters affected volume requirement and decreased the average distance when photon traveled in the material, which can design the physical characteristic of the radiation shielding specimens.

1. Introduction

The profound benefits interpretations of radiation had been being used in various fields such as medicine, nuclear industry, agriculture, science, high energy physics, and medical applications [1,2]. However, radiation is still harmful to humans and the surrounding environment. Thus, the radiation shielding materials are used for protecting workers from the adverse effects of radiation. From the literature reviews, U. Kaur and et al. were investigated the different concrete based on some photon interaction and illustrated that the photons interact with the matters in the material [3]. In 2017, M. Alwaeli had investigated the radiation shielding properties of the concrete containing scale and granulated lead-zing slag wastes and results found that the features of the material showed better radiation shielding than conventional concrete when were compared [4]. Recent years, K. Zalegowski and et al., have studied the neutron radiation shielding efficiency of the concrete material on microstructure and this case the material can be candidate neutron shielding and also the HVL attenuated neutron that absorbed. The dose is decreased [5]. This is one of the materials that are used as a radiation shielding material because it is a robust structural material and high density.

Moreover, lead is still used as a primary ingredient in radiation shielding materials. Many years ago, the researchers found the alternative materials is ono of excellent material for the radiation shielding glasses. Advantages of glass materials, chemicals can be added to the glass compositions for the improvable structure of the radiation shielding properties [6-9]. At the same time, many types of glass...
had been continuously developed by being a lack of lead. It is a well-known lead. It is toxic to humans, life, and the surrounding environment. The researchers avoided lead toxicity by adding heavy elements such as bismuth, tungsten, barium, or gadolinium instead of lead. In 2014 K.J. Singh had developed in the glass systems the PbO-SiO$_2$-Al$_2$O$_3$ compare with the Bi$_2$O$_3$-SiO$_2$-Al$_2$O$_3$ and resulted found that the Bi$_2$O$_3$ glasses are showed better the radiation shielding properties like the mass attenuation coefficient (MAC), the half value layer (HVL), and the mean free path (MFP) than the PbO glasses [10]. Afterwards, the heavy elements added in the glass compositions had been being developed continuously because glasses have unique properties such as transparency, natural to process, nontoxic, and high density [11-17].

Knowledge of the interactions between radiation with matter is an essential concept in the manufacture of the radiation shielding materials. The ideal of the materials should have a high density and high atomic number because it increases the probability of interaction between photons with the matter; when the radiation travels through the material the photon energy will be absorbed under the interaction. The coherent scattering, incoherent scattering, photoelectric absorption, pair productions and these are the partial interactions when they are combined; those are called the mass attenuation coefficient (MAC). The calculation of the MAC as the first parameter brings about to the atomic cross-sections and the electronic cross-sections until to the effective atomic number and the effective electron density, respectively [18].

In 1995 Hubble and Seltzer had developed the XCOM program in which the MAC computation of the elements, compounds, and mixture of the components goes into the mixture rules for based calculation. Moreover, the program can compute the MAC and the partial interactions under the range of the energies 1keV to 20 keV [19,20]. Ultimately, Gerward and et.al., have continuously developed the program available on the window system, which is called the WinXCom [21,22]. In 2013 N. Chanthima, and J. Kaewkhao had published in the topic “Investigation on radiation shielding parameters of bismuth borosilicate glass from 1 keV to 100 GeV” which the WinXCom are also used in this paper [23].

The purpose of this theoretical test was to examine the interaction between photon energy in the range 1keV to 100 GeV with the matter. The material that went into the experiment was the glass material in the composition of xBaO : (40-x)SiO$_2$ : 25ZnO : 30B$_2$O$_3$ : 5Al$_2$O$_3$ where x is the percent 10, 15, 20, 25, 30, 35, and 40 by mol of barium oxide of borosilicate glasses. The MAC, the $Z_{\text{eff}}$, the $N_{\text{e}}$, the atomic cross-section, the electronic cross-section, the MFP and the HVL, these are the profound significant quantities and demonstrate the quality of the material which those were put a figure on using the WinXCom program.

2. Theorem

2.1. Photoelectric absorption

The interaction of the high-energy photons with atomic electron bonds is one part of the photoelectric absorption. As a result of the phenomenon, when photons pass through a material and interact with electrons. The immaculate transfer of the threshold energy of the photon is more considerable binding energy than the electron, one of atomic electron throw it out from the shell of the atom. The phenomenon is more significant for high-Z substance. Consequently, at the heavy elements (high atomic number) and the photon energies $10^3$ MeV approximately, this condition will occur these phenomena of interactions [24-26].

2.2. Compton scattering or Compton effect

Compton scattering (incoherent scattering) is a collision between the photon energy with free electrons. The photon energy transferred to a free electron is reduced, and the photon energy is scattered with a decrease of the energy. However, only the gamma radiation energy was reduced. The occurrence of this phenomenon is also dependent on mid-energy and high atomic numbers as it increases the probability of interactions between photon energy with the matter [24-26].

2.3. Pair production
The complete absorption of photon energy, which results in the formation of the energy, is an electron-positron pair. Threshold energy 1.022 MeV has come about into this phenomenon (which is equivalent to the sum of the rest mass of an electron and positron). For the energy fluctuation into rest mass can be the wise specimen in this process. However, in the empty space, A gamma photon cannot be producing an electron and positron pair. Nevertheless, in the field of an electron, pair production comes about to 2.04 MeV of the threshold energy or $4m_0c^2$ by $m_0$ is rest mass of the electron [24-26].

2.4. The total mass attenuation coefficient

A compound or element mixture can compute by the mixture rule which the rule is gone into as the basis for calculations on the WinXCom program. The program can also analyze parameters of the partial interactions and cross-section (coherent, incoherent (Compton scattering), photoelectric absorption, pair production). This rule is explained according to the equation;

$$\mu_t (cm^2 / g) = \sum_i w_i \mu_i (cm^2 / g)$$

where $\mu_t$ is the total mass attenuation coefficient for a compound or a mixture, $w_i, \mu_i$ are the weight fraction of each element in the compound and the total mass attenuation coefficient of each element respectively [24]. The atomic cross-section, the electronic cross-section compute from the MAC that is calculated by using the program and relation as follow by the equation; [18,27]

$$\sigma_{i,el} = \frac{(\mu_i)_{material}}{N_A \sum_i (w_i / A_i)}$$

and

$$\sigma_{i,el} = \frac{1}{N_A} \sum_i f_i A_i Z_i \mu_i$$

where $N_A$ is Avogadro’s number, $A_i$ is the atomic weight of constituent elements of the material, $f_i$ is the number of atoms of element $i$ relative to the total number of atoms of all elements in the material, and $Z_i$ is the atomic number of the $i^{th}$ element in the material [27,28].

2.5. The effective atomic number

The effective atomic number is illuminated to the number of electrons per all atoms that interact with the photon. It has to be weighed differently for each of the different processes by which gamma rays can interact with the matter, which can calculate by the equation; [29]

$$Z_{eff} = \frac{\sigma_{i,el}}{\sigma_{i,ta}}$$

2.6. The effective electron density

It is the number of electrons per unit mass of the interacting material. The higher the value of electron density, the better are the chances of photon interaction. The electron density ($N_e$) is given by [29]

$$N_e = \frac{\mu_m}{\sigma_{i,el}}$$

2.7. The mean free path (MFP)
The MFP meaning is surveyed to the average distance of a photon that can travel in the material before occurring the interactions. The linear attenuation coefficient $\mu$ is gone into for MFP calculation by the relation of mass attenuation coefficients with its densities [26];

$$mfp = \frac{1}{\mu}$$

2.8. *The half value layers (HVL)*

HVL definition is the thickness of materials with the interaction in which the intensity of the radiation is decreased of one half. Half value layer can be computed by the relation [26];

$$HVL = \frac{\ln 2}{\mu}$$

3. Results & discussion

Table 1. Photon energies (in keV) of absorption edges above 1 keV.

| Elements | Z  | M5 | M4 | M3 | M2 | M1 | L3 | L2 | L1 | K  |
|----------|----|----|----|----|----|----|----|----|----|----|
| Al       | 13 | -  | -  | -  | -  | -  | -  | -  | -  | 1.560 |
| Si       | 14 | -  | -  | -  | -  | -  | -  | -  | -  | 1.839 |
| Zn       | 30 | -  | -  | -  | -  | -  | -  | -  | 1.020 | 1.043 | 1.194 | 9.659 |
| Ba       | 56 | -  | -  | 1.062 | 1.137 | 1.293 | 5.247 | 5.624 | 5.989 | 37.44 |

Table 2. Chemical composition of the glasses (weight %)

| BaO | xBaO : (40-x)SiO₂ : 25ZnO : 30B₂O₃ : 5Al₂O₃ |
|-----|------------------------------------------------|
|     | BaO | SiO₂ | ZnO | B₂O₃ | Al₂O₃ |
| 10  | 4.9528 | 5.1056 | 9.3114 | 4.5245 | 1.2795 |
| 15  | 7.0186 | 4.8234 | 8.7968 | 3.5620 | 1.2088 |
| 20  | 8.8680 | 4.5708 | 8.3361 | 2.7004 | 1.1455 |
| 25  | 10.5333 | 4.3433 | 7.9212 | 1.9245 | 1.0885 |
| 30  | 12.0407 | 4.1374 | 7.5456 | 1.2222 | 1.0369 |
| 35  | 13.4116 | 3.9501 | 7.2041 | 0.5834 | 0.9899 |
| 40  | 14.6638 | 3.7791 | 6.8921 | 0 | 0.9471 |
3.1. Total mass attenuation coefficient

Within this scope, the basic radiation shielding parameters of the xBaO : (40-x)SiO$_2$ : 25ZnO : 30B$_2$O$_3$ glass systems, where x = 10, 15, 20, 25, 30, 35, and 40 mol% was precisely examined by using the WinXCom program. The samples were computed entirely in the energy ranges from 1 keV to 100 GeV. For the calculated significance, shielding parameters were analyzed theoretically from the program; they are the MAC, the atomic cross-section, the electronic cross-section, the $Z_{\text{eff}}$, the $N_{\text{eff}}$, the HVL, and finally the MFP respectively. From Figure 1, the MAC increases slightly with the increase of BaO contents, and all MAC trend decreases with the increase of the energy. The computed MAC result illustrates graphically in Figure 1., found that at the lowest energy from 0.001 MeV until to 0.1 MeV approximately, the MAC decreases not continually owing to the absorption edges of the elements. Which Ba illustrated M3, M2, M1, L3, L2, L1, and K absorption edge at the energy (1.062, 1.137, 1.293, 5.247, 5.624, 5.989, and 37.44) keV for Zn showed L3, L2, L1, and K absorption edge at the energy (1.020, 1.043, 1.194, and 9.659) keV and finally, Si and Al displayed K absorption edge at the energy (1.560, and 1.839) keV which can see in Table 1., which demonstrated to the relevance of the binding energy of elements.

3.2. Total cross-sections

![Figure 2. The total atomic cross-section & the total electronic cross-section](image-url)
For the calculated, the total electronic cross-section and total atomic cross-section values were illustrated to the probability of interaction (absorption, scattering, or pair production) that occurs on the atomic nucleus or subatomic particle. As a result, total atomic cross-section and total electronic cross-section similar trends with the MAC owing to both values illustrate the probability of interaction and show photoelectric absorption at the low energy (0.001 to 0.01) MeV influence firmly with the MAC.

3.3. Effective atomic number

![Figure 3. The effective atomic number](image)

From $Z_{\text{eff}}$ definition it explains the number of electrons per all atoms that interacted with the photon. The calculated effective atomic number results are shown graphically in Figure. 3, the $Z_{\text{eff}}$ increase with the increasing of BaO content, and each of the concentrations showed to not continue of the values cause at the low energy; main interactions are the photoelectric absorption (0.001 MeV to 0.01 MeV), incoherent (Compton) scattering at intermediate energies (0.01 to 0.1 MeV) approximately, and pair production at high energies ($\geq 1.022$ MeV). Furthermore, the $Z_{\text{eff}}$ also turns on the cross-sections and the MAC. As a result, adding atoms BaO into the structural specimens resulted in the probability of interactions with the electrons within the atoms.

3.4. Effective electron density

![Figure 4. The atomic radius (in picometers) of representative elements according to their positions in the periodic table [30].](image)
Figure 5. The effective electron density

From the description of $N_e$, it is the number of electrons per unit mass of the interacting in the material see in Figure 5. The computed result of $N_e$ illustrated for the trend of $N_e$ that increases with the increasing of BaO contents at the energy ranges from 0.001 MeV to 0.01 MeV approximately, in adding BaO by varying ratio with SiO$_2$ which can be seen under the chemicals composition of the glasses in Table 2. In this energy ranges, when added BaO into the structure of the glasses that influence directly at the transferred low photon energy with an electron under the binding energy that illustrates the characteristic of the photoelectric absorption that is the main interactions which can remark in Figure 6., that showed all interaction. As a result, the electron density increases with increasing BaO concentration. On the other hand, in the energy range from 0.01 MeV until 1 MeV approximately, the $N_e$ trends should increase with the increase of adding BaO. However, the reason is described to an atomic radius that is illustrated in Figure 4. For the result, the analysis found that when added BaO increases by decreasing the ratio of SiO$_2$ in the glass formula, which impacted remarkably with the probability of interactions that decreased owing to an atomic radius of Ba larger than Si [30]. Hence, adding larger particles such Ba by decreasing smaller particles as Si, which occur free space into the structure of the specimens that greatly affected the probability of interactions between medium photon energy with an electron that illustrates the incoherent (Compton scattering) that is the primary interaction in these energy ranges.

Nevertheless, in the high photon energy ranges from 1 MeV to 100 GeV, pairs production phenomena are demonstrated in these ranges. The result of adding BaO into the fabric; in this case, high photon energy is interacted with the nucleus by the energy come to be two rest mass. Thus, adding a smaller atomic radius of SiO$_2$ that is replaced by adding a larger atomic radius of BaO; the interaction will increase with increasing BaO contents.
3.5. Half value layers & mean free path

![Figure 7](image1.png) ![Figure 8](image2.png)

Figure 7. The half value layers (HVL)

Figure 8. The mean free path (MFP)

From HVL definition is the thickness of materials with the interaction in which intensity of the radiation is decreased by one half. The radiation shielding specimen in terms of thickness is demanded influentially to lower the value of HVL. In the MFP, the meaning is surveyed to the average distance a photon can travel in materials before occurring the interactions. The results for computation found that both HVL and MFP are the same trends when adding more BaO demonstrated that could decrease the thickness of specimens, which referred to volume requisite in the HVL and can decrease the average distance when photon traveled in the material before being interacted in the MFP. Besides, when both values were adopted to compare with lead (Pb) found that Pb is less HVL and MFP than the total values of the specimens. However, choosing a substitute material is the right choice for replacing Pb, which is toxic to the environment. The radiation shielding glass is one of an excellent alternative material owing to less toxics, high transparency, lightweight, and suitable transportation.

4. Conclusion

This formula of the glass xBaO : (40-x)SiO₂ : 25ZnO : 30B₂O₃ : 5Al₂O₃ where x = 10, 15, 20, 25, 30, 35, and 40 mol % of borosilicate glasses that is gone into for computation of radiation shielding parameters. The results demonstrated that the MAC, the Z_eff, the atomic cross-section, and the electronic cross-section have the same trends when added BaO increase, those values increase with increasing of BaO adding, and when the energy increases, all values of the four parameters decrease with increasing of the energy ranges. For the special case of the N_e found that the atomic radius of BaO influences the interaction in the energy ranges of incoherent (Compton scattering energy). The lower both HVL and MFP parameters affected with volume requisite and decrease the average distance when photon traveled in the material, which can design the physical characteristic of the radiation shielding specimens and is one of an excellent alternative material by Pb replacement.

5. Reference

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