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Simulation of Gamma Radiation Shielding Parameters of Borosilicate Glass Using Phy-X/PSD Software

***Ibrahim Gana Geidam and Hassan Abdulsalam**

Department of Physics, Faculty of Science, Yobe State University Damaturu, Nigeria.

*Corresponding authors' email: ibgana55@gmail.com Phone: +2348064983026

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ABSTRACT
The increasing use of ionizing radiation in medical, industrial, and nuclear applications has created demand for effective environmentally friendly shielding materials. Lead free borosilicate glasses doped with barium oxide attracted significant attention due to their superb mechanical, optical, and radiation shielding properties. Therefore, this study radiation shielding properties of $5B_2O_3$-$40SiO_2$-(55-x) Al_2O_3-xBaO (BSABa) (where x = 25, 28, 31 and, 34 wt%) glass systems using Phy-X/PSD online software. Shielding parameters, such as linear attenuation coefficients (LAC), mass attenuation coefficients (MAC), mean free path (MFP) and half-value layer (HVL) give details information about the radiation shielding ability of the glasses. Therefore, the mass attenuation coefficients (MAC) for the 0.015–15 MeV gamma-ray energies are obtained to determine photon shielding efficiency of BSABa-x glass systems. The results shown that the glass system, which contains higher BaO concentration has higher mass attenuation coefficients. BSABa-34 glass has the highest MACs, ranging from 2285.007 cm^2/g to 2.795 cm^2/g, while BSABa-25 glass has the lowest values, ranging from 1817.409 cm^2/g to 2.597 cm^2/g. The BSABa-34 glass with the highest BaO contribution has the thinnest MFP and HVL values. The results revealed that adding BaO to aluminum borosilicate glasses at increasing rates, improves nuclear radiation resistance properties.

Keywords: Lead Free Glass, Simulation, Shielding, Borosilicate, Radiation

INTRODUCTION
Radiation obtains benefit when used for diagnosis and treatment within certain dose limitations, but it can also cause biological effects in human. In an advanced scientific and technological society, extreme ionizing radiation (X- and gamma-rays) exposure is increasing rapidly because of its vast applicability in different fields, such as nuclear industries (power generation, reactor fuel and probe), medicine (sterilization of equipment and biomedical), agriculture (food preservation and pesticides), sciences and engineering (research, optoelectronic devices, and telecom devices) (Geidam et al., 2022; Lakshminarayana et al., 2021).

X- and gamma-rays are ionizing electromagnetic radiation characterized by high frequencies, short wavelengths, and high penetrating power emitted upon transition from an excited energy state of a nucleus/electron to a lower energy state (Knoll, 2010). The interaction of matter with ionizing radiation transforms biological, physical, and chemical properties of the interacting medium, which might cause serious health complications that may lead to death (Sayyed et al., 2020; Sayyed et al., 2021). Concerns were raised by various radiation protection agencies and experts on how to minimize the risks of excessive human and environmental exposure to hazardous radiation.

Radiation shielding material depends on some factors, such as high density, atomic number, radiation resistance, ease at which heat dissipates, ability to lower levels of radiation, required thickness, possibilities of multi-use, and obtainability. Several research scholars studied and tested different materials, including alloys, polymers, concrete, glass, and glass-ceramics for radiation shielding applications (Geidam et al., 2022; Kavaz et al., 2020; Ozturk et al., 2020; Şensoy & Gökçe, 2020). Among all the materials, glasses demonstrated superb shielding suitability owing to their ease of fabrication, transparency, and flexibility of design (Issa et al., 2020; Nazrin et al., 2022). In all the different varieties of glasses, lead-based glasses were widely investigated and adopted as highly effective and reliable in providing protection against a source of ionizing radiation (Issa et al., 2020; Matori et al., 2017). Despite early recognition and utilization of Pb-glasses as a perfect conventional radiation shield, radiation experts recently challenged the usage of Pb due to its toxicity. Therefore, this poses the necessity of searching for a new eco-friendly material that could effectively replace lead for shielding applications.

Among the materials considered for gamma radiation shielding, borosilicate glass has garnered attention due to its unique properties. The glass is composed primarily of silica (SiO_2) and boron oxide (B_2O_3), which gives it several advantageous characteristics for shielding purposes: such as high thermal resistance, low thermal expansion, transparency, chemical inertness high mechanical strength, and high durability (Geidam et al., 2022). These outstanding properties makes borosilicate glass a potential candidate for gamma radiation shielding application (Chutithanapanon et al., 2019; Zakaly et al., 2021).

The ability to simulate and predict the gamma shielding parameters of materials like borosilicate glass is essential for designing effective and formidable shielding materials. The simulation process allows for a comprehensive understanding of how gamma radiation interacts with the material and provide insights into parameters such as linear attenuation coefficients (LAC), mass attenuation coefficients (MAC), mean free path (MFP), half-value layer (HVL).

The Phy-X/PSD software serves as a powerful tool for simulating the gamma radiation shielding ability of the proposed glass system (B_2O_3-SiO_2-Al_2O_3-BaO). This software has been employed by researchers and engineers to model radiation interactions and calculate relevant shielding parameters accurately (Lacomme et al., 2021).

MATERIALS AND METHODS

Glass Preparation by Melt Quenching Technique

Firstly, the crucible containing the precursor was put into the electric furnace preset at a temperature of 400 °C for 1 hour to evaporate any water vapor trapped in the mixture (Saudi et al., 2021). Then, the sample was heated at 1100 °C for 3 hours, and the crucible containing melt was shaken every 15 min to increase the bubble acceleration rate because gas bubbles from the oxide would be trapped in the viscous glass melt during the process of melting (Asyikin et al., 2020). The melt was cast in stainless-steel slip. The solid transparent glass sample was then transferred to another electrical furnace for an annealing process at 400 °C for 1 hour to prevent the glass sample from cracking (thermal shock phenomenon). After 1 hour, the furnace was switched off and the glass sample was left inside before it was taken out after cold to room temperature (Geidam et al., 2021). The samples were cut using a diamond cutter and polished using fine grains sandpapers. The sample thickness was measured using a digital Vernier caliper.

Theoretical Radiation Shielding Measurement

The radiation shielding parameters of the $5B_2O_3$ - $40SiO_2$ - (55-x) Al_2O_3 - xBaO (BSABa-x), (where x = 25, 28, 31 and 34) glass systems, where considered to be tested using phy-X/PSD online software using different parameters such as mass attenuation coefficient (μ_m), linear attenuation coefficient (μ), half-value layer (HVL) and mean free path (MFP). The weight fraction and theoretical density of the investigated sample are given in the Table 1.

The Phy-X/PSD Software

Phy-X software is one of the most well-known theoretical programs for the calculation of the radiation shielding parameter, through which different shielding interaction coefficient can be accurately determine over wide range (Şakar et al., 2020). The flow chart of the PSD online software shows in Figure 1.
There are three steps which are necessary for calculation in the software and are listed as follows (Şakar et al., 2020).

Table 1: Glass Composition and Density of $5B_2O_3$-$40SiO_2$-(55-x)Al_2O_3-xBaO Glass System

Sample Code	B_2O_3 (%)	SiO_2 (%)	Al_2O_3 (%)	BaO (%)	Density (gcm^{-3})
BSABa25	5	40	30	25	3.798
BSABa28	5	40	27	28	3.851
BSABa31	5	40	24	31	3.904
BSABa34	5	40	21	34	3.957

Definition of Materials

The first step is to define the composition of the material to be used in calculations accurately. In the software, the material composition can be entered in two different ways such as mole fraction and weight fraction. After the selection of mole or weight fraction in the software, then make sure that the sum of mole fractions or weight fractions is equal to 100 or 1, and if necessary, users must normalize them before entering fractions to the program (Şakar et al., 2020). The PSD online software can produce data for unlimited number of different materials, which can be added by using + symbol in the main screen of the software, at the same time. Namely, when clicks each + sign, a new line is opened up so that to enter a new material composition. Additionally, the density (g/cm^3) of the phase state in which the material is used as shielding is required for LAC, HVL, TVL and MFP parameters, and label of the materials to be calculated must be written to the boxes in the relevant line (Ozpolat et al., 2020; Şakar et al., 2020).

Selection of Energies

Two energy regions have been predefined in the software as 15 keV-15 MeV (relevant to ANSI database and is used in calculation of EABF and EBF) and 1 keV-100 GeV. Also, some well-known radioactive sources (^{22}Na, ^{55}Fe, ^{60}Co, ^{109}Cd, ^{131}I, ^{133}Ba, ^{137}Cs, ^{152}Eu and ^{241}Am) along with their energies and some characteristic X-ray energies obtained through secondary sources (the K-shell energies of Cu, Rb, Mo, Ag, Ba and Tb elements) are available in the software and can be selected by the user (Şakar et al., 2020).

Selection of Parameters to be Calculated

Users can choose which parameter(s) they want to calculate depending on their studies. After defining the materials as described, the software needs some parameters for the selected calculations (Şakar et al., 2020). The MAC values used in these calculations are taken from the NIST (National Institute of Standard and Technology) database (Berger & Hubbell, 1987). The users are free to choose both the energies and the number of parameters to be calculated.

Calculation of Shielding Parameters (MAC, LAC, HVL and MFP)

As a measure of the absorption of a photon by the material, the linear attenuation coefficients (LAC) of the materials are examined. The LAC, which is a quantity that needs to be investigated in many materials to be effectively protected from radiation, gives the probability of any interaction per unit length of a photon, and it expresses the total probability of occurrence of photoelectric events, Compton scattering, and pair production. The LAC is express as (Geidam et al., 2022);

$$\mu = \frac{I\,/I_{\circ}]}{t} \quad (1)$$

Where I and $I_{\circ}$ show intensities of the incident and attenuated gamma rays, respectively, and t denote the mass thickness of the sample. Mass attenuation coefficient (MAC) is calculated by dividing the LAC by the specific gravity of the material. The MAC gives the rate of attenuation of the beam per unit mass and is expressed as (Geidam et al., 2022).

$$\mu_m = \frac{\mu}{\rho} \quad (2)$$

Where μ shows the linear attenuation coefficient (expressed in cm^{-1}) defines a measure of the possibility of photon interaction when radiation passes through a target material, depending on the thickness of the material, where μ_m shows mass attenuation coefficient, and ρ shows the density of the material. The appropriate material thickness that causes the intensity of radiation passing through a target to decrease to half intensity by interacting with the material is also called the half-value layer (HVL) and is expressed with the formula (Olarinoye et al., 2020).

$$HVL = \frac{ln ln\, 2}{\mu} \quad (3)$$

The mean free path (MFP), is another of the shielding parameters, defined by the following formula as the distance traveled by a particle before possible collisions with other particles (Geidam et al., 2022).

$$mfp = \frac{1}{\rho} \quad (4)$$

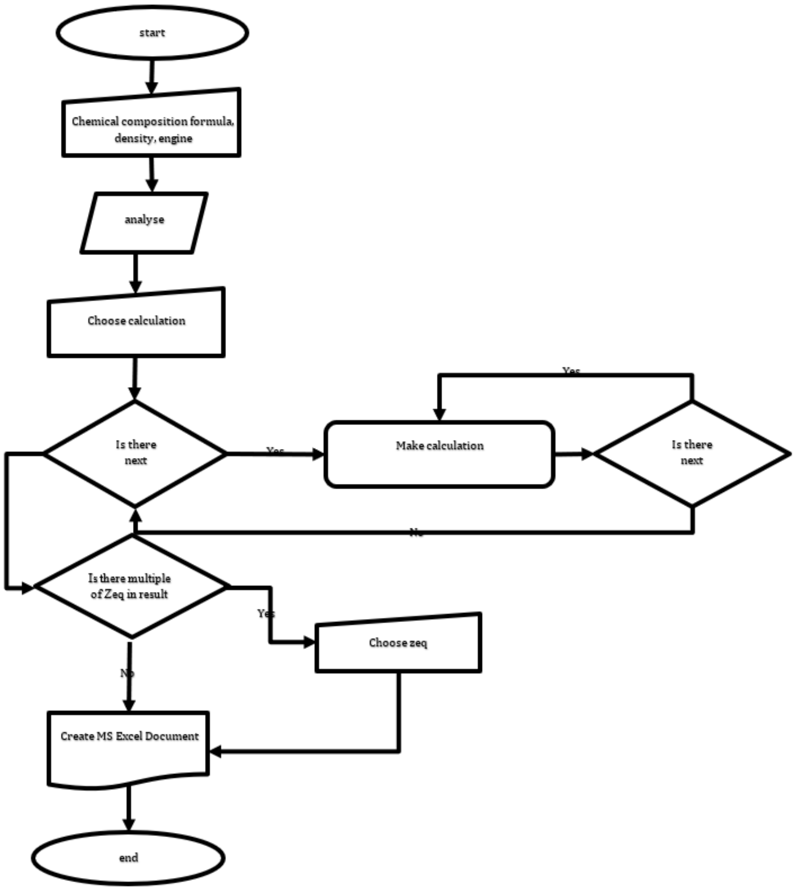

Figure 1: Flow Chart of Phy-X/PSD Online Software

RESULTS AND DISCUSSION

In the present study, the basic radiation parameters of barium doped aluminum borosilicate glass system with different composition of barium, were study by direct method over wide energy range from 0.015 to 15 MeV using Phy-x/PSD online software. These parameters are MAC, LAC, HVL and MFP. The calculated results were shown in Figure 2 to 5. Figure 2 shows the value of the mass attenuation coefficient in the context of different compositions of barium-doped aluminum borosilicate glass systems denoted as BSABa25, BSABa28, BSABa31, and BSABa34, respectively each with varying levels of barium (BaO) content. These MAC values are pivotal in understanding how well these glass compositions attenuate gamma radiation, with higher MAC values signifying more effective shielding. The table highlights trends such as decreasing MAC values as energy increases and the impact of altering the glass composition on shielding properties. Linear attenuation coefficient (LAC) is a fundamental parameter used to assess the material's ability to interact with and attenuate gamma radiation, expressed in cm^{-1}.

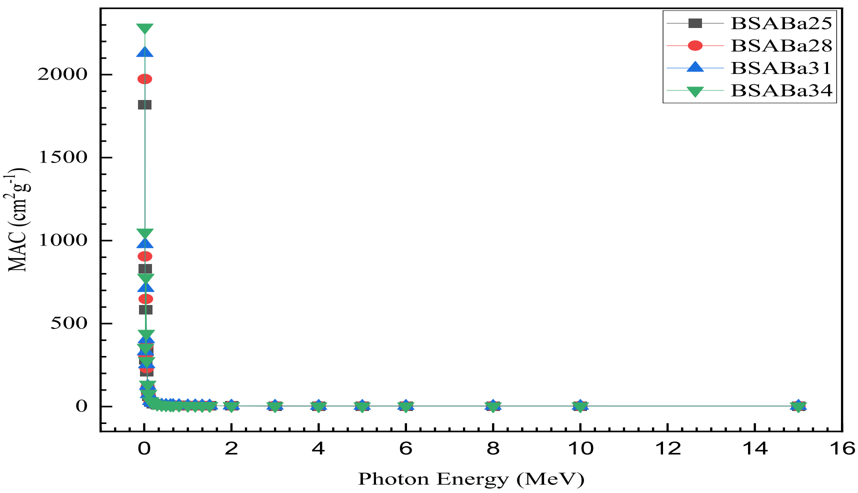

Figure 2: Mass Attenuation Coefficient for B_2O_3-SiO_2-Al_2O_3-BaO Glasses in the Energy Range 0.015 – 15 MeV

Figure 3 presents the values of the LAC for different BaO concentration. Sample BSABa34 with higher BaO content has the highest value of LAC 9041.77 cm^{-1} at 0.015 MeV, but the LAC value decrease to 11.06 cm^{-1} with increase in photon energy to 15 MeV. The observed trend was as a result of the three major fundamental interaction mechanism namely, PE, CS, PP (Dong et al., 2017; Sayyed et al., 2021). These indicates, that the addition of BaO in the glass system enhance its shielding ability at low photon energy and less effective at higher photon energy (Alrowaili et al., 2022). Figure 4 contains data for the half-value layer (HVL). The term HVL is a crucial parameter for determining the thickness of shielding material needed to reduce radiation intensity by 50%. The values of HVL of the glass sample increase as the incident photon energy increases from 0.015 to 15MeV. But, the value decreases BSABa25 > BSABa28 > BSABa31 > BSABa34, respectively. The observed decreasing value of HVL across the samples may be attributed to increase in density resulted from the introduction of BaO which has high atomic number compared to the glass precursors (Kilic et al., 2021; Saudi et al., 2021). Figure 5, presents the value of mean free path (MFP) of the $5B_2O_3$–$40SiO_2$–(55-x)Al_2O_3–xBaO glass system. The value of MFP exhibits decreasing trend, that is BSABa25 > BSABa28 > BSABa31 > BSABa34. The result of HVL is in agreement with MFP of $5B_2O_3$–$40SiO_2$–(55-x)Al_2O_3–xBaO glasses.

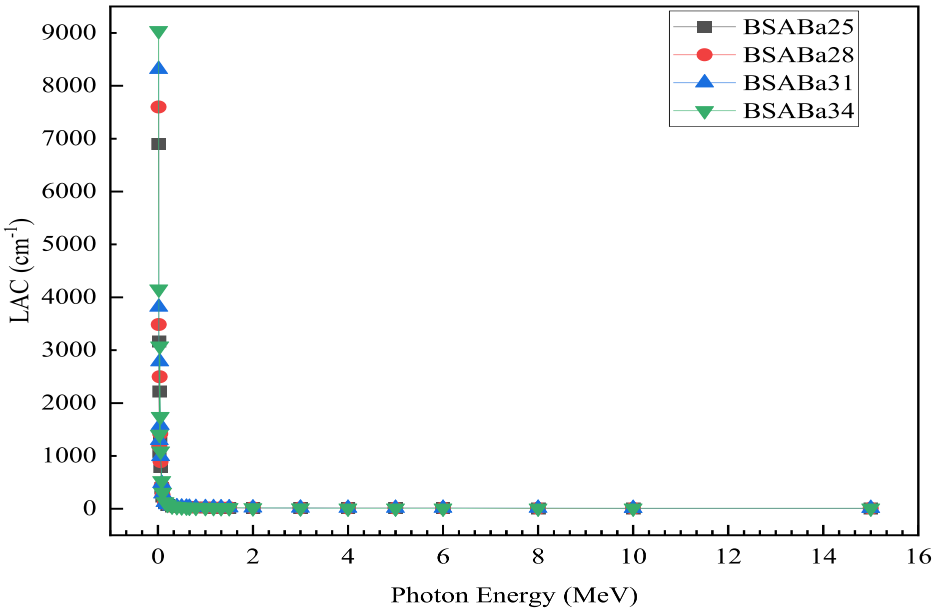

Figure 3: Linear Attenuation Coefficient for B_2O_3-SiO_2-Al_2O_3-BaO Glasses in the Energy Range 0.015 – 15 MeV

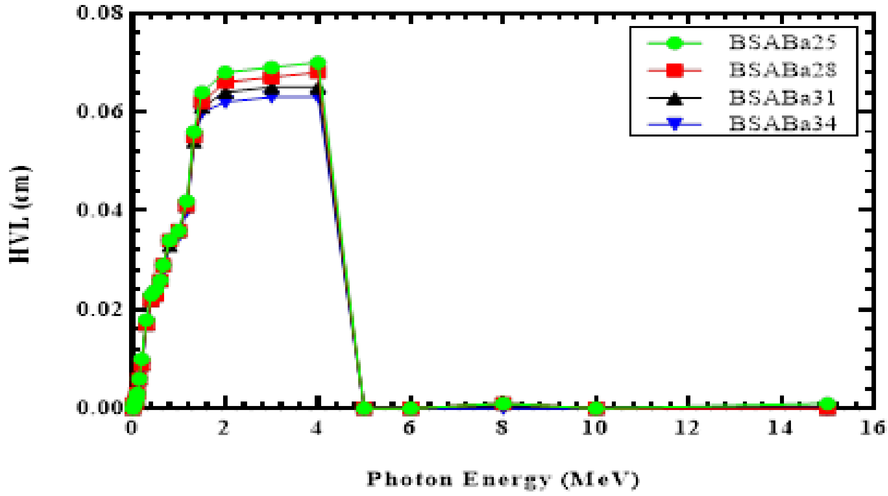

Figure 4: Half Value Layer for B_2O_3-SiO_2-Al_2O_3-BaO Glasses in the Energy Range 0.015 – 15 MeV

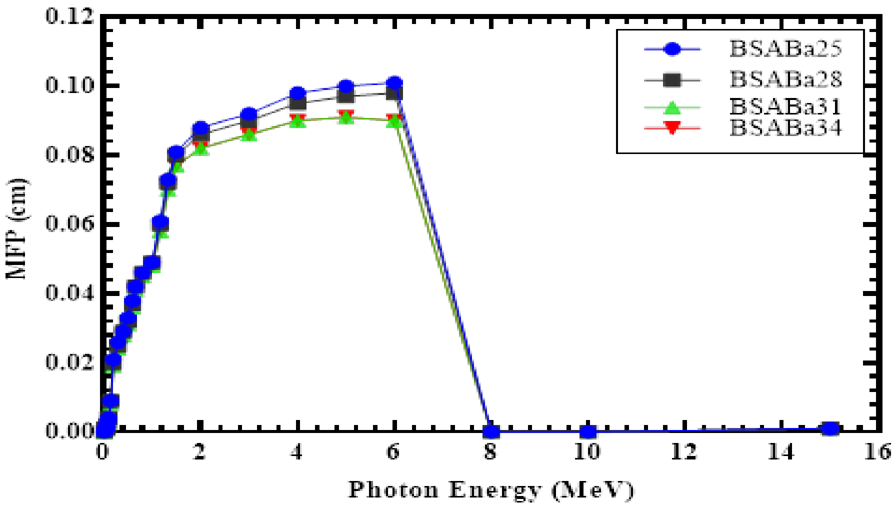

Figure 5: Mean free path for B_2O_3-SiO_2-Al_2O_3-BaO glasses in the energy range 0.015 – 15 MeV

CONCLUSION

The study focuses on the gamma radiation shielding ability of borosilicate glass and its potential application in protecting against harmful ionizing radiation. The methodology involves using the Phy-X/PSD software to calculate various radiation shielding parameters, such as linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), and mean free path (MFP). The study examines different compositions of barium oxide-doped aluminum borosilicate glasses, to determine their shielding capabilities. The study provides valuable insights into the gamma shielding potential of borosilicate glass and establish baseline data for further research in this area. Radiation shielding properties of $5B_2O_3$ - $40SiO_2$ - $(55-x)Al_2O_3$ - xBaO glass system (where x = 25, 28, 31 and 34) were determined. The glasses densities were evaluated and found to increase from 3.798 g/cm^3 to 3.957 g/cm^3 by the addition of BaO concentration linearly (i.e. 25, 28, 31 and 34% mole). On the other hand, from 25 to 34 mole percent BaO reinforcement, a total increase of 0.159 g/cm^3 was observed (i.e. between BSABa25 and BSABa34). As a result, 34% mole substitution of BaO results in a net density difference of 0.159 g/cm^3. The BSABa34 with the highest BaO content exhibits the greatest attenuation of photons, these indicates that the introduction of BaO into B_2O_3-SiO_2-Al_2O_3 glass network has significantly enhance the gamma radiation attenuation capability of the studied glass system.

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