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Determination of gamma-ray shielding properties for silicate glasses containing Bi_2O_3, PbO, and BaO

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ABSTRACT

The mass attenuation coefficients (μ_m), effective atomic cross section (σ_a), effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of silicate glasses containing different concentrations of Bi_2O_3, PbO, and BaO (30–70% by weight) were obtained using MCNP-4C code, XCOM and XMuDat programs, in the energy range of 10 keV–10 MeV. The interpolation method was employed to extract Z_{eff} and N_{eff}. The Auto-Z_{eff} software was used to determine the Z_{eff} as well. The MCNP-4C Code, XCOM and XMuDat programs and Auto-Z_{eff} results were in good agreement. It was found that the μ_m and σ_a values decrease with photon energy. Also the results indicate that σ_a and Z_{eff} of glasses improve by increasing their Bi_2O_3, PbO and BaO contents, while increasing these contents to the same fraction has no significant effect on μ_m in the energy range of 0.3–5 MeV, where the Compton Effect takes over as dominant process and N_{eff} do not follow certain rule. Above 0.1 MeV, lead oxide silicate glass showed the highest values of Z_{eff} and σ_a. Wherever possible, the simulated and calculated values were compared with experimental data.

1. Introduction

With the extensive application of radiation sources and radioactive materials in various fields such as nuclear power production, nuclear medicine, industry, and agriculture, the study of attenuation and absorption of X-rays and gamma-rays in several materials has become an essential and interesting field of research [1–5]. Concrete is the most common radiation-shielding material, because it is inexpensive and is easily adapted to any construction method [6–8]. However, concrete has many disadvantages and can be damaged by the expansion of aggregates, freezing of trapped water, fire or radiant heat, bacterial corrosion, leaching, and physical and chemical processes [9].

Glass materials are possible alternatives of concretes for radiation-shielding materials that have several major advantages such as transparency to visible light, 100% recyclability, and easy property modification through composition and preparation techniques [10-13].

Various types of glasses have been used in different nuclear applications. Appreciable variations were observed in the attenuation coefficients because of changes in the chemical composition of glasses. Singh et al. [5] calculated gamma-ray attenuation coefficients experimentally for the $xPbO(1-x)SiO_2$ ($x = 0.45–0.70$) glass system at 662–, 1173–, and 1332–keV photon energies using a narrow beam transmission method. Mass attenuation coefficients and effective atomic numbers in phosphate and silicate glasses containing Bi_2O_3, PbO, and BaO at 662-keV gamma-ray energy were investigated by Kaewkhao et al. [14] and Kirdsiri et al. [11] respectively. Lead sodium borate glasses were prepared using the melt-quenching method by Limkitjaroenporn et al. [15]. Bootjomchai et al. [16] calculated the attenuation coefficients of barium–bismuth–borosilicate glasses for gamma-ray photon energies of 662–, 1173–, and 1332–keV.

Furthermore, the variation in mass attenuation coefficient for three different oxide glasses was studied using software package XCOM by Gupta and Sidhu [17]. El-Khayatt et al. [18,19] reported simulated values for mass attenuation coefficient, total interaction cross-section, the effective atomic number and effective electron density of heavy metal oxide glasses by Monte Carlo simulation code MCNP. Al-Saadi and Saadon [20] calculated experimental and theoretical the mass attenuation coefficients, effective atomic number, and half-value layer

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Table 1
Densities of the three silicate glass systems.

Weight %	Glass sample		
	BaO-glass	Bi_2O_3-glass	PbO-glass
30	3.422	4.887	3.944
40	3.454	5.054	4.374
50	3.504	5.127	4.734
60	3.501	5.487	5.036
70	3.515	5.701	4.939

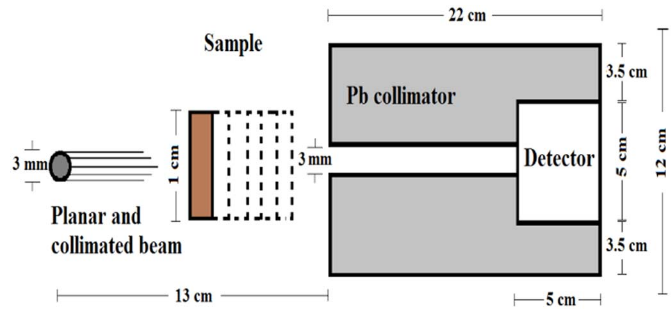

Fig. 1. Geometry of modeled configuration (sizes are not in scale).

(HVL) parameters for silicate mixed with various levels of lead oxide and iron oxide as reinforced materials. Lead (Pb) is a pollutant with environmental toxicity properties; hence, bismuth (Bi) and barium (Ba) are the two alternatives that as mentioned above, are most extensively explored and are now playing important roles in the radiation shielding field. Bismuth contributes to the stabilization of the glass structure and improves chemical durability [11]. Also, because of their high atomic number, bismuth and barium enhance gamma-ray shielding properties of glass. Silicate glasses are the most common glasses used in radiation shielding field because of ease of fabrication and excellent transmission of visible light [21,22].

In this study, three silicate glass systems, namely xBi_2O_3:(100-x) SiO_2, xPbO:(100-x)SiO_2, and xBaO:(100-x)SiO_2 glasses (where $30 \leq x \leq 70$ is the composition by weight%) were considered. The mass attenuation coefficients, effective atomic cross section, effective atomic number and electron density values of these silicate glasses were calculated in the energy range of 10 keV–10 MeV using MCNP-4C code and XCOM and XMuDat computer programs. The Auto-Z_{eff} software was used to determine the effective atomic number as well. Auto-Z_{eff} software is user-friendly software which computes of the average atomic numbers and spectral-weighted mean atomic numbers for predefind and user-defined compound and mixtures for photon energies ranging between 10 keV and 1GeV. This software surpasses dubious power-law approach. Effective atomic number is determined via exploitation of the smooth correlation between atomic cross section and atomic number [23].

The MCNP code is a general-purpose Monte Carlo radiation transport code, which models the interaction of radiation with matter [24]. On the contrary, the theoretical values for mass attenuation coefficients of different elements, compounds, and mixtures over wide photon energy range were tabulated by Hubbell and Seltzer [25] and Boone and Chavez [26]. From these tables and computerized programs, WinXCom, or its predecessor, XCOM and XMuDat program, mass attenuation coefficients were calculated at energies 1 keV to 100 GeV [27–29]. XCOM program employs Hubbell and Seltzer database while XMuDat program is able to produce a mass attenuation coefficient values on the basis of both Hubbell and Seltzer and Boone and Chavez data. In this research Boone and Chaves data source was chosen in XMuDat program. To verify and validate the simulated and calculated values, the obtained results were compared with the available experimental data [11].

2. Materials and methods

2.1. Simulation

Cubical geometries were used for modeling of glass samples. Eight sections of sub-rectangular cuboids were defined using macrobodies card of MCNP code for every type of sample.

The attenuation coefficients of the glass samples were measured in narrow beam transmission geometry using sources as planar, collimated beam and monoenergetic energy that emit gamma rays perpendicular to the front face of the glass samples. A disk source with 3-mm diameter and parallel to the surface of the glass samples was defined in MCNP data card using ERG, PAR, POS, and DIR commands for energy, type of particle, position, and direction, respectively. According to the experimental condition [11], bismuth, lead, and barium silicate glasses were considered as xBi_2O_3:(100-x)SiO_2, xPbO:(100-x)SiO_2, and xBaO:(100-x) SiO_2 glass systems, where x is the composition by weight% (x = 30, 40, 50, 60, and 70). The densities of the glass samples are shown in Table 1. The percentages by weight of each element in the glass samples used in material card of MCNP are presented in Table 2.

A small cylinder with diameter and length of 2 in. was considered as the detector volume, with an inner 12-cm-thick lead shield and a 3 mm diameter holed collimator. The geometry of the system for simulation is shown in Fig. 1.

Tally F4 was used to obtain MCNP-4C simulation data. It facilitates the calculation of average flux in a cell (detector volume) for each gamma-ray emitted from the source.

Simulations were performed with 100,000 to 1 million histories depending on the type and thickness of the glass sample. All simulated results by MCNP-4C code were reported with $\leq 0.1\%$ error.

Table 2
Percentages by weight of elements in the glass samples.

Element	Atomic number	BaO-glass					Bi_2O_3-glass					PbO-glass				
		30	40	50	60	70	30	40	50	60	70	30	40	50	60	70
Oxygen	8	40.41	36.13	31.85	27.56	23.28	40.37	36.07	31.78	27.48	23.19	39.43	34.82	30.21	25.60	20.99
Silicon	14	32.72	28.05	23.37	18.70	14.02	32.72	28.05	23.37	18.70	14.02	32.72	28.05	23.37	18.70	14.02
Barium	56	26.87	35.83	44.78	53.74	62.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	27.85	37.13	46.42	55.70	64.98
Bismuth	83	0.00	0.00	0.00	0.00	0.00	26.91	35.88	44.85	53.82	62.79	0.00	0.00	0.00	0.00	0.00