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Exploration of gamma radiation shielding features for titanate bismuth borotellurite glasses using relevant software program and Monte Carlo simulation code

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ABSTRACT

In this work, gamma radiation shielding parameters for six titanate bismuth borotellurite glasses were investigated. The mass attenuation coefficients (μ/ρ) have been calculated using XCOM software and MCNP5 code within the photon energy range 0.015–10 MeV. The (μ/ρ) values were then used to calculate the effective atomic number (Z_{eff}), electron density (N_e), mean free path (MFP) and half-value layer (HVL) values. By using the Geometric progression (G–P) method, the exposure buildup factor (EBF) values at 0.015 MeV–15 MeV photon energy range, with penetration depths up to 40 mfp at intervals 1, 5, 10, 20, 30, and 40 mfp were evaluated. The 30 TeO_2–30 B_2O_3–30 Bi_2O_3–10 TiO_2 (mol %) glass possesses better gamma ray shielding effectiveness due to a higher value of (μ/ρ), Z_{eff} and lower values of HVL and MFP. The studied glasses exhibit excellent gamma ray shielding features compared to different types of concretes.

1. Introduction

In recent years, there has been growing interest among researchers to fabricate and apply different kinds of radiation shielding materials, which can effectively attenuate the harmful gamma and neutron radiations in various fields such as outer space exploration, nuclear reactors, nuclear medicine, nuclear waste storage sites, agriculture, and industries etc. [1–3]. Particularly, nowadays, at radiation sites (nuclear power plants etc.) various kinds of concrete are most commonly in use to protect the workers and surrounding environment from the neutral radiations direct or scattered and leakage effects. Here, concrete possesses advantages like cheap cost, ease of preparation for different types of construction, and relatively high density etc. [4]. However, several disadvantages associated with concrete like aggregates expansion, leaching, decrease in its structural strength and porosity due to radiolysis of water content and the evaporation of pore water under radiation heat and cracks formation etc. [5,6]. Additionally, concrete is opaque to visible light, which makes impossible for onsite workers to real-time monitoring of the situation inside nuclear radiation source. On the other hand, glasses can be considered as suitable substitutes for absorbing gamma rays and neutrons instead of concrete because glasses are highly transparent to visible light, easy to fabricate, 100% recyclable and their mechanical and physical features can be altered to meet the requirements by adding other chemical compounds [7].

To understand the radiation shielding features of any material, several γ-ray interaction parameters such as mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}), electron density (N_{el}), mean free path (MFP), half-value layer (HVL), and total interaction cross-section (σ_t) estimation is an important aspect [8–11]. In general, before utilizing in practical onsite radiation protection applications, materials are first tested for their radiation shielding effectiveness using Monte Carlo simulations. Different research groups have been reported the mentioned γ-ray interaction parameters for numerous glass systems for their potential applications as radiation shielding materials ([7,12,13] and the references therein).

In the present study, for TeO_2-B_2O_3-Bi_2O_3-Ti_2O glasses, by using XCOM program first we evaluated the (μ/ρ) values within the energy range 0.015–10 MeV, and from them, the γ-ray shielding parameters

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Table 1
Chemical composition (mol %) and elements (wt%) present in the studied glasses, including their density [14].

Sample code	(mol %)				Chemical composition of elements (wt%)					Density (g/cm^3) [14]
	TeO_2	B_2O_3	Bi_2O_3	TiO_2	Ti	B	Te	O	Bi	
S1	65	20	10	5	1.4229	2.5702	49.2948	21.871	24.8412	5.48 ± 0.01
S2	55	20	20	5	1.2037	2.1743	35.286	19.3065	42.0295	6.15 ± 0.01
S3	45	30	20	5	1.2607	3.416	30.2384	21.0640	44.0211	5.930 ± 0.002
S4	40	30	20	10	2.5755	3.4892	27.4548	21.5155	44.9649	5.820 ± 0.001
S5	35	30	25	10	2.3794	3.2236	22.1943	20.2752	51.9275	6.060 ± 0.002
S6	30	30	30	10	2.2111	2.9955	17.6779	19.2104	57.905	6.39 ± 0.01

such as Z_{eff}, N_e, MFP, HVL, and exposure buildup factor (EBF) values using Geometric progression (G–P) fitting method are derived for their potential applications as γ-ray shielding materials. Additionally, the μ/ρ values of the present glasses were calculated using MCNP5 simulation code and compared with XCOM results.

2. Materials and method

The selected glasses density values with the chemical composition (100-x-y-z) TeO_2 - (x) B_2O_3 - (y) Bi_2O_3 - (z) TiO_2 [(x = 20; y = 10, 20; and z = 5), (x = 30; y = 20; and z = 5), (x = 30; y = 20, 25, 30; and z = 10) (mol %)] were taken from Ref. [14]. The chosen 6 glasses were labelled as 'S1', 'S2', 'S3', 'S4', 'S5', and 'S6', for convenience (see Table 1).

2.1. MCNP5 simulation process

MCNP5 is a Monte Carlo code for simulation of different physical interactions at large energy range. MCNP5 is fully three-dimensional and it utilizes extended nuclear cross-section libraries and uses physics models for particle types [2,7]. Fig. 1 shows the defined cross-sectional geometry setup in MCNP5 Monte Carlo code. In this work, γ-ray sources with various energies have been defined as a point isotropic source. The source has been defined in the mode card of the MCNP5 input file as a point source of photon energy in the range of 0.015–10 MeV. As it can be seen from Fig. 1, glass sample has been located as an attenuator sample between the source and detection area. A point isotropic radiation source was also placed at a point before the glass sample. MCNP5 calculations were done by using Intel® Core™ i7 -6700CPU 3.40 GHz computer hardware. To get absorbed dose amounts in the detection area, average flux tally F4 was utilized. This type of tally mash gives the sum of average flux in the cell. For the simulation process, Tally F4 value simulated by MCNP5 code without shielding material was 'I_0', the value of Tally F4 simulated by MCNP5 with a certain thickness, '*t*' of the shielding material was 'I'. Then the linear attenuation coefficient of the shielding material, μ can be calculated as follows:

$$\mu = \frac{-ln\left(\frac{I}{I_0}\right)}{t} \quad (1)$$

For the purpose of calculations of mass attenuation coefficients of each sample, 10^8 particles were used during the simulation.

2.2. Calculation of different radiation shielding parameters-theory

2.2.1. Mass attenuation coefficient

Electromagnetic radiation interacts with the certain material through different processes i.e. the photoelectric absorption, Compton absorption and scattering and electron-pair production. Associated with each of these interaction processes are linear interaction coefficients (μ), which measure the probability per unit path length that a photon of certain energy in a particular material will interact [15].

When a parallel beam of monoenergetic photons entering through a certain material, it is attenuated due to absorption and scattering. Attenuation due to absorption follows the Lambert-Beer law, which can be expressed as above Eq. (1) [16].

On the other hand, the mass attenuation coefficient (μ/ρ) measures the number of photons interacted with the interacting material and can be evaluated using XCOM software [17] based on the mixture rule, namely [18]:

$$(\mu/\rho)_{glass} = \sum_i w_i(\mu/\rho)_i \quad (2)$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the 'i'th constituent element, respectively. It is the essential quantity to calculate many other parameters such as effective atomic number, electron density, half-value layer, mean free path etc.

2.2.2. Effective atomic number and electron density

The effective atomic number (Z_{eff}) for a composite material cannot represent by a single number. It has to be weighed differently for each of the various processes by which photons can interact with a material.

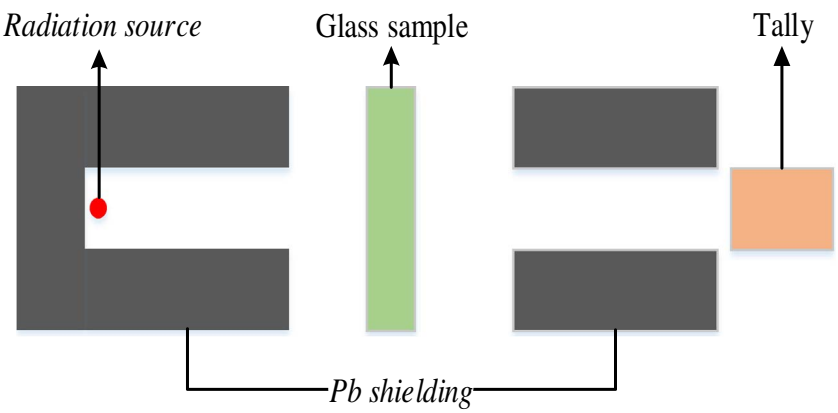

Fig. 1. MCNP5 total simulation geometry.