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Gamma-ray shielding properties of Bismuth silicate glasses at 662 and 1173keV photon energies

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ABSTRACT— *The mass attenuation coefficient (μ/ρ) and Half value layer (HVL) parameters of* $xBi_2O_3.(1-x)SiO_2$ *(x=0.50 upto 0.75) glass system have been calculated theoretically by using XCOM computer software developed by National Institute of standards and technology (NIST) at 662 and 1173eV photon energies. The obtained results have been compared with standard radiation shielding concretes at same energies. The prepared glass samples have higher values of mass attenuation coefficients and lower values of HVL parameters. The density, molar volume and X-Ray diffraction measurements have been used to study the structural properties of the prepared samples. Reported glass samples can find applications in the areas of nuclear reactors and nuclear waste storage containers.*

Keywords— Glasses, X-ray Diffraction, Mass attenuation coefficient, shielding materials

I INTRODUCTION

Bismuth silicate glasses are employed in a number of applications because Bi_2O_3 containing glasses exhibit a high refractive index, low transition temperature and high atomic weight [1]. Heavy metal oxide glasses containing Bi_2O_3 is interesting because such information helps better understanding of glass and glass-ceramic processing [2]. Today, bismuth is playing an important role of radiation glass shielding material and replacing lead and has protection in world economy [3]. However, Bi is much safer than Pb because Bi-based materials have been used as substitutes for the Pb-based materials and the prepared glass systems have been explored in glass industries. Heavy metal oxide glasses like Bi_2O_3 has good gamma-ray shielding properties as compared to existing concrete shielding materials [4,5]. But concretes has many limitations like water contents decreases density and structural strength of concretes. Another limitation is loss of water occurs in concretes. Concretes are opaque to the visible light so it is impossible to see through concrete material [6,8]. Bismuth contained glasses are one of the possible alternatives to concretes because their properties can be modified by varying composition and preparation techniques

The theoretical values of mass attenuation coefficient and half value layer (HVL) of bismuth silicate glasses have been calculated by using XCOM computer software developed by National institute of standards and technology (NIST) at photon energies 662 and 1173keV. The obtained values have been compared with the theoretical values of concretes at same energies [7]. Bismuth silicate glasses has higher mass attenuation coefficient values and lower HVL parameters so small volume is required during design of the shield.

Authors have carried out investigation of Bi_2O_3-SiO_2 glass system. Silicate glasses are commonly available glasses and bismuth is used to enhance the gamma ray attenuation due to higher atomic number.

II THEORETICAL BACKGROUND

Mass attenuation coefficient has been computed at photon energies 662 and 1173keV using the WinXCOM computer software developed by National Institute of Standards and Technology (NIST) [9,10]. It has been verified that the aforesaid software can provide authentic values at 662 and 1173keV gamma energies for glass system. The mass attenuation coefficient (μ/ρ) is given by the relation;

$$\mu/\rho=\sum w_i(\mu/\rho)_i, \quad (1)$$

here $(\mu/\rho)_i$ mass attenuation coefficients and w_i is weight fractions of the several elements.

HVL can be calculated by using the relation;

$$HVL=0.693/\mu, \quad (2)$$

Here, μ is linear attenuation coefficient.

Zeff can be computed from the formula;

$$Z_{eff}=\frac{\sum_i f_i A_i (\mu/\rho)_i}{\sum_i f_i \frac{A_i}{Z_i}(\mu/\rho)_i} \quad (3)$$

Where f_i is the molar fraction of the i^{th} constituent element (normalized so that $\sum_i f_i = 1$; A_i is the atomic mass, Z_i is the atomic number, and $(\mu/\rho)_i$ is the mass attenuation coefficient of i^{th} element.

MFP is calculated as [11];

$$MFP=\int_0^\infty x\, e^{-\mu x} / \int_0^\infty e^{-\mu x}\, dx=1/\mu \quad (4)$$

The density was calculated according to the following known formula

$$\rho = [W_1/(W_1-W_2)]\, d \quad (5)$$

where d is the specific density of benzene and the value of d is 0.763

W_1 is the weight of sample in air.

and W_2 is the weight of sample in benzene.

The molar volume V_g is evaluated from;

$$V_g=M/\rho, \quad (6)$$

here ρ is the density and M is the molar mass.

III EXPERIMENTAL TECHNIQUES

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Six glass samples of the system xBi_2O_3. (1-x) SiO_2 (x=0.50 up to 0.75) were prepared by melt quenching technique in our laboratory. Appropriate amounts of Bi_2O_3 and SiO_2 were weighted with an accuracy of 0.001g. Chemicals of Analytical Reagent grade were mixed thoroughly. Melts of the aforesaid systems with different compositions were obtained in electrically heated furnace (at around 1050-1100^0 C). Dry Oxygen was bubbled through melt using quartz tube to ensure homogeneity. The melt was annealed in another furnace at 270^{0}C in preheated copper mould. Samples were grounded and polished by using different grades of silicon carbide and aluminum paper respectively. Density of these samples was measured by Archimedes's principle using benzene as the immersion liquid. X-ray diffraction studies were carried out in order to study the amorphous nature of the prepared samples. Absence of any sharp peak shows that the prepared samples are amorphous.

Mass attenuation coefficient has been calculated theoretically by using XCOM computer software developed by NIST. By using the values of gamma-ray attenuation coefficient, the values of HVL and effective atomic number has been calculated and verified experimentally by several authors and good agreement between the obtained values has been established. Therefore, it is expected that XCOM software can be used as an authentic tool to evaluate the gamma-ray shielding parameters [9].

IV RESULTS AND DISCUSSION

Mass attenuation coefficient and HVL values of prepared samples at photon energies (662 and 1173keV) are shown in figures 1 and 2. . Mass attenuation coefficient increases and HVL values decreases with the increase in mole fraction of Bi_2O_3.

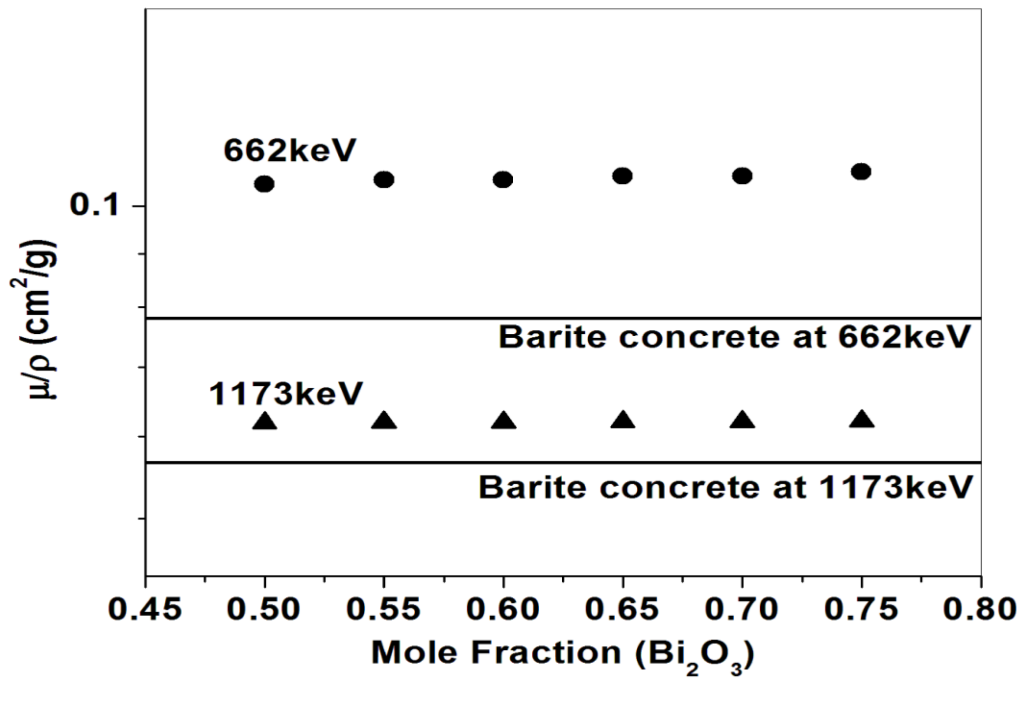

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Fig 1: Variation of mass attenuation coefficient with mole fraction of Bi_2O_3 at 662 and 1173keV. Theoretical values (——) for Barite concretes at same energies are included for comparison.

This can be attributed to increasing values of Bi which has higher atomic number as compared to other elements. In the light of this situation author has chosen barite and ferrite concretes for comparison for mass attenuation coefficient and HVL values respectively. The mass attenuation coefficient and HVL parameters of different concretes are also evaluated by using XCOM software at 662 ans 1173keV energies energies [7,10] is shown. Our glass samples show better mass attenuation coefficient and HVL parameters than existing concretes, for example barite concrete and ferrite concrete. In the light of this situation, it is suggested that as we increase the contents of Bi_2O_3 in the Bi_2O_3-SiO_2 glass system will improve the radiation shielding properties in terms of mass attenuation coefficient and HVL parameters. Zeff versus mole fraction Bi2O3 has been evaluated for glass samples at these energies. It has been found that effective atomic number increases with the increasing content of Bi2O3.

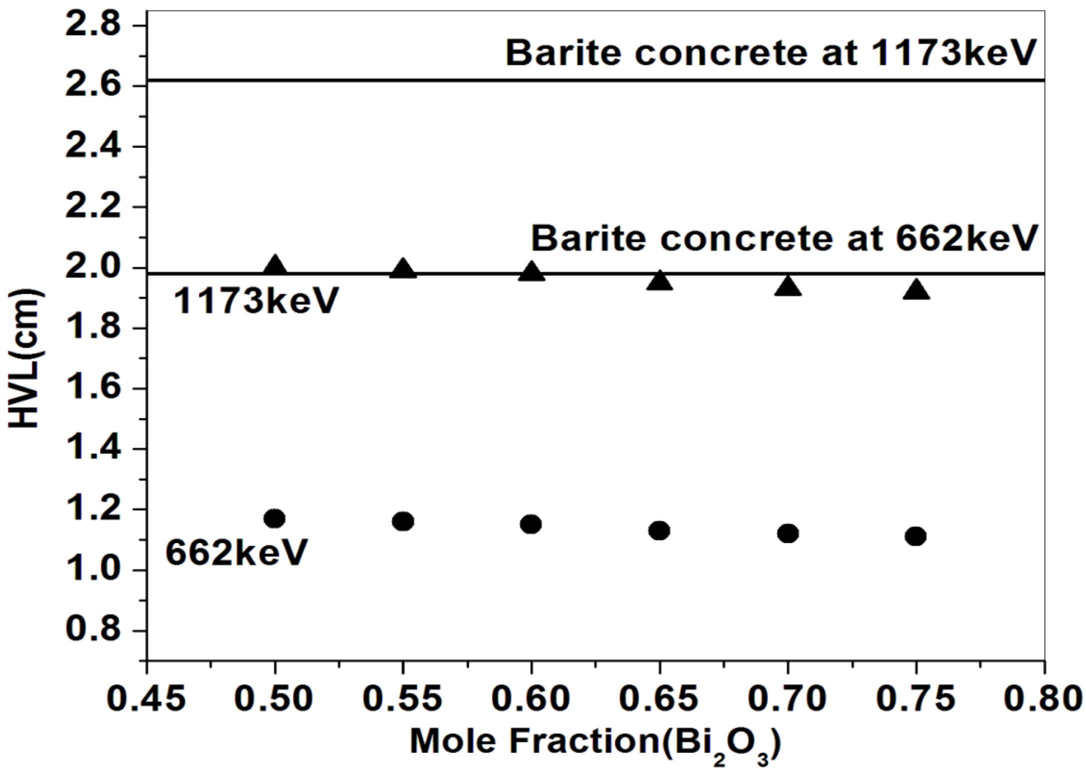

Fig 2: Variation of half value layer with mole fraction of Bi_2O_3 at 662 and 1173keV. Theoretical values (——) for Barite concretes at same energies are included for comparison.

Materials for shielding gamma rays are typically measured by the thickness required to reduce the intensity of the gamma rays by one half (the half value layer or HVL). For example, gamma rays that

require 1 cm (0.4″) of lead to reduce their intensity by 50% will also have their intensity reduced in half by 4.1 cm of granite rock, 6 cm (2½″) of concrete, or 9 cm (3½″) of packed soil. Mass attenuation coefficient and HVL values of prepared samples at 662 and 1173keV energies of gamma-rays have been shown in figures 1 and 2. Values of linear attenuation coefficient have been used to estimate the values of HVL by the standard relation. Authors have already compared the experimental and XCOM results of mass attenuation coefficient and HVL parameters for several glasses at 662 and 1173keV gamma ray energies and established that XCOM provides accurate results for the aforesaid shielding parameters at the above-mentioned energies.
The composition, thickness, density and molar volume are given in Table 1. It can be seen in Table 1 that the density values of our glass system increases with the increase in the content of Bi_2O_3. This can be attributed to higher atomic mass of bismuth as compared to silicate. The molar volume was calculated by using density values. It can be observed that the density value increases and molar volume values also increases with the concentration of Bi_2O_3 because it behave like a network former at higher concentration of Bi_2O_3.

Table 1: Chemical composition, Thickness, Density and Molar volume of Bi_2O_3-SiO_2 glass system.

Sample No.	Composition (Mole Fraction)		Thickness t(cm)	Density (g/cm^3) (±0.0001)	Molar Volume (cm^3/mol)
	Bi_2O_3	SiO_2			
BiSiG1	0.50	0.50	2.101	5.617	46.82
BiSiG2	0.55	0.45	1.743	5.630	50.32
BiSiG3	0.60	0.40	1.542	5.661	53.63
BiSiG4	0.65	0.35	2.072	5.727	56.54
BiSiG5	0.70	0.30	1.324	5.787	59.47
BiSiG6	0.75	0.25	1.762	5.804	62.79

X-ray diffraction studies of bismuth borate glass samples denote the amorphous nature and shows broad halo around 2θ=300 which indicates the absence of long range order.

V CONCLUSIONS

Bi_3O_3-SiO_2 glasses are the potential candidates as gamma-ray shielding materials as compared to concretes. Higher the values of mass attenuation coefficient and lower values of HVL parameter of our glass system shows that volume requirements for shielding with bismuth silicate glass system will be lesser. Results of density and molar volume measurements of bismuth silicate glass system indicate the formation of non-bridging oxygens with the increase in the mole fraction of Bi_2O_3.

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