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Gamma radiation shielding and optical properties measurements of zinc bismuth borate glasses

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ABSTRACT

In this work, the zinc bismuth borate (ZBB) glasses of the composition $10ZnO{:}xBi_2O_3{:}(90-x)B_2O_3$ (where x = 15, 20, 25 and 30 mol%) were prepared by the melt quenching technique. Their radiation shielding and optical properties were investigated and compared with theoretical calculations. The mass attenuation coefficients of ZBB glasses have been measured at different energies obtained from a Compton scattering technique. The results show a decrease of the mass attenuation coefficient, effective atomic number and effective electron density values with increasing of gamma-ray energies; and good agreements between experimental and theoretical values. The glass samples with Bi_2O_3 concentrations higher than 25 mol% (25 and 30 mol%) were observed with lower mean free path (MFP) values than all the standard shielding concretes studied. These results are indications that the ZBB glasses in the present study may be developed as a lead-free radiation shielding material in the investigated energy range.

1. Introduction

Nowadays, there has been an increasing interest in the synthesis and characterization of structure and physical properties of heavy metal oxide (HMO) glasses due to their high refractive index, high density, high nonlinear optical susceptibility, high infrared transparency and good radiation shielding for γ-rays. Heavy metal oxide (HMO) based glasses such as bismuth oxide based glasses have attracted the scientific community due to its important applications of thermal and mechanical sensors, reflecting windows, glass ceramics' etc. (Stehle et al., 1998; Luciana et al., 2000; Cheng et al., 2008; Ali and Shaaban, 2008). Bi_2O_3 possess high refractive index, and exhibit high optical basicity, large polarizability and large optical susceptibility values (Dimitrov and Komatsu, 1999; Sindhu et al., 2005; Zhao et al., 2007) which make them ideal candidates for applications as infrared transmission components, ultra fast optical switches, and photonic devices. Moreover, the HMO such as lead or bismuth oxide containing glasses shows extremely high radioactive resistance because of their high density and atomic number. Currently lead oxide glasses have been restricted in various applications as it is hazardous to health and environment (Singh et al., 2010). In this context, bismuth oxide has been a suitable substitution of lead oxide in glass preparation for its high refractive index, non-toxicity, bismuth oxide alone cannot be considered as network former due to small field strength of Bi^{3+} ion (Volf, 1984). However, in combination with other glass formers, the glass formation is possible in a relatively larger composition range (Gerth and Russel, 1997). Due to their ideal combination of high γ-ray absorption coefficient and good glass forming ability as oxides, Bi is useful in γ-ray absorbing windows in the nuclear industry and high energy physics (Brekhovskikh, 1957; Singh and Singh, 2004; El Batal, 2007; El Batal et al., 2007; Sharma et al., 2007; Kaewkhao et al., 2010; Ou et al., 2010).

Boric acid (B_2O_3) is one of the most popular and excellent glass formers known to form glass at lower melting point with good transparency, high chemical durability, and thermal stability (Varshnaya, 1994). Because of its higher bond strength, smaller cation size and heat of fusion, so the structural investigation of boron in borate glass and related doped systems is one of the most attractive points. Zinc oxide (ZnO) is one of the important constituents and known for large amounts of ZnO can lower the melting temperatures in the formation of oxide glasses. The previous widely used constituent for lowering the melting temperature of glasses, PbO, is now unfavorable from the environment concerns point of view. This gives rise to the importance of lowering the melting temperature of glasses with large amounts of ZnO instead of PbO. Indeed for instance, $ZnO–B_2O_3$ glasses with high ZnO contents have been used as a sintering aid for the fabrication of low temperature eco-fired ceramics. Glasses with high ZnO contents; therefore, are very attractive materials (Inoue et al., 2010). From above reviews, the zinc bismuth borate (ZBB) glasses are preferred

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as they possess a low melting temperature (easy to synthesis), a large refractive index, and good physical and chemical properties (large glass forming region, high thermal stability, good rare earth ions solubility and a large window transmission) (Pal et al., 2012).

Several studies on ZBB glass samples have been published so far. (Shanmugavelu and Ravi Kanth Kumar, 2012) studied on crystallization and phase transformation of the ZBB glasses heated at intermediate temperatures of the exothermic peaks to exhibit both the β-BiB_3O_6 and $Bi_2ZnOB_2O_6$ phases which indicating the presence of surface and bulk crystallizations. (Nam Jin et al., 2009) studied the effect of ZnO on physical and optical properties of bismuth borate glasses and found the systematic variation in density and molar volume of these glasses with ZnO content. Differential thermal analysis (DTA) studies showed that the glass transition temperature (T_g) decreases from 423 °C to 390 °C as the content of ZnO increases. (Koushik et al., 2013) studied on electrical transport characteristics of ZBB glasses. The conduction and relaxation phenomena were rationalized using universal AC conductivity power law and modulus formalism respectively. The activation energy for relaxation determined by the imaginary parts of modulus peaks was 2.54 eV. The obtained value was close to the DC conduction which implying the involvement of similar energy barriers in both the processes. (Feng et al., 2010) studied on structure of ZBB system low-melting sealing glass. The results show that with the increase of B_2O_3 content, the transition temperature and softening temperature of ZBB glass system low-melting sealing glasses are increased, which leads to the increasing of liquid phase precipitation temperature and promotes the structure stability in the glass. (Shashidhar et al., 2008) reported on the effects of Bi_2O_3 content on physical, optical and vibrational studies in ZBB glasses. The variations in density and molar volume of the glasses with Bi_2O_3 content indicate that the glass structures are depended on Bi_2O_3 concentration. In the optical absorption analysis, it is observed that the optical band gap is decreased with increasing of bismuth content; this is corresponding with the increasing of optical basicity. Raman and infrared spectra analysis of ZBB glasses revealed that Bi^{3+} cations are incorporated in the glass network as [BiO_3] pyramidal and [BiO_6] octahedral units.

Although the ZBB is a high density glass system and can be applied as radiation shielding materials, from literatures, there has been no report on radiation shielding properties of ZBB glass system. This work is therefore the first to report on radiation shielding properties of ZBB glass at different gamma-rays energies based on Compton scattering technique.

2. Theoretical backgrounds

2.1. Compton scattering

The inelastic scattering of X-ray and gamma-ray from electrons had been known for a decade when the American researcher Compton (Trousfanidis, 1983) showed a mathematical relationship between incident and scattered gamma-ray energies as follows:

$$E_{\gamma'} = \frac{E_\gamma}{1 + (1 - \cos\theta)E_\gamma/\mathrm{mc}^2} \tag{1}$$

where $E_{\gamma'}$ is the scattered gamma-ray energy, E_γ is the incident gamma-ray energy, θ is the scattering angle, and m is the electron rest mass. This formula is easily derived by assuming a relativistic collision between the gamma-ray and an electron initially at rest. Certainly, under normal circumstances, all the electrons in a medium are not free but bound. If the energy of the photon, however, is of the order of keV or more, while the binding energy of the electron is of the order of eV, the electron may be considered at rest. The collision is inelastic in the sense that one photon is absorbed and another of different frequency and momentum is emitted.

2.2. Mass attenuation coefficient and effective atomic number

The mass attenuation coefficient is written as follows (Limkitjaroenporn et al., 2011):

$$\mu_m = \frac{\ln(I_0/I)}{\rho t} \tag{2}$$

where ρ is the density of material (g/cm^3), I_0 and I are the incident and transmitted intensities and t is the thickness of absorber (cm).Theoretical values of the mass attenuation coefficients of mixture or compound have been calculated by WinXCom, based on the rule of mixture (Gerward et al., 2004):

$$\mu_m = \sum_i w_i(\mu_m)_i \tag{3}$$

where w_i is weight fraction of element in an alloy, $(\mu_m)_i$ is mass attenuation coefficient for individual element in alloy. The value of mass attenuation coefficients can be used to determine the total atomic cross-section ($\sigma_{t,a}$) by the following relation (Limkitjaroenporn et al., 2011):

$$\sigma_{t,a} = \frac{(\mu_m)_{\text{alloy}}}{N_A \sum_i^n (w_i/A_i)} \tag{4}$$

where N_A is Avogadro's number, A_i is atomic weight of constituent element of alloy. The total electronic cross-section ($\sigma_{t,el}$) for the element is also expressed by the following formula (Limkitjaroenporn et al., 2011):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \tag{5}$$

where f_i is the number of atoms of element i relative to the total number of atoms of all elements in alloy, Z_i is the atomic number of the ith element in alloy. Total atomic cross-section and total electronic cross-section are related to effective atomic number (Z_{eff}) of the compound through the formula (Limkitjaroenporn et al., 2011):

$$Z_{\text{eff}} = \frac{\sigma_{t,a}}{\sigma_{t,\text{el}}} \tag{6}$$

The electron density can be defined as the number of electrons per unit mass, and it can be mathematically written as follows (Kaewkhao et al., 2008):

$$N_{\text{el}} = \frac{\mu_m}{\sigma_{t,\text{el}}} \tag{7}$$

3. Experimental setup and procedure

The ZBB glasses of the composition $10ZnO{:}xBi_2O_3{:}(90{-}x)B_2O_3$ (where x = 15, 20, 25 and 30 mol%) were prepared by the melt quenching technique. All chemicals; ZnO, Bi_2O_3 and H_3BO_3, used in the present work were of high purity (Fluka, 99.99%). Appropriate amounts of the raw materials were thoroughly mixed and ground in a pestle and mortar for half an hour. The prepared mixture was then heated in a high purity alumina crucible at 1100 °C inside an electric furnace for about 3 h to ensure complete melting of all components. The melt was then quickly poured into a preheated stainless steel mold and annealed at 500 °C for 3 h before left it to cool down slowly to room temperature. The amount of the glass batch is about 30 g/melts. The chemical compositions of the glasses, prepared in the present work, are summarized in Table 1.