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Development of BaO–ZnO–B_2O_3 glasses as a radiation shielding material

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HIGHLIGHTS

- *x*BaO: 20ZnO: (80 − *x*) B_2O_3, where *x* = 5, 10, 15, 20 and 25 mol%, glasses were prepared.
- The μ_m, Z_{eff} and N_e were increased with increase BaO concentrations and decrease gamma-ray energy.
- Glasses show excellent shielding properties compared with standard shielding materials.
- Developed glasses will be practical potentials in the environmental friendly shielding material.

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ABSTRACT

The effects of the BaO on the optical, physical and radiation shielding properties of the *x*BaO: 20ZnO: (80 − *x*)B_2O_3, where *x* = 5, 10, 15, 20 and 25 mol%, were investigated. The glasses were developed by the conventional melt-quenching technique at 1400 °C with high purity chemicals of H_3BO_3, ZnO, and $BaSO_4$. The optical transparency of the glasses indicated that the glasses samples were high, as observed by visual inspections. The mass attenuation coefficients (μ_m), the effective atomic numbers (Z_{eff}), and the effective electron densities (N_e) were increased with the increase of BaO concentrations, and the decrease of gamma-ray energy. The developed glass samples were investigated and compared with the shielding concretes and glasses in terms of half value layer (HVL). The overall results demonstrated that the developed glasses had good shielding properties, and highly practical potentials in the environmental friendly radiation shielding materials without an additional of Pb.

1. Introduction

In the field of radiation physics and dosimetry, several γ-ray interaction parameters, i.e., mass attenuation coefficient, effective atomic number, electron density, total interaction cross-section, half value layer, and mean free path, are very important. Accurate values of these interaction parameters are required in many scientific and industrial applications. Among these parameters, the mass attenuation coefficient is the most fundamental parameter in the study of γ-radiation interactions with matters. For different materials, this parameter has been determined and compiled by many publications. X-ray and γ-ray attenuations have been studied for concrete (Un and Demir, 2013; Akkurt et al., 2012a, 2012b), alloys (Kaewkhao et al., 2008; Limkitjaroenporn et al., 2012, 2013; Singh et al., 2014), stainless steel (Akkurt et al., 2011), gemstones (Limkitjaroenporn and Kaewkhao, 2014; Korkut et al., 2011), glasses (Limkitjaroenporn et al., 2011; Kaewjaeng et al., 2012; Kirdsiri et al., 2011; Singh et al., 2004, 2014; Kharita et al., 2012), polymer (Mann et al., 2015; Singh et al., 2015) and superconductors (Baltas et al., 2005, 2007; Çevik and Baltas, 2007). Glasses, one of the suitable materials which can be used for radiation materials due to their high transparency in visible region. Among glass materials, the borate is the most popular as a glass forming material. With an addition of alkali oxides to B_2O_3, the covalent network of amorphous boron oxide changes considerably, resulting in the creation of anionic sites that accommodate the modifying alkali cations (Singh et al., 2004). The glasses containing PbO, Bi_2O_3 and BaO were used in radiation applications due to their high effective atomic number and hence strong absorption of

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X-ray and γ-ray. Recently, there are many literatures reported the study on X-ray and γ-ray shielding properties for different glasses such as alumino silicate glass with PbO and Bi_2O_3 (Singh et al., 2014), $BaO:B_2O_3$:fly ash glass (Tuscharoen et al., 2012), PbO:BaO: P_2O_5 glass (Kaur et al., 2015), PbO, Bi_2O_3 and BaO in borate glass, phosphate and silicate glasses (Kaewkhao and Limsuwan, 2010; Kaewkhao et al., 2010; Kirdsiri et al., 2011; Chanthima et al., 2012). The data from literatures show that the BaO can be used as a good radiation shielding material in several glass matrices with good optical properties. Therefore, the BaO was used in this work to replace PbO, which has high cost and causes harmful toxic effect on the environment (Saeed et al., 2014).

In the present study, the barium oxide (BaO) was added in the form of $BaSO_4$ to the glass system that contained boron, whereas ZnO was also added in order to improve its transparency. The glass systems of BaO–ZnO–B_2O_3 were synthesized by a melt quenching technique and investigated for radiation shielding properties, mass attenuation coefficient, effective atomic number, electron density, and half value layer at energy range of 220–662 keV. The studies were based on a Compton scattering technique for the change of photon energies obtained from a Cs-137 source (Limkitjaroenporn et al., 2013).

2. Theoretical background

When monoenergetic gamma-rays are collimated into a narrow beam and allowed to pass through an absorber of variable thickness to strike a detector, there are interactions between gamma-rays photon with absorber. Each of the interaction process, the gamma-rays photon is removed from the beam either by absorption or by scattering away from the detector direction. It can be characterized by a fix probability of occurrence per unit path length that the gamma rays removes from the beam according to Eq. (1) (Knoll, 2010):

$$\mu = \tau(\text{photoelectric}) + \sigma(\text{Compton}) + \kappa(\text{pair}) \quad (1)$$

where μ is the linear attenuation coefficient which equal to the sum of the three possibilities (Tsoulfanidis, 1983). In the photoelectric effect, a photon disappears and an electron is ejected from an atom. The electron carries away all the energy of the absorbed photon, minus the energy binding the electron to the atom (Hubbell, 1999). At low energies, the photoelectric effect dominates, although Compton scattering, Rayleigh scattering, and photonuclear absorption also contribute (Olive et al., 2014). The interaction process of Compton scattering takes place between the incident gamma-rays photon and an electron in the absorbing material. It is the predominant interaction mechanism for typical radioisotope sources of gamma-rays (Knoll, 2010). Pair production is an interaction between a photon and a nucleus. As a result of the interaction, the photon disappears and an electron-positron pair appears (Tsoulfanidis, 1983).

Use of the linear attenuation coefficient is limited by the fact that it varies with the density of absorber, even though the absorber materials is the same. Therefore, the mass attenuation coefficient is much more widely used and is defined (Knoll, 2010; Hubbell, 2006)

$$\frac{\mu}{\rho} = t^{-1}\ell n\{I_0/I_{(t)}\} \quad (2)$$

where ρ is the density of material (g/cm^3), I_0 and I are the incident and transmitted intensities, t is the thickness of an absorber (cm) and μ is the linear attenuation coefficient. Theoretical values of the mass attenuation coefficients of mixture or compound can be calculated by WinXCom, based on a mixture rule (Knoll, 2010)

$$\frac{\mu}{\rho} = \sum_i w_i\left(\frac{\mu}{\rho}\right)_i \quad (3)$$

where w_i is the weight fraction of each element in the mixture, $(\frac{\mu}{\rho})_i$ is the mass attenuation coefficient for an individual element in the mixture.

The half-value thickness, or half-value layer (HVL), is defined in terms of the attenuation of a parallel beam of gamma or X rays, namely (Shultis and Faw, 2010)

$$HVL_{(x)} = \frac{-\ell n2}{d\ell nA_f(x)/dx} \quad (4)$$

For the special case of uncollided monoenergetic photons, $A_f(x) = e^{-\mu x}$, and

$$HVL_{(x)} = \frac{-\ell n2}{d\ell nA_f(x)/dx} = \frac{\ell n2}{\mu} \quad (5)$$

A_f is an attenuation factor which depends on the nature and thickness of the shielding material, the source energy characteristics, and the angle of incidence photon.

Calculations of photon interaction data are generally in terms of atomic cross sections, in units of cm^2/atom, customarily in units of barns/atom (or b/atom) where 1 barn$=10^{-24}$ cm^2. The total atomic cross section (σ_{tot}) is, thus, related to the total mass attenuation coefficient according to (Hubbell, 2006)

$$\mu/\rho(\text{cm}^2\text{g}^{-1}) = \sigma_{tot}(\text{cm}^2/\text{atom})/\left\{mu_{(g)}A\right\} = \sigma_{tot}(\text{b}/\text{atom})\times 10^{-24}/\left\{m_u(g)A\right\} \quad (6)$$

where m_u (g)$=1.66053886\times 10^{-24}$ g, and A is the relative atomic mass of the target element. It can be noted that m_u (g)$=1/N_A$, where N_A is Avogadro's number (6.0221415×10^{23} atoms mol^{-1}).

From Eq. (5), the total atomic cross-section (σ_{tot}) is the sum over the cross sections for the most probable individual processes by which photons interact with atom. The total atomic cross-section for compound and mixture are, thus, related to the mass attenuation coefficient according to (Limkitjaroenporn et al., 2011)

$$\sigma_{tot} = \frac{\left(\frac{\mu}{\rho}\right)_{alloy}}{N_A\sum_i^n (w_i/A_i)} \quad (7)$$

A_i is the atomic weight of constituent element of mixture or compound. On the other hand, the total electronic cross-section ($\sigma_{t,el}$) is the cross section by which photons interact with electron (b/electron). The total electronic cross-section ($\sigma_{t,el}$) for the element is expressed by (Limkitjaroenporn et al., 2011)

$$\sigma_{t,el} = \frac{1}{N_A}\sum_i^n \frac{f_iA_i}{Z_i}\left(\frac{\mu}{\rho}\right)_i \quad (8)$$

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 the mixture. The energy delivered through the photon interactions in composite substances cannot represent the atomic number uniquely across the entire energy region. This number, in composite substances, is called the effective atomic number and it varies with energy and is denoted here by Z_{eff} (Kaginelli et al., 2009). 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)

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \quad (9)$$

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