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Investigation into the optical, physical and radiation shielding properties of sodium borate glasses with the addition of Gd_2O_3 in the energy range of 1 keV to 100 GeV

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Abstract

This research studied the optical, physical and radiation shielding properties of glass samples produced using the melt quenching technique. Samples were prepared with differing concentrations of gadolinium sodium borate. The density of glass samples produced was measured using Archimedes' principle. The optical properties and the hardness were measured using a UV-spectrometer and a micro vickers hardness tester. The theoretical radiation shielding properties of glass samples were calculated using the WinXCom program in the energy range of 1 keV to 100 GeV. The results showed that the density, molar volume and hardness of glass samples was increased with concentration of Gd_2O_3 in the samples. The transmission all of the glass samples produced was found to be between 65% and 80%. From the calculations it was found that the mass attenuation coefficients increased with increasing of Gd_2O_3 concentration and decreased with increasing energy. Photoelectric absorption was found to be the main interaction in the low energy range. At the medium energy range it was found that the radiation shielding parameters were almost constant and were dominated by Compton's scattering process. In the high energy range it was found that pair production became the main interaction process.

Keywords: mass attenuation coefficient, γ-rays, glass

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1. Introduction

In the field of radiation physics and dosimetry, γ-ray interaction parameters, i.e., mass attenuation coefficient, photoelectric interaction, Compton scattering and pair production are very important to investigation for development and characterizations. Accurate values of these interaction parameters are required in many scientific and industrial applications. The mass attenuation coefficient is the most important parameter in the study of γ-radiation interactions with matter. This parameter has been determined for a wide range of materials and details can be found in many publications [1, 2]. Sodium borate glasses can be used as radiation materials due to their high transparency in visible region when compared to other glass materials [3]. Gadolinium (Gd) is paramagnetic at room temperature with a ferromagnetic curie point of 20 °C. Paramagnetic ions, such as gadolinium, move differently within a magnetic field. This trait makes gadolinium useful for magnetic resonance imaging (MRI). Gadolinium has high atomic number (64) and a high density (7.895 g/cm^3) [4, 5] and does not alter the color of glass when it is added.

Glass is an interesting radiation shielding material. This is due to its ability to be transparent to visible light and absorbent to gamma-rays. Other advantages of this type of glass is its ease of fabrication, good homogeneity and excellent transparency. In addition to this its radiation shielding properties can be improved by addition of oxides to the glass when it is manufactured. In addition to this the production cost of this type of glass is not high and it can be easily produced in large size pieces [6]. Sodium oxide is used to expand the glass-forming region, to facilitate ion exchange and to provide glass with a lower melting point. Due to these benefits the structure of sodium glass has attracted increasing attention in recent years. There has been technological and industrial interest in its use in applications such as enamels, photonics, optoelectronic and radiation shielding [7]. Boric acid (B_2O_3) is one of the most commonly used glass formers and vary attractive points because of higher bond

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strength, smaller caption size and heat of fusion. It is known to produce glass at lower melting point with good transparency, high chemical durability and good thermal stability [8].

In this research, glass samples consisting of xGd_2O_3: $30Na_2O$: (70-x) B_2O_3 were manufactured using the melt quenching technique. The samples produced were investigated for their radiation shielding properties. For each sample produced, The mass attenuation coefficient, effective atomic number, photoelectric interaction, Compton scattering and pair production for the samples we predicted using the WinXCom program in the energy range of 1 keV to 100 GeV. [9].

2. Materials and methods

2.1. Glasses preparation

The chemical compositions of sodium borate glasses doped with xGd_2O_3 (where x = 0, 5 and 10 mol%) were are as follows:

$$xGd_2O_3 : 30Na_2O : (70 - x)B_2O_3$$

Names of all of the glass samples produced are shown in Table 1

Glass samples were prepared using the melt-quenching technique. Firstly the ingredients were mixed thoroughly. A 20 gram sample of each mixture was taken and melted in porcelain crucible at 1200 °C for 3 hrs or until a homogeneous mixture was obtained. The samples were annealed in a muffle furnace at 500 °C for 3 h and slowly cooled to room temperature. The glass samples that were produced were in circular in shape and had the dimensions of 1.5×1×0.3 cm^3.

2.2. Density and molar volume calculations

The weights of the prepared glass samples were measured in air and in water using a 4-digit sensitive microbalance (AND, HR200). Then the density (ρ) was determined from the Archimedes principle [2]

$$\rho = \frac{w_a}{w_a - w_w} \times \rho_w \quad (\text{g/cm}^3) \tag{1}$$

where w_a is weights of the glass simple in air, w_b is weights of the glass simple in water and ρ_w is density of water. The corresponding molar volume was calculated using the following equation

$$V_m = \frac{M_T}{\rho} \quad (\text{cm}^3/\text{mol}) \tag{2}$$

where V_m is the molar volume, M_T is the total molecular weight and ρ is the calculated density of the glass.

2.3. Optical transmission and micro vickers hardness measurement

The optical transmission spectra of the glass samples in the UV-VIS-NIR region in the wavelength from 200-1100 nm were measured at room temperature using a double-beam spectrophotometer (Varian cary-50). The micro vickers hardness was measured for each sample using a digital micro vickers hardness tester (DHV-1000). The micro vickers hardness is obtained by dividing the kilogram force (kgf) by the surface area of the indentation produced in testing (mm^2)

$$HV = \frac{2F\sin\frac{136°}{2}}{d^2} \tag{3}$$

where HV = Vickers hardness, F = Load in kgf, d = Arithmetic mean of the two diagonals, $d1$ and $d2$ in mm

2.4. Calculation of the theoretical gamma-rays transmission [2]

The mass attenuation coefficient can be calculated from

$$HV = \text{In}\frac{\left(\frac{I_0}{I}\right)}{\rho t} \quad \text{cm}^2/\text{g} \tag{4}$$

where ρ is the density of the material (g/cm^3), I_0 and I are the incident and transmitted intensities, respectively, and t is the thickness of absorber (cm). In this research, theoretical values of the mass attenuation coefficients were calculated for the samples using WinXCom, based on the mixture rule. This states that;

$$\mu_m = \sum_i w_i\,(\mu_m)_i \quad \text{cm}^2/\text{g} \tag{5}$$

where w_i weight fraction of each element in mixture, $(\mu_m)_i$ is mass attenuation coefficient for individual element in mixture.[10]

3. Results and Discussion

Fig.1 shows a photograph of the glass samples that were prepared. It can be seen that all the glasses appear colorless. This confirms that, for the concentrations that were tested, the Gd ion does not produce color in the glass matrix.

It was found that the density and the molar volume of the samples increased with increasing Gd_2O_3 concentration. The density of the samples were found to be in the range 2.34-2.91 g/cm^3. Theseare shown in Fig. 2. The molar volumes (V_M) of the samples were found to be in the range 28.70-33.10 cm^3/mol. These are are shown in Fig. 3. It is thought that the increase in density of the glass samples that was observered was due to the higher molecular weight of Gd_2O_3 when compared to other components in the glass samples. It was thought that the increasing molar volume indicated increasing inter-atomic spacing in the glass network within the samples. It was thought that the Gd_2O_3molecules act as a network modifier and produce more bridging oxygen (BOs) in glass matrices leading to a larger molar volume overall.

The micro vickers hardness of the samples which were calculated using equation (3) are shown in Fig.4. The results of these calculations show that the hardness was found to increase with increasing concentrations of Gd_2O_3. The transmission spectra of Gd^{3+} ions in the glass samples was measured. As an example, the transmission spectra of the samples in the range from 200 to 1,100nm can be found in Fig.5. The transmission spectra results demonstrate the high transparency of the samples and show that, for the concentrations tested, the transmission spectra was not found to be dependent on the concentration of Gd_2O_3 that was added to the mixture. Fig.6 shows the mass attenuation coefficients of glass samples that were found. These were evaluated from gamma-rays incidented (I_0) and transmitted (I) intensities. Theoretical values were calculated using WinXCom program and equation (5). It was found that the value of μ_m peaks in the low energy regions which correspond to the photoelectric absorption edge. These results reflect the theory that the photoelectric effect is the main interaction at the low energy level. Fig.7 shows the photoelectric absorption at low photon energy (1 keV to 10^3 keV). It can be seen that the values were found to decrease with increasing photon energy. The photoelectric absorption value was found to increase suddenly around the L absorption edge of Gd 8.376 keV. It was also found to increase at the K absorption edge (50.24 keV). These effects were thought to be due to the gadolinium oxide concentration.

Fig.8 shows the incoherent scattering measured in the samples. It was found that these values increased with increasing photon energy range from 10^{-2} MeV to 1 MeV. In contrast to this it was found that they decreased in photon energy range 10^{-1} MeV to 10^3 MeV. Overall the incoherent scattering was found to increase with increasing concentrations of Gd2O3 in the samples. Incoherent scattering was found to be the main interaction at energy levels from10^{-3} MeV to 10 MeV.

Pair production in the nuclear field occurs at photon evergy 1.022×10^3 keV. This corresponds to the total rest mass energy of the electron position. It increases with increases in photon energy. For the glass samples it was found to be the main interaction at photon energy levels higher than 1.022 MeV. The results from the pair productions analysis shows that they increase with increasing Gd_2O_3 concentrations. This is shown in Fig.9.

4. Conclusions

The density, the molar volume and micro vicker's hardness of the samples that were produced were found to increase with increasing Gd_2O_3 concentrations within the range tested. The transmission spectra results found that the transmission spectra was not dependent on the Gd_2O_3 concentrations within the range tested. Mass attenuation coefficients were investigated in order to understand the total photon interactions in the energy range 1 keV to 10^5 keV. This was done using the WinXCom program. It was found that photoelectric interactions were the main interactions at low photon energy levels. It was also found that the values obtained decreased with increasing levels of photon energy. The values were found to increase suddenly near to the L and K absorption edges of the glass samples. They were found to increase along with increasing Gd_2O_3 concentrations within the range tested. . It was found that incoherent scattering was the main photon interaction process in photon energy range 10^{-2} MeV-1 MeV. It was found to increase along with Gd_2O_3 concentrations within the range tested. It was found that the pair production in nuclear field occurred at a photon level of 1.022×10^3 keV. It was found to increases with increasing in photon energy. Pair productions was also found to increase with Gd_2O_3 concentrations within the range tested.

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