Progress in Nuclear Energy 97 (2017) 53–59

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

A comparative study of gadolinium based oxide and oxyfluoride glasses as low energy radiation shielding materials

L. Shamshad [a], G. Rooh [a], P. Limkitjaroenporn [b, c, **], N. Srisittipokakun [b, c], W. Chaiphaksa [b, c], H.J. Kim [d], J. Kaewkhao [b, c, *]

[a] Department of Physics, Abdul Wali Khan University, Mardan 23200, Pakistan
[b] Center of Excellence in Glass Technology and Materials Science (CEGM), Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand
[c] Physics Program, Faculty of Science and Technology, Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand
[d] Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea

ARTICLE INFO

Article history:
Received 26 June 2016
Received in revised form
9 December 2016
Accepted 30 December 2016

Keywords:
Mass attenuation coefficient
Effective atomic number
Half value layer
Radiation shielding

ABSTRACT

The Gadolinium based oxide and oxyfluoride glass systems were prepared using conventional melt quenching method and studied for their radiation shielding properties. The mass attenuation coefficients (μ_m), effective atomic numbers (Z_{eff}) and effective electron densities (N_e) of the glasses at different photon energies were calculated theoretically by WinXcom program and experimentally determined by the transmission method. Moreover, the mass attenuation coefficient was investigated using Geant4 Monte Carlo code and compared with each other. The gamma ray energies were varied by Compton scattering technique. The values of attenuation parameters of both the glass systems have been found to be decrease with the increase in gamma ray photon energy. The results show that, the experimental values of mass attenuation coefficients, effective atomic numbers and effective electron densities are in good agreement with the theoretical values. It seems that Geant4 values are systematically lower than WinXCom. It could be caused by the simplification of geometry in Geant4. Although, the oxide glass system have superior shielding properties than oxyfluoride glass system, but, still, it has better shielding properties than commercial window glass and some existing concretes indicating the potential of this glass to be used as gamma ray shielding material. Moreover, there is no effect of fluoride component on the optical spectra. The optical absorption spectra of the glass systems under investigation have been shown with light transparency which is an edge to be used as radiation shielding material.

1. Introduction

Radiation (X-ray/gamma-ray) shielding is an ongoing problem and up till now it has been extensively investigated. The interaction of energetic radiations X/γ-ray and neutron with the matter is essential in radiation technologies, medical, nuclear engineering, agriculture, space technology, industries, and other shielding applications (Singh and Badiger, 2014). Nowadays, the shielding of the two types of most frequently encountered indirectly ionizing radiations, photons and neutrons, became the subject of interest due to required appropriate safeguards to evade from the radiation hazards.

Transparent radiation shielding materials have been a fascinating field in nuclear engineering (Singh and Badiger, 2014) which offer not only sufficient protection from radiation but also visibility through it. Glasses can perform the double task of allowing visibility while absorbing radiations like gamma-rays and neutrons, and ensuring the protection of onlooker (Singh and Badiger, 2014; Saudi, 2013). Moreover, their properties can be altered to a great extent by altering the composition and adopting variations in the preparation techniques (Singh and Badiger, 2014; Kaur and Singh, 2013; El-Kameesy et al., 2013). Typically, the radiation shielding glasses found its applications in the fields of airport security X-ray screens, for dental clinic, X-ray and radiation protection spectacles, hospital X-ray rooms, laboratories, nuclear facilities, space

* Corresponding author. Center of Excellence in Glass Technology and Materials Science (CEGM), Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand.
** Corresponding author. Center of Excellence in Glass Technology and Materials Science (CEGM), Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand.
E-mail addresses: golfpo@hotmail.com (P. Limkitjaroenporn), mink110@hotmail.com (J. Kaewkhao).

http://dx.doi.org/10.1016/j.pnucene.2016.12.014
0149-1970/

technology for protecting human being (Gupta and Sidhu, 2012, 2015).

Glasses containing B_2O_3 belong to a particular system of glass that showed significant importance for fundamental scientific as well as technological perspective. The high strength of the (B–O) bond of boron atom and its existence in three- and four-oxygen coordinated environments, facilitates the formation of stable borate glasses (Thirumaran and Karthikeyan, 2013). When mixed with glass modifiers, such as Li_2CO_3 or other alkali oxides, its internal structure rearranged through transformation of the structural units of the borate network from BO_3 to BO_4 due to the formation of non-bridging oxygen (Saddeek and Abd El Latif, 2004). Borate based glass compositions have various commercial uses for example chemically durable and heat-resistant neutral glass, fiber glass, encapsulation of radioactive nuclear wastes and recently as biomaterial (Ezz-Eldin, 2001; Liang et al., 2008; Ouis et al., 2012; Abdelghany et al., 2012).

Strontium oxide is one of the heavy metal oxides which has technologically important owing to their optical, mechanical, electrical and thermal properties and has the property to increase the rigidity of the glass samples (Tuscharoen and Kaewkhao, 2014). Moreover, SrO in the glass composition is effective in improving the X-radiation absorption qualities (Connelly Etal, 1969).

Gadolinium (Z = 64), a lanthanide metal, is attractive because of its colossal area of application. It possesses high density (7.895 g/cm^3) and high stopping power with a melting point of 1313 °C and therefore found its applications in the fields of shielding nuclear reactors and gamma and neutron detectors. Also, it has a very high probability of interaction with gamma rays. In X-ray systems, gadolinium contained in phosphor layer, take part in the conversion of X-rays released from the source into light (Ryzhikov et al., 2005). Additionally, it does not produce color centers in the glass.

Oxyfluoride glasses are interesting from fundamental point of view owing to their high mechanical, chemical and thermal stability (Krishnaiah et al., 2013) in a largely-sized formable material (Tang et al., 2004). These unique properties make them an excellent candidate material for application in the UV spectral range (Polishchuk et al., 2011), visible–IR window (Tang et al., 2004) and gamma ray scintillator.

Looking into the importance of all the aforementioned materials regarding radiation shielding, two Gadolinium based oxide and oxyfluoride glass systems were prepared and a comparative study between these glasses have been carried out for their radiation shielding properties.

2. Experimental procedure

The glasses with composition $30Li_2O$-$10SrO$-$15Gd_2O_3$-$45B_2O_3$ and $30Li_2O$-$10SrO$-$15GdF_3$-$45B_2O_3$ have been prepared by the conventional melt quenching method. An appropriate amounts of high purity (99.99%) analytical grade chemicals H_3BO_3, $SrCO_3$, Gd_2O_3, GdF_3 and Li_2CO_3 were used for a 10 g batch/melt.

The starting chemicals were thoroughly mixed in a porcelain crucible and then melted at 1200 °C by an electrical muffle furnace for 3 h in air atmosphere. After complete melting, the melts were quickly poured into a preheated stainless steel mould and annealed at 500 °C for 3 h before being cooled down to room temperature to reduce thermal stresses. Finally, the as-prepared glass samples were cut and then fine polished to a dimension of (W × D × H) 1.0 cm × 0.3 cm × 1.5 cm for further investigation.

2.1. Physical properties

The weight of the prepared glass samples was measured in air and in water with the help of a 4-digit sensitive microbalance (A&D, HR-214) by applying Archimedes principle. Then, the density, ρ, was calculated by using the relation;

$$\rho = \frac{w_a}{w_a - w_b} \times \rho_b \tag{1}$$

where w_a is the weight in air, w_b is the weight in water and ρ_b is the density of water ($\rho_b = 1.00$ g/cm^3). The corresponding molar volume (V_M) was calculated using the relation;

$$V_M = M_T/\rho_b \tag{2}$$

where M_T is the total molecular weight of the multi-component glass system.

The optical absorption spectra of the glass samples were recorded across the UV-Visible-NIR region (200–1100 nm), using a Shimadzu UV-3600 spectrometer. All the measurements were performed at room temperature.

The chemical compositions, density and molar volume and thickness along with referred codes are presented in Table 1.

2.2. Measurement of radiation shielding properties

The experimental set up and block diagram of transmission method for the measurement of mass attenuation coefficient (μ_m) using Compton scattering technique for varying gamma ray energies is presented in Fig. 1(a) and (b) respectively.

The source and the absorber systems were placed on a composite adjustable stands. For proper beam alignment, these stands are cable to move in transverse direction. An aluminum scattering rod was used in this experiment which was placed at an optimum distance of 20 cm from both the radioactive source and detector. The γ-emitter radioactive source, ^{137}Cs having a strength of 15 mCi (555 MBq), have been used in this experiment which was obtained from the Office of Atom for Peace (OAP), Thailand. The intensities of incident and transmitted gamma rays for a fixed preset time in each experiment were determined by recording the corresponding counts with the help of 2″ × 2″ rotatable NaI(Tl) scintillator detector (BICRON model 2M2/2) in a scattering plane having an energy resolution of 8% at 662 keV energy with a CANBERRA photomultiplier tube base (model 802-5). A CANEBERRA PC-based multi-channel analyzer (MCA) was used for recording the spectra. Instant counts in each of 1024 bins, divided by voltage, were obtained from the spectrum on MCA. Calibration on the associating channel number of MCA spectrum has been made with known energies of gamma-ray sources and varied the angle of the detector for the measurement of the angular dependency of Compton scattering. To measure the mass attenuation coefficient, the Compton scattering technique was applied at different angles (θ) to produce γ-rays of different energies. The validity of the system has been confirmed with an energy calibration of the system as shown in Table 2.

In this study the same procedure is followed for the measurement and calculation of mass attenuation coefficient, effective atomic number, effective electron densities and half value layer (HVL) of glasses under investigation as described in the literature (Limkitjaroenporn et al., 2013; Yasaka et al., 2014).

The statistical error in this experiment has been calculated from the standard error of ray-sum (the product of linear attenuation coefficient (m) with thickness (x)) measurement calculated from experiment, density measurement and thickness measurement. Eventually, the total standard error has been determined through combining errors for the three quantities i.e. ray-sum measurement, density measurement and thickness measurement in quadrature.