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Gamma-ray attenuation studies of PbO–BaO–B_2O_3 glass system

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Abstract

PbO–BaO–B_2O_3 glass system has been investigated in terms of molar mass, mass attenuation coefficient and half value layer parameters by using gamma-ray at 511,662 and 1274 keV photon energies. Gamma-ray attenuation coefficients of the prepared glass samples have been compared with tabulations based upon the results of XCOM. Good agreement has been observed between experimental and theoretical tabulations. Our results have uncertainty less than 3%. Radiation shielding properties of the glass system have been compared with some standard radiation shielding concretes.

Keywords: Attenuation coefficient; Glasses; Concretes

1. Introduction

Study of the fundamentals of radiation interactions with materials has become an important research area for investigation. Data on the attenuation of X-rays and gamma-rays in matter is required for many scientific, engineering and medical applications. Gamma-ray and X-ray attenuations have been studied for biological materials (Yang et al., 1987), elements (Goswami and Chaudhari, 1973), alloys (Siddappa et al., 1986; El-Kateb et al., 2000) and compounds (Singh et al., 1996; Turgut et al., 2002, 2004). With the advancement of technology, there is a constant need to develop materials which can be used under a hostile environment of high radiation exposure and can act as good radiation shield (Krocher and Browman, 1984). Material to be used for this purpose should have high attenuation coefficient and the effect of irradiation on its mechanical and optical properties should be small. The experimental measurements of attenuation coefficient is essential for shield design because it provide basic data such as interaction cross-section and half value layer parameters which determine transport and attenuation of radiations in materials. In general, different concretes are used for gamma-ray shield design but considerable variations in their compositions and water contents add uncertainty to the calculation of radiation attenuation coefficient. Being opaque to visible region of light can also be a disadvantage. Freely available computer programs, such as XCOM, facilitate a comparison between measurements and the tabulations i.e. without having to interpolate sparsely populated tables of data.

Measurements of mass attenuation coefficient began with the work of Barka and Sadler (1907, 1909). First compilation of μ/ρ was provided by Allen (1935). In line with the work of Allen, a major compilation of μ/ρ was the semi-empirical set by Victoreen (1949), based upon his earlier (1943, 1948) evaluations. Shortly thereafter, Davison and Evans (1952) published the tables for 24 elements for photon energies in the region of 102.2 keV to 6.13 MeV. NIST entered the area of collection, evaluation, analysis and compilation of μ/ρ data with the work of Fano (1953), White (1952) and

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White Grodstein (1957). Following this foundation work, new theories and measurements were incorporated by Hubbell and Berger (1968). Hubbell (1982) published the tables of mass attenuation coefficients and mass energy absorption coefficients for 40 elements, 45 mixtures and compounds over the energy range from 1 keV to 20 MeV. Later on, these tables were replaced by Berger and Hubbell (1987) followed by development of XCOM computer program for calculating cross-section and attenuation coefficients for elements, compounds or mixtures at photon energy from 1 keV to 100 GeV. Extensive new calculations and theoretical tabulations of scattering cross-sections and quantities related to mass attenuation coefficient have recently become available for photon energies from a few eV to 1 MeV (or less), for $Z = 1$–92 (Chantler, 1995). In our paper, attempt has been made to check the accuracy of the tabulations by comparing the results of the data obtained from experimental values with the theoretical results obtained by XCOM.

The present work has been undertaken to evaluate the applicability of PbO–BaO–B_2O_3 glass system as gamma-ray radiation shields. Gamma-ray mass attenuation coefficients have been determined experimentally and calculated theoretically. A meaningful comparison of their radiation shielding properties has been made in terms of their half value layer parameter with some standard radiation shielding concretes.

2. Theoretical background

Mass attenuation coefficient may be written as

$$\mu/\rho = \ln(I_0/I)/\rho t, \tag{1}$$

where ρ is the density of material, I_0 and I the incident and transmitted intensities and t is the thickness of absorber.

The maximum error in mass attenuation coefficient was determined from errors in intensities, thickness and mass density. Using the propagation of error formula, this gives

$$\Delta(\mu/\rho) = 1/\rho t\{(\Delta I_0/I_0)^2 + (\Delta I/I)^2 + [\ln(I_0/I)]^2 \cdot [(\Delta\rho/\rho)^2 + (\Delta t/t)^2]\}^{1/2}. \tag{2}$$

The following relation relates half value layer to linear attenuation coefficient

$$\mathrm{HVL} = 0.693/\mu. \tag{3}$$

The molar volume V_g, of a glass is given by

$$V_g = M/\rho, \tag{4}$$

where ρ is the mass density of glass and M is the molar mass given by

$$M = xM_1 + (0.50 - x)M_2 + 0.50M_3, \tag{5}$$

where M_1, M_2 and M_3 are the molar mass of PbO, BaO and B_2O_3, respectively. We can define the excess volume, V_e as

$$V_e = V_g - [xV_1 + (0.50 - x)V_2 + 0.50V_3], \tag{6}$$

where V_1, V_2 and V_3 are the molar volumes of PbO, BaO and B_2O_3, respectively.

3. Experimental procedure

Glass samples of the system xPbO $\cdot$ $(0.50 - x)$BaO $\cdot$ $0.50B_2O_3$ ($x = 0.25$, 0.30, 0.35, 0.40 and 0.45 mole fractions) were prepared by melt quenching technique. Appropriate amounts of PbO, $BaCO_3$ and H_3BO_3 of analytical reagent grade were mixed thoroughly. Melts of aforesaid system with different compositions were obtained in electrically heated furnace. Dry oxygen was bubbled through melts at 950 °C using quartz tube to ensure homogeneity followed by annealing in a copper mold whilst returning to room temperature. These samples were ground and polished using silicon carbide and aluminum paper, respectively. Samples have been obtained in cylindrical shape. Density of these samples was measured by Archimedes' principle using Benzene as the immersion liquid.

Attenuation coefficients of the glasses were measured in narrow beam transmission geometry (Fig. 1) by using a 2″ × 2″ NaI(TI) crystal with energy resolution of 12.5% at 662 keV in conjunction with Multi-Channel Analyzer (MCA). Source was contained in a lead cylinder (7 cm thick × 10 cm long) placed behind the source collimator. Samples were placed on specimen holder at the distance of 33 cm from source. The collimators were placed with their front faces at 10, 30 and 58 cm from source and their apertures were 0.57, 0.50 and 0.28 cm. Hence, the incident beam divergence was 1.68° and the acceptance angle at the detector was 0.64°. Overall scatter acceptance angle was 2.32°. The distance between source and detector was 64 cm. Radioactive sources ^{22}Na and ^{137}Cs having activities 185 MBq (5 mCi) each were used for different photon energies. Incident and transmitted intensities of photons were measured on MCA for fixed preset time for each sample by selecting a narrow region symmetrical with respect to the centroid of the photo peak. Counting time was chosen such that 10^5–10^6 counts were recorded under

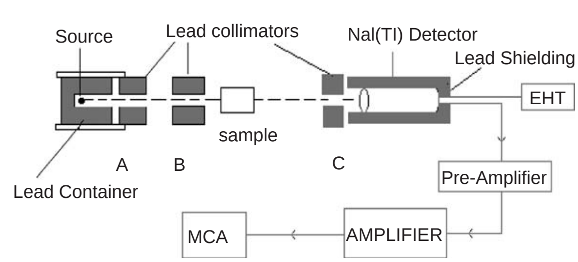

Fig. 1. Narrow beam geometrical setup.