International Journal of Pure and Applied Physics. ISSN 0973-1776 Volume 13, Number 1 (2017), pp. 13-16

Photon Energy Absorption Parameters for Some Sm^{3+} Doped Lead Alumino Phosphate Glasses

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***Abstract*— In sequel to our previous work (P. Kaur et al., 2016 in which optical, photoluminescence and physical properties of Sm^{3+} doped lead alumino phosphate glasses were reported), the work has been extended to visualise the scope of same glasses as gamma-rays shielding materials. In the present work, the gamma-ray shielding parameters viz. mass energy absorption coefficient (μ_{en}), mean free path (mfp), photon energy absorption effective atomic number (Z_{PEAeff}), elctron density (N_e) and kerma relative to air have been evaluated. Further the variation of these parameters with incident photon energy has been investigated.**

***Index Terms*—Glasses, gamma-rays, shielding parameters.**

I. Introduction

Gamma radiations are extensively being used in medical, agriculture and industrial applications. However, the exposure to these highly penetrating radiations is extremely harmful to living beings. For effective handling of these radiations, radiation physicists are searching for viable material. Materials to be used for radiation shielding should have homogeneity of density and composition, and sufficient thickness to absorb the radiations to a safe level. Mass energy absorption coefficient (μ_{en}), mean free path (MFP), effective atomic number (Z_{eff}), the electron density (N_e) and KERMA (kinetic energy released per unit mass) relative to air are the basic quantities which determine the absorption of X-rays and gamma rays photons in matter.

Concretes were used earlier for radiation shielding [1] because of their easy construction design. Now-a-day, various oxide glasses are being explored for gamma ray shielding applications as they have advantage of being transparent beside good radiation absorber and have high flexibility of composition.

Rare earth doped glasses have long been the topic of research owing to their prominent optical properties viz. low optical dispersion, high refractive indices and high transparency to UV light as compared to other oxide glasses [2]. Phosphate glasses serve as excellent material for optical amplifier as it possess good chemical durability, high gain co-efficient, lower transition temperature and higher electrical conductivity [3]. Besides, these glasses have low melting temperature and high thermal expansion coefficient [4]. Phosphate glasses are found to have environmental applications for disposal of radioactive waste [5]. Sm^{3+} doped phosphate glasses exhibit strong fluorescence intensity, large stimulated emission, large absorption cross-section, long fluorescent life time, high luminescence efficiency and rich energy levels [6].

The mass energy absorption coefficient is a measure of the fractional amount of incident photon energy transferred as kinetic energy of charged particles as a result of photon interactions. It also includes energy taken by bremsstrahlung and other escaping secondary photons.

The mean free path (mfp) measures the average distance travelled by a photon between two consecutive collisions/scatterings in the material. The lower is the value of mfp, the better is the radiation shielding material in terms of thickness requirement. The effective atomic number for a material composed of several elements cannot be expressed by a single number. It has to be weighed differently for each of the different processes by which gamma rays can interact with matter [7]. The effective atomic number is defined as the ratio of total atomic cross-section to the total electronic cross-section. Another parameter named photon energy absorption effective atomic number (Z_{PEAeff}) signifies that a compound or a mixture would absorb same amount of energy from the photon as a single element of atomic number equivalent to that number at a given energy.

KERMA is defined as the sum of the initial kinetic energies of all the charged particles liberated per unit mass of a sample of matter by uncharged ionizing radiation. It has the same unit as the absorbed dose.

In sequel to our previous work [8], an attempt has been made to study the radiation shielding properties of the same glass systems. The main objective of this study is to prepare and investigate (a) mass energy absorption coefficient, photon energy absorption effective atomic number, mean free path, electron density and KERMA relative to air of four samples of xP_2O_5-(98-x)PbO-$1.8Al_2O_3$-$0.2Sm_2O_3$ glass systems (x = 48,46,44,42) for photon energies of 1 keV to 100 GeV.

II. Experimental Details

A. Sample Preparation

Four samples of xP_2O_5-(98-x)PbO-$1.8Al_2O_3$-$0.2Sm_2O_3$ glass systems (x = 48,46,44,42) have been synthesized by melt-quenching technique. Analytical grade chemicals were weighed in an electric balance (least count 0.1 mg) and grinded to fine powder in an agate mortar and mixed well. The

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mixture was heated at 1000 °C in a silica crucible for 2 h. The melt was then poured onto a preheated graphite mould of dimensions 1.5 cm (inner diameter) × 1.5 cm (thickness). The glass samples so obtained were annealed at 350 °C for 12 h to eliminate any mechanical and thermal stress.

B. X-ray diffraction

The characterization of glass samples was performed by X-ray diffraction (XRD) studies using Rigaku Miniflex Table Top spectrometer with Cu−kα line of width 1.5418Aº at the scanning rate of 2°/min and 2θ was varied from 5° to 70°.

C. Density Measurement

The density of the prepared glass samples was measured using Archimedes' principle at room temperature. Benzene was used as an immersion liquid. The experiment was performed using sensitive microbalance (Shimadzu ELB300). The chemical composition and respective densities of prepared glass samples is given in TABLE I.

TABLE I
CHEMICAL COMPOSITION AND DENSITY OF GLASS SAMPLES

Sample	Chemical Composition (mol %)	Density (g/cc)
1	PbO: 50; P_2O_5: 48; Al_2O_3: 1.8; Sm_2O_3: 0.2	5.132
2	PbO: 52; P_2O_5: 46; Al_2O_3: 1.8; Sm_2O_3: 0.2	5.216
3	PbO: 54; P_2O_5: 44; Al_2O_3: 1.8; Sm_2O_3: 0.2	5.269
4	PbO: 56; P_2O_5: 42; Al_2O_3: 1.8; Sm_2O_3: 0.2	5.351

III. COMPUTATIONAL WORK

The computational work concerning the computation of different photon interaction parameters is given as follows:

A. Mass Energy Absorption Coefficient

The mass energy absorption coefficient (μ_{en}/ρ) values of the prepared glass samples were obtained in the energy region from 1 keV to 20 MeV based on the mixture rule (equation 1) [9].

$$\left(\frac{\mu_{en}}{\rho}\right)_{glass} = \sum_i w_i \left(\frac{\mu_{en}}{\rho}\right)_i \quad (1)$$

where $\frac{\mu_{en}}{\rho}$ and w_i are the mass energy absorption coefficient and weight fraction of the i^{th} constituent element respectively. Mass energy absorption coefficient for elements (Z = 1 to 92) and some additional compounds of dosimetric interest has been provided by Hubbell and Seltzer (1995) [10] in energy range of 1 keV–20 MeV.

B. Mean Free Path

The mean free path has been determined from the linear energy absorption coefficient (μ) using the relation

$$mfp = \frac{1}{\mu} \quad (2)$$

Linear energy absorption coefficient of the glass samples is obtained by multiplying the corresponding values of mass energy absorption coefficients with its densities.

C. Photon Energy Absorption Effective Atomic Number

The molecular cross-section has been calculated by the relation

$$\sigma_m = \left(\frac{\mu_{en}}{\rho}\right)_{glass} \frac{M}{N_A} \quad (3)$$

where $M = \sum_i n_i A_i$ is the molar mass, N_A is Avogadro number, n_i and A_i are the number of formula units and the atomic weight, respectively, of the i^{th} element in the glass system.

The average atomic cross-section is obtained by dividing the molecular cross-section by the total number of formula units as follow:

$$\sigma_a = \sigma_m \frac{1}{\sum_i n_i} \quad (4)$$

The average electronic cross-section is calculated by the relation

$$\sigma_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} \left(\frac{\mu_{en}}{\rho}\right)_i \quad (5)$$

where $f_i = \frac{n_i}{\sum_j n_j}$ is the fractional abundance of i^{th} element w.r.t. total number of atoms.

The photon energy absorption effective atomic number has been calculated by the relation

$$Z_{PEAeff} = \frac{\sigma_a}{\sigma_e} \quad (6)$$

D. Electron Density

The electron density N_e is derived using the following expression

$$N_e = \frac{\left(\frac{\mu_{en}}{\rho}\right)_{glass}}{\sigma_e} \quad (7)$$

E. KERMA relative to Air

KERMA is the product of the energy fluenece and the mass energy absorption coefficient. The ration of mass energy absorption coefficient values for prepared glass samples $\left(\frac{\mu_{en}}{\rho}\right)_{glass}$ and air $\left(\frac{\mu_{en}}{\rho}\right)_{air}$ is used to find the Kerma relative to air.

$$\frac{K_{glass}}{K_{air}} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_{glass}}{\left(\frac{\mu_{en}}{\rho}\right)_{air}} \quad (8)$$

IV. Results And Discussion

A. XRD Spectral Analysis

XRD spectra of similar glass systems are shown somewhere else [8]. Broad humps are observed in X-ray diffraction pattern of prepared glass samples, which confirms their amorphous nature. Absence of any sharp peak further verifies the glassy nature of Sm^{3+} doped lead alumino phosphate glasses.

B. Density Analysis

Density is a tool for determining the degree of change in a structure with composition of glass. Measured values of densities of the prepared glass samples are presented in TABLE I. All the glass samples are shown to have high density values ranging from 5.132 to 5.351 g cm^{-3}. This is attributed to the high atomic weight provided by PbO. It is further verified that the density values are increasing with increasing concentration of lead which make these glass systems potentially useful for radiation shielding.

C. Photon Energy Absorption Parameters

Variation of mass energy absorption coefficients (μ_{en}/ρ) with incident photon energies ranging from 1 keV to 20 GeV for prepared glass samples has been shown in Fig. 1. The observed variation can be explained on the basis of dominance of different photon interaction processes in different energy regions. It is found that mass energy absorption coefficient has maximum value initially and decreases rapidly with some discontinuities for all glass samples with an increase in incident photon energy upto 1 MeV. It is due to the photoelectric effect (dominant process in lower energy region) as its cross-section varies inversely with the incident photon energy as E^{3-5}. The discontinuities are observed due to various absorption edges of constituent elements. After that, μ_{en}/ρ becomes almost independent of incident photon energy. It may be explained due to the dominance of Compton scattering in the intermediate energy region (1 – 20 MeV).

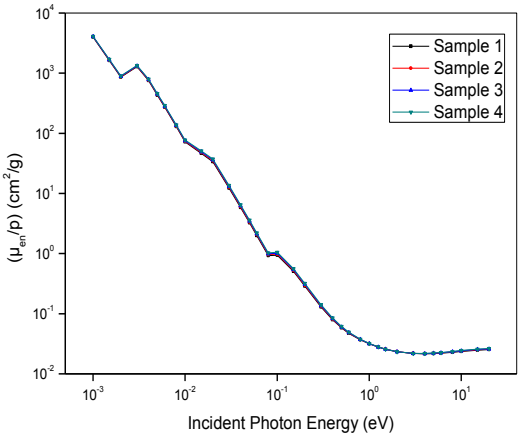

Fig. 1. Variation of mass energy absorption coefficient with the energy of gamma radiations for prepared glass samples

The variation of mean free path with incident photon energy has been shown in Fig. 2. It is observed that mfp increases with increase in incident photon energy at lower and intermediate energy but the rate is slow in latter region. It is in good agreement with the results of mass energy absorption coefficients.

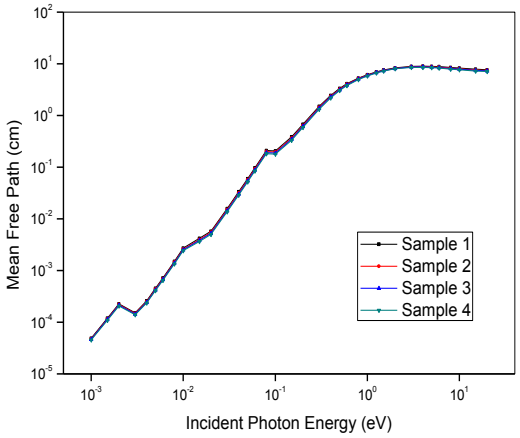

Fig 2: Variation of mean free path with the energy of gamma radiations for prepared glass samples

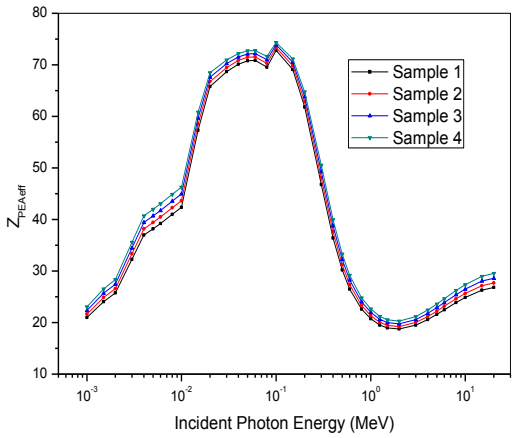

Fig 3: Variation of Photon Energy Absorption Effective Atomic Number with the energy of gamma radiations for prepared glass samples

Photon energy absorption effective atomic number (Z_{PEAeff}) is computed for selected glass samples from the contribution of all partial photon interaction processes in different energy regions. Higher values of photon energy absorption effective atomic number are required for a better gamma rays shielding material as it provides higher probability of photons interaction with the material. Its variation with energy has been shown in Fig. 3. It has been observed that the Z_{PEAeff} for all glass sample remains in the range of the atomic number of its constituent elements ($1< Z< 82$). All the glass sample shows lower values of Z_{PEAeff} initially at 1 keV of incident photon energy. It is due to the absorption edges of various constituent elements. Z_{PEAeff} then increases rapidly upto 30 keV, then becomes almost constant in the energy region 30 – 200 keV. It is due to Z-dependence of cross-sectional values

(Z^{4-5}) of photoelectric effect at low energy as compared to other photon interaction process. Hence maximum value of Z_{PEAeff} is observed in the lower energy region. On further increasing incident photon energy, Z_{PEAeff} values decreases rapidly upto almost 2 MeV. In this energy region, there is competition between the two photon interaction processes namely, photoelectric effect and Compton effect, which results in significant decrease in Z_{PEAeff} values. Minimum values of Z_{PEAeff} is observed in intermediate energy region where Compton scattering is the dominant process and its cross-section depends linearly on the atomic number of elements. After that, it shows a slow increase.

Sample 4 is shown to have the maximum value of Z_{eff} at almost all the energies in the given energy range. Variation of electron density (N_e) with energy is following the same trend as that by Z_{PEAeff} (Fig.4). Higher values of electron density correspond to the presence of more number of electrons per unit mass and hence more probability of photon interaction with these electrons.

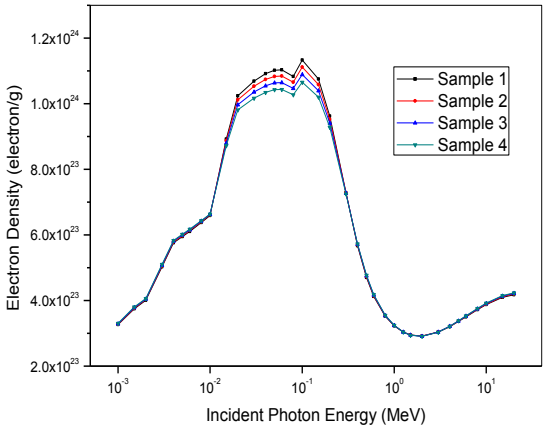

Fig 4: Variation of electron density with the energy of gamma radiations for prepared glass samples

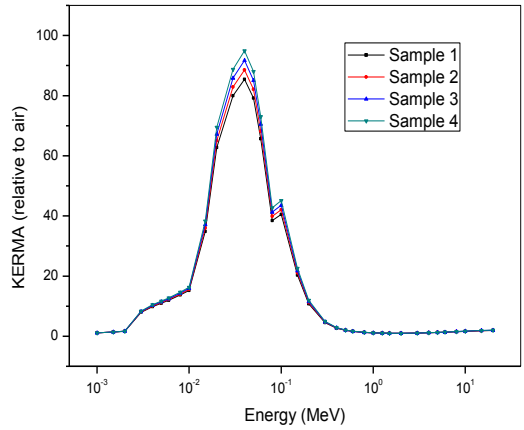

Fig 5: Variation of KERMA relative to air with the energy of gamma radiations for prepared glass samples

The variation of KERMA relative to air with incident photon energy for prepared glass samples is shown in Fig 5. It is observed that the KERMA relative to air is almost following the trend shown by Z_{PEAeff}. It may be due to the reason that KERMA is directly related to mass energy absorption coefficient which thereby shows strong dependence on photon energy absorption effective atomic number of the interacting materials. In the intermediate energy region, the value KERMA relative to air for all glass samples approaches to 1. This is because in this region, where Compton scattering is dominant process, there is only partial energy absorption within the interacting medium. Hence KERMA relative to air reduces and approaches to unity.

V. Conclusion

Sm^{3+} doped lead alumina phosphate glasses, synthesised by melt quenching technique, have been analysed in terms of photon energy absorption parameters viz. mass energy absorption coefficient, mean free path, photon energy absorption effective atomic number, electron density and KERMA relative to air. All the parameters are found to be dependent on the energy of incident photons and shows significant variation whenever there is shifting between the dominance of photon interaction process. Glass samples have shown improved photon energy absorption parameter in terms of radiation shielding with increasing mole percentage of lead. Among all the glass samples, Sample 4 is observed to have maximum values of density, photon energy absorption effective atomic number, electron density KERMA relative to air which makes it efficient absorber of gamma radiations and hence, best radiation shielding material among the prepared samples.

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