Investigation of Photon InteractionParameters of Lead-Alumino-Borophosphate Glass System at Energies from 1 keV to 100 GeV

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ABSTRACT *The mass attenuation coefficient (μ_m), effective atomic number (Z_{eff}) and effective electron density (N_e) of -* $xPbO-(49-0.5x)B_2O_3-(49-0.5x)P_2O_5-1.6Al_2O_3-0.2Sm_2O_3-0.2Gd_2O_3(x=0,10,20,30,40,50)$ *glass system are calculatedtheoretically using WinXCom (2001) programin the energy region from 1 keV to 100 GeV. The variations of μ_m, Z_{eff} and N_e with energy are showngraphically for total photon interaction. It is observed that the value of these parameters has changed with energy and composition of the Lead-Alumino- Borophosphate glasses. Among the selected glass samples the sample with 50% mol fraction of PbOshows maximum values for μ_m, Z_{eff} and N_e in the entire energy grid.These results indicate thatglasses in the present study can be used as radiation shielding materials and among the selected series,50% molfraction of PbO glass is the best. It is also found that these samples may also be used for gamma ray sensing/detection.*

Key words: *Borophosphate glasses, PbO, Shielding properties, Rare earth metals.*

I. INTRODUCTION

Natural glass, existedfrom the beginning of the formation of Earth, formed when certain types of rocks melt due to the volcanic explosion, lightning strikes or the collision of meteorites. Modernglass is a resourceful material that is commercially available over a wide range ofcompositions and can be fabricated in huge varieties.The advantages of glass are they are easy to fabricate with high homogeneityand transparency. They also show radiation shielding propertyand this property can be further improved by the addition of high atomic number element oxide in the glasscomposition. The glass materials are considered as good substituteof concrete for shielding purpose[1].Glasses also have potential application in developing materials for detecting gamma rays through down conversion of energy[2].

In dealing with mixture of molecules, such as composites and glasses, it is convenient to describethe mixture by an effective atomic number (Z_{eff}). This parameter is dependent on incident photon energy and it points out that at a given energy, photons interacts with a composite material in a similar manner as a single element of atomic number corresponding to that composite material.The mass attenuation coefficient (μ_m) and Z_{eff}areessential quantities fordetermining the penetration of gamma-ray photons in matter.Effectiveelectron density (N_e) is also a suitableparameter in designing radiation shielding,computing absorbed dose, energy absorption and build-upfactor which represent radiation interaction with matter[3].

Various investigations[4-10]have been made to study the shielding properties of glass systems. In present measurements it is expected that addition of PbO in alumino-borophosphate glass will increase its density and refractive index making it appropriate for radiation shielding application. In the studied glass system, the choice of Sm^{+3} and Gd^{+3} doped glassesis based on the criteria that they exhibit strong fluorescence intensity, large stimulated emission, large absorption cross-section, high luminescence efficiency and rich energy levels[11-12]. Consequently these glasses may be used as gamma ray sensing/detecting materials. Host lattice of lead and borophosphate have a large attenuation coefficient for gamma rays photons. Thus the same glass matrix exhibits dual properties of radiation detection and shielding.In recent years glasses doped with rare-earth ions haveattracted much attention because of these applications.

The present study is made toinvestigate theμ_m, Z_{eff} andN_e, for photon interactions of- $xPbO-(49-0.5x)B_2O_3-(49-0.5x)P_2O_5-1.6Al_2O_3-0.2Sm_2O_3-0.2Gd_2O_3(x=0,10,20,30,40,50)$gla

ss systemin the energy region of 1 keV to 100 GeVand to further check the radiation shielding properties in the aforesaid energy region.Considering the advantage of borophosphate glasses, an attempt has been made to check lead-alumino-borophosphate glasses doped with Sm^{+3} and Gd^{+3} in different composition of PbO, B_2O_3, P_2O_5 and constant weight fraction of Gd_2O_3 and Sm_2O_3 and to explore its feasibility as gamma ray shielding material.

II. THEORETICAL CONSIDERATION

A mass attenuation coefficient (μ_m) measures the number of photons interacting with the associated material. The μ_m values of the selected glass samples were generated in the energy region from 1 keV to 100 GeV using WinXCom[13]energy grid based on the mixture rule as given by Equation 1. The WinXCom program provides total cross section and attenuation coefficients as well as partial cross sections for various interaction processes for about 100 elements:

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i (cm^2/g) \quad (1)$$

where w_i is the weight proportion of the ith constituent element, $(\mu/\rho)_i$ is mass attenuation coefficient of constituent element. For glasses, the mixture rule is valid with the assumption that the effects of molecular binding and the chemical and crystalline environment are negligible.

Using $\mu_m$of the sample,the total photon interaction cross-section σ_t is obtained as:

$$\sigma_t = \frac{M}{N_a}(\mu_m)_{glass}(barn/molecule) \quad (2)$$

where M is molecular weight of sample and N_a is Avogadro's number. The total atomic cross-section σ_a is related to σ_t as:

$$\sigma_a = \frac{\sigma_t}{\sum_i n_i}(barn/atom) \quad (3)$$

where $\sum_i n_i$ is total number of atoms in a molecule.

The average electronic cross-section is(Singh, T. et al. 2010):

$$\sigma_e = \frac{1}{N_a}\sum_i \frac{f_i A_i}{Z_i}(\mu_m)_{glass}(barn/electron) \quad (4)$$

Effective atomic number (Z_{eff}) is:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e}(unitless) \quad (5)$$

Electron density (i.e., number of electron per unit mass) for glass sampleis:

$$N_e = \frac{\mu_m}{\sigma_e}(e/g) \quad (6)$$

III. RESULTS AND DISCUSSION

The chemical composition of glasses studiedin present work is given in Table 1.The mass attenuation coefficients for the selectedPbO-B_2O_3-P_2O_5-Al_2O_3-Sm_2O_3-Gd_2O_3 systems wereobtained using WinXCom (2001) software for photon energiesranging from 1 keV to 100 GeV. The variation of $\mu_m$with incident photon energy is shown in Fig 1.

TABLE 1. Chemical composition of glasses studied in the present work

Sample	Chemical composition (weight fraction)					
	B_2O_3	P_2O_5	PbO	Al_2O_3	Sm_2O_3	Gd_2O_3
Pb-50	0.24	0.24	0.5	0.016	0.002	0.002
Pb-40	0.29	0.29	0.4	0.016	0.002	0.002
Pb-30	0.34	0.34	0.3	0.016	0.002	0.002
Pb-20	0.39	0.39	0.2	0.016	0.002	0.002
Pb-10	0.44	0.44	0.1	0.016	0.002	0.002
Pb-00	0.49	0.49	0.0	0.016	0.002	0.002

The μ_m of the selected glasses varies with the photon energy for all the compositions and this variation of μ_m with photon energy can be divided on the basis of three dominant photon interaction processes in different energy regions: (*i*) photoelectric absorption from 1 to 100 keV, (*ii*) Compton scattering from 100 keV to 1.02 MeV, and (*iii*) pair production at energy above 1.02 MeV.The role of coherent scattering is not significant here because it occurs mainly at very low energies. Below 100 keV, there has been observed discontinuities in the variation of μ_m which arises from the photoelectric effect around various absorption edges of elements as shown in Table 2.

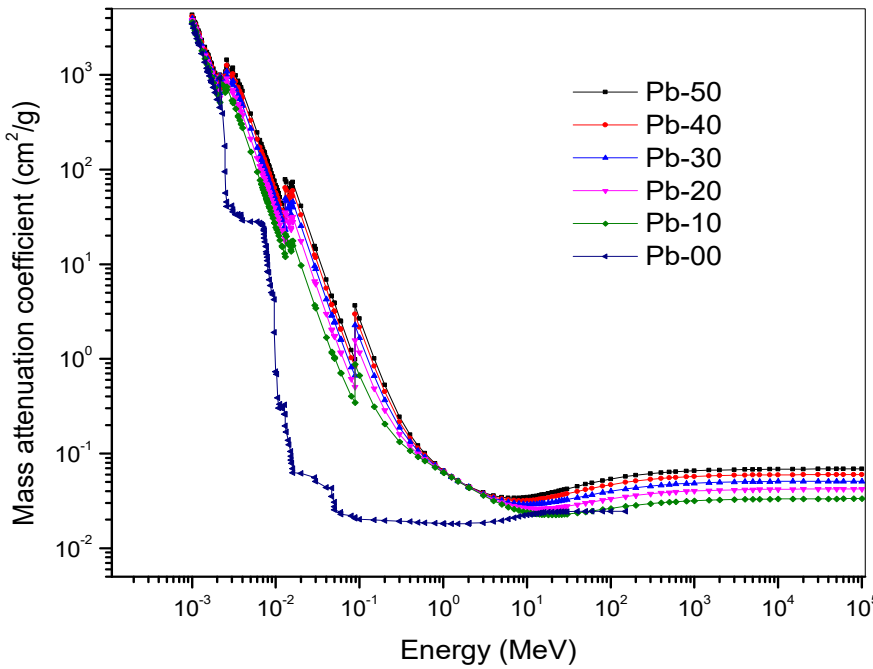

FIG 1. Variation of mass attenuation coefficient with energy for selected borophosphate glasses.

TABLE 2. Photon energies (in keV) of absorption edges above 1 keV

Element	Z	M5	M4	M3	M2	M1	L3	L2	L1	K
Al	13	--	--	--	--	--	--	--	--	1.560
P	15	--	--	--	--	--	--	--	--	2.145
Sm	62	1.080	1.106	1.420	1.541	1.723	6.716	7.321	7.737	46.830
Gd	64	1.185	1.217	1.544	1.688	1.881	7.234	7.930	8.376	50.240
Pb	82	2.484	2.586	3.066	3.554	3.851	13.035	15.200	15.861	88.005

Z_{eff} has been calculatedfor selected glass samples from the contribution of allpartial photon interaction processes in differentenergy regions. The variation of Z_{eff} with incident photon energy isshown in Fig. 2.It shows that Z_{eff} is a function of the weight fraction of samarium, gadolinium and leadfor some selected energies. Below2.15 keV,a discontinuous decrease in $Z_{eff}$is observed. This may be due toabsorption edges of various constituent elements.

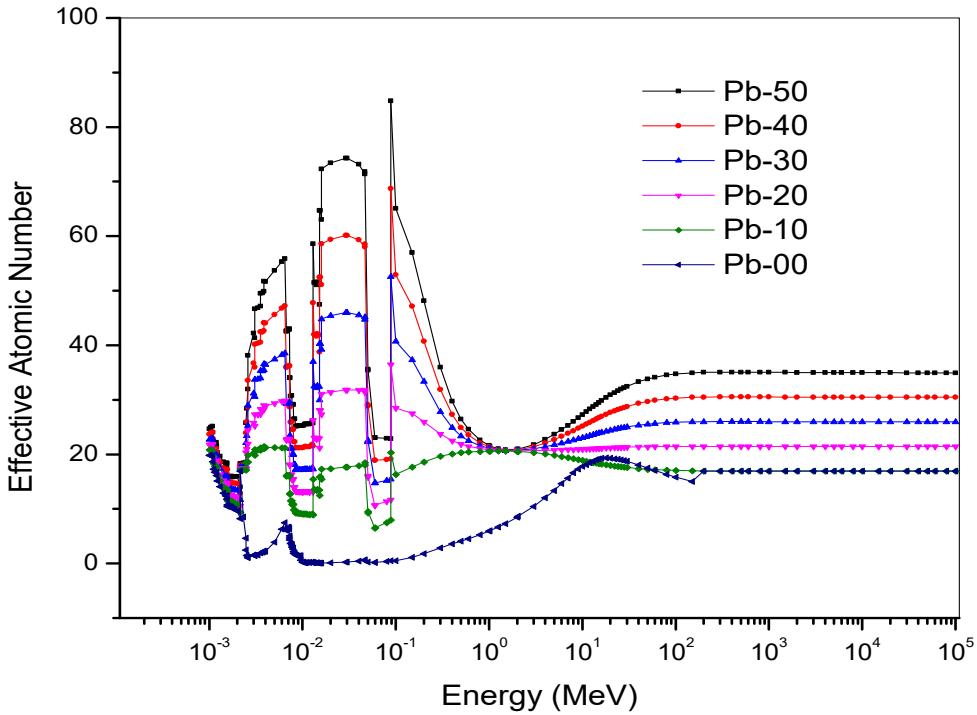

FIG 2. Variation of effective atomic number with energy for selected borophosphate glasses.

From 2.4 to 8.4 keV, there is a region of increased $Z_{eff}$and is shown as a broad peak in Fig 2.The increase in Z_{eff} in this region may be due to the presence of L X-rays of Sm and Gd.There is a similar increase in Z_{eff} in the energy region of 12 keV to 50 keV and this may be due to reason of presence of the L X rays of Pb and K X rays of Gd and Sm. A sharp peak at 87 keV is due the K X-rays of Pb. Further, thereis a sharp decrease inZ_{eff} due to dominance of photoelectric absorption inthis region. Z_{eff}becomes constant from 1 MeV to2.5MeV due to Compton scattering. Thereafter, Z_{eff}increases with increase in photon energy above 5 MeVdue to dominance of pair production in the higherenergy region. The glass sample Pb-50 has the maximum value of Z_{eff}in comparison to all other samples at almost all the energiesin the given energy range. It is observed that the variation of μ_m and $Z_{eff}$is increased with increasing weight fraction of PbO. Variation of electron density(Ne) with energy is following the same trend as that byZ_{eff}(Fig. 3).

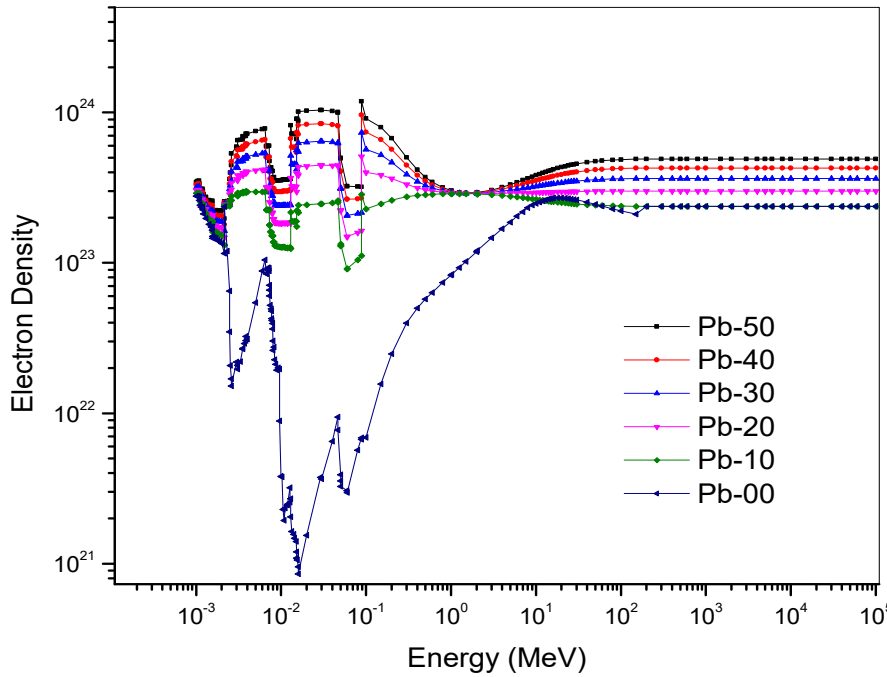

FIG 3. Variation in electron density with energy for selected borophosphate glasses.

Fig. 4is drawn withZ_{eff} as a function of the weight fraction of lead, for some selected energies.It is clear that the Z_{eff}increases slightly with increase in the weight fraction of lead. Figure shows that the Z_{eff} of lead-alumino-borophosphateglass at 100 keV has higher value than 10 keV. Also, it was observed that the variation of (μ_m), Z_{eff} and $N_e$is increased with increasing weight fraction of lead in the glass system.

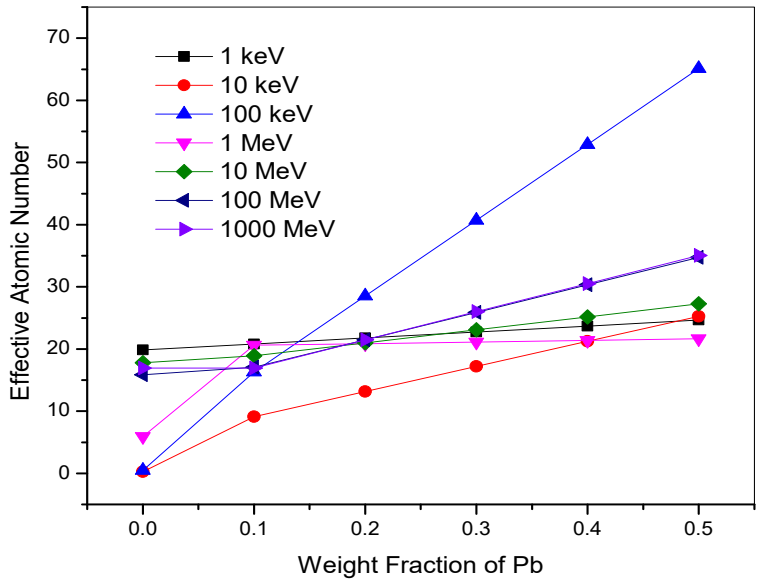

FIG 4. The Z_{eff} of borophosphate glasses as a function of the weight fraction of PbO.

Fig. 1-3show that for sample Pb-00, the values of μ_m, Z_{eff} and Ne are very low in comparison of other glass samples.It is evident that PbO plays a vital role in the shielding properties of the glass samples and related parameters.

IV. CONCLUSION

The photon interaction of borophosphate glasses containing PbO, Gd_2O_3 and Sm_2O_3 depends on the photonenergy. The material density is the main contribution in thephoton attenuation coefficient which is important for radiationshielding. The total $\mu_m$of the glass is increased with theincrease inPbOconcentration as a result ofincreasing photoelectric absorption. The parameter Z_{eff} and $N_e$are energy dependent and vary from a higher value at lower energies to a lower value athigher energies due to photoelectric effect near the M-, L- and Kabsorptionedge of samarium andgadolinium. This suggests that contribution ofPbOimproves the radiation shielding properties of alumino-borophosphateglasses. On the basis of Z_{eff} and N_e it is clear that for these glasses there are energy regions in which the shielding properties are greater than other regions.Among the selected glass samples, Pb-50 sample has the best radiation shielding parametersin terms of mass attenuation coefficient and effective atomic number.

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