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

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ABSTRACT

The mass attenuation coefficient ($\mu_m$), effective atomic number ($Z_{eff}$) and effective electron density ($N_e$) of $xPbO-(49-0.5x)B_2O_3-(49-0.5x)P_2O_5-1.6Al_2O_3-0.25m_2O_5-0.2Gd_2O_3(x = 0.10, 0.20, 0.30, 0.40, 0.50)$ glass system are calculated theoretically using WinXCom (2001) program. The energy region from 1 keV to 100 GeV. The variations of $\mu_m$, $Z_{eff}$ and $N_e$ with energy are shown graphically for total photon interaction. It is observed that the property 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 PbO shows maximum values for $\mu_m$, $Z_{eff}$ and $N_e$ in the entire energy grid. These results indicate that glasses in the present study can be used as radiation shielding materials and among the selected series, 50% mol fraction 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, existed from 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 objects. Modern glass is a resourceful material that is commercially available over a wide range of compositions and can be fabricated in huge varieties. The advantages of glass are that they are easy to fabricate with high homogeneity and transparency. They also show radiation shielding property and this property can be further improved by the addition of high atomic number element oxide in the glass composition. The glass materials are considered as good substitute of concrete for shielding purpose. Glasses also have potential application in developing materials for detecting gamma rays through down conversion of energy.

In dealing with mixture of molecules, such as composites and glasses, it is convenient to describe the 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 ($\mu_m$) and $Z_{eff}$ are essential quantities for determining the penetration of gamma-ray photons in matter. Effective electron density ($N_e$) is also a suitable parameter in designing radiation shielding, computing absorbed dose, energy absorption and build-up factor which represent radiation interaction with matter.

Various investigations 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 glasses is based on the criteria that they exhibit strong fluorescence intensity, large stimulated emission, large absorption cross-section, high luminescence efficiency and rich energy levels. 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 have attracted much attention because of these applications.

The present study is made to investigate the $\mu_m$, $Z_{eff}$ and $N_e$ for photon interactions of $xPbO-(49-0.5x)B_2O_3-(49-0.5x)P_2O_5-1.6Al_2O_3-0.25m_2O_5-0.2Gd_2O_3(x = 0.10, 0.20, 0.30, 0.40, 0.50)$ glass samples.
ss system in the energy region of 1 keV to 100 GeV and 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$_2$O$_3$, P$_2$O$_5$ and constant weight fraction of Gd$_2$O$_3$ and Sm$_2$O$_3$ and to explore its feasibility as gamma ray shielding material.

II. THEORETICAL CONSIDERATION

A mass attenuation coefficient ($\mu_m$) measures the number of photons interacting with the associated material. The $\mu_m$ 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:

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i \left( \frac{\mu_i}{\rho_i} \right) \text{(cm}^2/\text{g)}$$

where $w_i$ is the weight proportion of the $i^{th}$ 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 $\sigma_t$ is obtained as:

$$\sigma_t = \frac{M}{N_a} \left( \mu_m \right)_{\text{glass}} \text{(barn} / \text{molecule)}$$

where $M$ is molecular weight of sample and $N_a$ is Avogadro’s number. The total atomic cross-section $\sigma_a$ is related to $\sigma_t$ as:

$$\sigma_a = \sum_i n_i \sigma_i \text{(barn} / \text{atom)}$$

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

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

$$\sigma_e = \frac{1}{N_a} \sum_i f_i A_i \left( \mu_m \right)_{\text{glass}} \text{(barn} / \text{electron)}$$

Effective atomic number ($Z_{\text{eff}}$) is:

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

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

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

III. RESULTS AND DISCUSSION

The chemical composition of glasses studied in present work is given in Table 1. The mass attenuation coefficients for the selected PbO-B$_2$O$_3$-P$_2$O$_5$-Al$_2$O$_3$-Sm$_2$O$_3$-Gd$_2$O$_3$ systems were obtained using WinXCom (2001) software for photon energies ranging from 1 keV to 100 GeV. The variation of $\mu_m$ with incident photon energy is shown in Fig 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Chemical composition (weight fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B$_2$O$_3$</td>
</tr>
<tr>
<td>Pb-50</td>
<td>0.24</td>
</tr>
<tr>
<td>Pb-40</td>
<td>0.29</td>
</tr>
<tr>
<td>Pb-30</td>
<td>0.34</td>
</tr>
<tr>
<td>Pb-20</td>
<td>0.39</td>
</tr>
<tr>
<td>Pb-10</td>
<td>0.44</td>
</tr>
<tr>
<td>Pb-00</td>
<td>0.49</td>
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</table>
The $\mu_m$ of the selected glasses varies with the photon energy for all the compositions and this variation of $\mu_m$ 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 $\mu_m$ which arises from the photoelectric effect around various absorption edges of elements as shown in Table 2.

![Graph](image.png)

**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

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

$Z_{\text{eff}}$ has been calculated for selected glass samples from the contribution of all partial photon interaction processes in different energy regions. The variation of $Z_{\text{eff}}$ with incident photon energy is shown in Fig. 2. It shows that $Z_{\text{eff}}$ is a function of the weight fraction of samarium, gadolinium and lead for some selected energies. Below 2.15 keV, a discontinuous decrease in $Z_{\text{eff}}$ is observed. This may be due to absorption 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 \( Z_{\text{eff}} \) and is shown as a broad peak in Fig 2. The increase in \( Z_{\text{eff}} \) in this region may be due to the presence of L X-rays of Sm and Gd. There is a similar increase in \( Z_{\text{eff}} \) 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, there is a sharp decrease in \( Z_{\text{eff}} \) due to dominance of photoelectric absorption in this region. \( Z_{\text{eff}} \) becomes constant from 1 MeV to 2.5 MeV due to Compton scattering. Thereafter, \( Z_{\text{eff}} \) increases with increase in photon energy above 5 MeV due to dominance of pair production in the higher energy region. The glass sample Pb-50 has the maximum value of \( Z_{\text{eff}} \) in comparison to all other samples at almost all the energies in the given energy range. It is observed that the variation of \( \mu_{\text{m}} \) and \( Z_{\text{eff}} \) is increased with increasing weight fraction of PbO. Variation of electron density (\( N_{\text{e}} \)) with energy is following the same trend as that by \( Z_{\text{eff}} \) (Fig. 3).
FIG 3. Variation in electron density with energy for selected borophosphate glasses.

Fig. 4 is drawn with Z_{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-borophosphate glass at 100 keV has higher value than 10 keV. Also, it was observed that the variation of (\mu_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. 1-3 show that for sample Pb-00, the values of $\mu_m$, $Z_{eff}$ and Ne are very low in comparison with 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$_2$O$_3$ and Sm$_2$O$_3$ depends on the photon energy. The material density is the main contribution in the photon attenuation coefficient which is important for radiationshielding. The total $\mu_m$ of the glass is increased with the increase in PbO concentration as a result of increasing photoelectric absorption. The parameter $Z_{eff}$ and Ne are energy dependent and vary from a higher value at lower energies to a lower value at higher energies due to photoelectric effect near the $M_\gamma$, $L_\gamma$ and Kabsorption edge of samarium and gadolinium. This suggests that contribution of PbO improves the radiation shielding properties of alumino-borophosphate glasses. On the basis of $Z_{eff}$ and Ne, 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 parameters in terms of mass attenuation coefficient and effective atomic number.

REFERENCES