EXPERIMENTAL AND THEORETICAL CHARACTERIZATION OF LEAD GLASS COMPOSITES AS A GAMMA RAY ATTENUATOR

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The present work is concerned with the determination of linear attenuation coefficient, mass attenuation coefficients, the effective atomic number and electron density for different leaded glass composites by \textsuperscript{60}Co gamma-ray source. Linear attenuation coefficient (\(\mu\)) has been measured by the transmission method in a good geometry setup. The measurements have been carried out using a collimated beam emerging from \textsuperscript{60}Co radioactive source and the NaI(Tl) scintillation detector. Also, NCNP5 code has been used to calculate (\(\mu\)) by modeling the experimental technique. The mass attenuation coefficients (\(\mu/\rho\)) have been achieved using the evaluated linear attenuation coefficients (\(\mu\)). The effective atomic number (\(Z_{\text{eff}}\)) and electron density (\(N_{\text{el}}\)) have been calculated depending on the experimental results. Also, WinXCom program has been used to compute the same parameters theoretically. The general trend of the calculated parameters show increase with the increasing of PbO concentration.

**Keywords:** Lead Glass Composites, Mass Attenuation Coefficient, Effective Atomic Number, Effective Electron Number.

INTRODUCTION

Study of the absorption of gamma-rays in materials used for shielding purposes is an important subject in the fields of radiation physics and radiological safety. The Parameters as total mass attenuation coefficient \(\mu/\rho\) (cm\(^2\).gm\(^{-1}\)), effective atomic number (\(Z_{\text{eff}}\)) and electron density (\(N_{\text{el}}\)) are very important for X and gamma rays
interaction; in the shielding design and estimation of absorbed dose in the medical diagnostics. The leaded glass composites had been prepared to be used as radioactive waste immobilisation forms and radiation shielding glass. Glasses are 100% recyclable and are one of the safest packaging materials due to their composition and inherent properties; it does also obtain shielding properties upon the introduction of lead oxide additives. To evaluate the integrity of the formulated leaded glass composites; fast, slow neutrons and gamma-rays attenuation parameters had been experimentally measured and theoretically calculated. A comparison was held between both values and a reasonable agreement could be recognized [1]. A thorough knowledge of the interaction of photons of different energies with the investigated composites and the data related to their mass attenuation coefficients, effective atomic number ($Z_{\text{eff}}$) and electron density ($N_{\text{el}}$) should be compiled.

This paper reports the experimental measurements of linear gamma ray attenuation coefficients using the $^{60}\text{Co}$ radioactive source, which possess two gamma lines (1.173 and 1.332 MeV). To conclude and complete the most attenuation parameters of gamma rays for the five leaded glass composite samples, the total mass attenuation coefficient $\mu/\rho$ (cm$^2$.gm$^{-1}$), effective atomic number ($Z_{\text{eff}}$) and electron density ($N_{\text{el}}$) have been evaluated. WinXCom computer program developed for calculating mass attenuation coefficients or photon interaction cross-section for any element, compound or mixture at energies from 1 keV to 100 GeV [2, 3] was used to calculate the attenuation parameter $\mu/\rho$ for the investigated samples. As well, the computer code MCNP5 [4] was used to calculate the same parameter for the concerned composites to conforming the obtained results. A comparison was held between the evaluated and both theoretically calculated shielding parameters, where a reasonable agreement was found. In composite materials, scattering and absorption of gamma rays is related to density as well as effective atomic number ($Z_{\text{eff}}$). Both parameters do have a role in visualizing the material characteristics and the latter is defined as the ratio of total atomic cross-section to the total electronic cross-section. The effective atomic numbers ($Z_{\text{eff}}$) and electron number densities ($N_{\text{el}}$) have been determined experimentally and were calculated theoretically [2, 5].

**EXPERIMENTAL DETAILS**

1-Materials

Leaded glass composites with different PbO concentrations ($x= 0, 5, 10, 15$ and $25$ wt%) had been prepared by the Nasser Glass Crystal Company as shielding composites for neutrons and gamma rays. The blank sodalime silica glass consisted of: white sand $53.08\%$, soda ash $21.42\%$, lime stone $13.26\%$ and dolomite $12.24\%$, respectively. The details of fabricated leaded glass composites are given elsewhere [1].

2-Gamma-Ray Attenuation Measurements

To determine the linear attenuation coefficients for the investigated composites, the narrow beam gamma–ray transmission experiment was utilized. The experimental
layout in details is given elsewhere in the published ref. [6]. The source (\(^{60}\)Co with strength of 433 MBq at the time of experiment) was enclosed in a lead container with one face aperture (10 mm in height and 4 mm in diameter). The samples were positioned on the samples holder close to the beam exit. A NaI(Tl) crystal detector of (5” diameter and 2” thick) with an energy resolution of 8% at 662 keV and a Multi-Channel Analyzer (MCA) plug-in-card (1024 channel) running with associated electronics was used to record the pulse-height spectrum of the \(^{60}\)Co radioactive source under Maestro-32 software package. The intensities of photons were measured without and with placing the samples between the source and the detector. A typical pulse-height distribution of gamma-ray spectrometer at 1173 and 1332 keV is shown in Fig.1, where the intensities of incident and transmitted photons were \((I_0)\) and \((I)\), respectively. Measured \((I_0)\) and \((I)\) have a fixed preset time and were counted by selecting a narrow symmetrical region with respect to the centroid of photo peak. The net area under each peak gives the intensity of gamma-rays. The counting time for each measurement was chosen so that sufficient counts were recorded for each condition giving a statistical accuracy better than 0.3 %.

![Figure 1. Pulse-height distribution of the gamma-ray spectra without and with attenuator leaded glass sample.](image)

**CALCULATIONAL METHODS**

1- Gamma-Ray Total Mass Attenuation Coefficients (\(\mu/\rho\))

According to Beer-Lambert’s rule, narrow beam linear attenuation coefficient \(\mu\) (cm\(^{-1}\)) is given by the following relation:
\[ \mu = \frac{\ln(I_o/I)}{t} \]  

where \( I_o \) and \( I \) are the incident and transmitted beam intensities and \( t \) - the thickness of absorber in cm. Linear attenuation coefficient \( \mu \) (cm\(^{-1}\)) is independent on \( \rho \) (g.cm\(^{-3}\)), which means it does not have a unique value but rather depends on the physical state of material. Therefore, the attenuation quantity is usually tabulated as mass attenuation coefficient \( \mu/\rho \) (cm\(^2\).gm\(^{-1}\)), where the dependence on density \( \rho \) has been removed [7]. Theoretical calculations of the mass attenuation coefficients \( \mu/\rho \) (cm\(^2\).gm\(^{-1}\)) have been achieved by a two methods.

**First;** WinXCom program which is originally the XCom program developed by Berger and Hubbel [8] and transformed to the Windows platform [3]. The mass attenuation coefficients \( \mu/\rho \) (cm\(^2\).gm\(^{-1}\)) has been calculated and the obtained results are given in table 1.

**Second;** MCNP5 code was used to calculate the linear attenuation coefficient and the obtained values were divided on the corresponding densities of the current composites to obtain the mass attenuation coefficients \( \mu/\rho \) (cm\(^2\).gm\(^{-1}\)). This process starts with designing a three dimensional model using MCNP5 to simulate the experiment geometry. For the source term, the related \( \text{Co}^{60} \) parameters were used; as well, the variance reduction method DXTRAN sphere was used at the detection term to improve the results accuracy. The obtained mass attenuation coefficients \( \mu/\rho \) (cm\(^2\).gm\(^{-1}\)) calculated values are given in table 1.

**2- Effective Atomic Number and Effective Electron Density**

These parameters have been evaluated depending on the theoretical calculations and experimental measurements. They have a physical meaning and allow the characteristics of material to be visualized. First, the investigated glass samples \( Z_{eff} \) values were obtained theoretically. This could be achieved by running WinXCom program, based on mixture rule [10, 5]

\[ \mu_{m}=\sum w_{i} \mu_{ii} \]  

where \( (\mu_{ii}) \) : is the mass attenuation coefficient for individual elements in sample and \( (w_{i}) \) : is the weight fraction of element in sample. The total atomic cross-section \( (\sigma_{at}) \) could be determined by the following relation [10]

\[ \sigma_{at} = \frac{\sum_{i=1}^{\text{Sample}} N_{A_i} (w_i) \sigma_{at_i}}{N_{A} \text{Sample}} \]
where \( N_A \): Avogadro's number and \( A_i \): atomic weight of each constituent element in sample. As well, the total electronic cross-section \( (\sigma_{el}) \) is obtained by [10] 

\[
\sigma_{el} = \frac{1}{N_A} \sum_{i} f_i A_i \left( \frac{1}{Z_t} \right)
\]

where \( f_i \): the fractional abundance of the \( i^{th} \) element and \( Z_i \): the atomic number of the \( i^{th} \) element in the sample. The effective atomic number could be given now by definition as in [2].

\[
Z_{eff} = \frac{\sigma_{el}}{\sigma_{t,e} + \sigma_{t,e}}
\]

And the effective electron number \( (N_{el}) \) could be given as follows [5],

\[
N_{eff} = \frac{\nu_m}{\sigma_{t,e} + \sigma_{t,e}}
\]

Second, the parameters \( Z_{eff} \) and \( N_{el} \) were determined experimentally for the same samples. The calculations were carried on by using the mass attenuation coefficient values from the present study, whereas for the individual elements, the mass attenuation coefficient values were taken from external experimental measurements [11].

RESULTS AND DISCUSSION

The fabricated five composites which consist of a number of samples making the total thicknesses ranging from 1.06 to 5.288 cm were carefully positioned on the sample holder in order to perform the experimental measurements. Figures 2 and 3 display the transmitted gamma rays (photons/sec) at energies 1.173 and 1.332 MeV for the concerned composite samples. The attenuation curves show the gamma ray count rate to decrease exponentially with increase in composite thicknesses. It is observed that, the fall off is greater as sample density increases for both lines e.g. the largest fall off own the 25 wt% lead composite and the smallest for the blank composite.

**Figure 2.** Measured gamma ray counts behind different thicknesses of leaded glass composites at 1.173 MeV.

**Figure 3.** Measured gamma ray counts behind different thicknesses of leaded glass composites at 1.332 MeV.
Table 1. Measured and calculated attenuation parameters of gamma-rays for the leaded glass composites

<table>
<thead>
<tr>
<th>Composites</th>
<th>Blank Glass</th>
<th>PbO 5%</th>
<th>PbO 10%</th>
<th>PbO 15%</th>
<th>PbO 25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>1.173</td>
<td>1.332</td>
<td>1.173</td>
<td>1.332</td>
<td>1.173</td>
</tr>
<tr>
<td>μ (cm⁻¹)</td>
<td>0.10464 ± 1.97 %</td>
<td>0.10321 ± 1.86 %</td>
<td>0.11078 ± 3.41 %</td>
<td>0.10887 ± 3.27 %</td>
<td>0.12038 ± 4.40 %</td>
</tr>
<tr>
<td>λ (cm)</td>
<td>9.55657</td>
<td>9.6888</td>
<td>9.02690</td>
<td>9.18526</td>
<td>8.30702</td>
</tr>
<tr>
<td>H.V.L. (cm)</td>
<td>6.62411</td>
<td>6.71582</td>
<td>6.25697</td>
<td>6.36674</td>
<td>5.75799</td>
</tr>
<tr>
<td>Exponentially evaluated mass attenuation coefficients, ( \mu/\rho ) (cm² g⁻¹)</td>
<td>0.04060</td>
<td>0.04005</td>
<td>0.04136</td>
<td>0.04065</td>
<td>0.04219</td>
</tr>
<tr>
<td>WinXCom mass attenuation coefficients, ( \mu/\rho ) (cm² g⁻¹)</td>
<td>0.05853</td>
<td>0.05486</td>
<td>0.05888</td>
<td>0.05505</td>
<td>0.05907</td>
</tr>
<tr>
<td>MCNP5 evaluated mass attenuation coefficients, ( \mu/\rho ) (cm² g⁻¹)</td>
<td>0.05726</td>
<td>0.05444</td>
<td>0.05735</td>
<td>0.05450</td>
<td>0.05750</td>
</tr>
<tr>
<td>Experimentally evaluated mass attenuation coefficients, ( \mu/\rho ) (cm² g⁻¹)</td>
<td>0.04128</td>
<td>0.04102</td>
<td>0.04340</td>
<td>0.04180</td>
<td>0.04164</td>
</tr>
</tbody>
</table>

The attenuation relations Figures 2, 3 have been used to evaluate the linear attenuation coefficient \( \mu \) (cm⁻¹) of the gamma rays for the five concerned leaded glass composites.
composites. The obtained results have been used to calculate the related attenuation parameters which are; mean free path \( \lambda \) (cm), Half value layer H.V.L. (cm) and Tenth value layer T.V.L. (cm) and are presented in the table 1. Evaluated and calculated attenuation parameters indicate that, the shielding proficiency for the investigated composites increases with the increase of PbO loading fraction for both gamma lines. Also, the attenuation is higher for the lower line of energy 1.173 MeV. In addition the table shows the mass attenuation coefficients values which are carried out by the experimental evaluation and the two calculated methods for both energy lines.

It is shown that, a reasonable agreement could be observed between the experimentally determined and the both theoretically evaluated results. As well, it is clear that the values determined by WinXCom and MCNP5 are very close, and the results approve and confirm the precision of the MCNP5 model design. It is shown that, \( \mu/\rho \) experimental values are small compared to theoretical values and this may be attributed to the sample preparation where the samples could acquire H\(_2\)O and OH from ambient air during their preparation process.

The effective atomic number (\( Z_{\text{eff}} \)) and electron density (\( N_{\text{el}} \)) have been determined using equations 5 and 6 respectively and are given in table 2. It is shown that, a reasonable agreement could be recognized between measured and calculated values. Furthermore, for particular value of incident photon energy, \( Z_{\text{eff}} \) and \( N_{\text{el}} \) are found to increase with PbO loading fraction. The measured and calculated effective atomic number (\( Z_{\text{eff}} \)) and electron density (\( N_{\text{el}} \)) values tend to be almost constant as a function of energy.

**Table 2.** Measured and calculated values of the effective atomic numbers \( Z_{\text{eff}} \) and electron densities \( N_{\text{el}} \) for the leaded glass composites.

<table>
<thead>
<tr>
<th>Composites</th>
<th>Energy (MeV)</th>
<th>( Z_{\text{eff}} )</th>
<th>( N_{\text{el}} \times 10^{23} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank Glass</td>
<td>1.173</td>
<td>7.02515</td>
<td>10.17235</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>7.39908</td>
<td>10.15400</td>
</tr>
<tr>
<td>PbO 5%</td>
<td>1.173</td>
<td>7.45055</td>
<td>10.61823</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>7.81958</td>
<td>10.60107</td>
</tr>
<tr>
<td>PbO 10%</td>
<td>1.173</td>
<td>7.92501</td>
<td>11.10780</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>8.23024</td>
<td>11.07042</td>
</tr>
<tr>
<td>PbO 15%</td>
<td>1.173</td>
<td>8.51695</td>
<td>11.63129</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>8.76379</td>
<td>11.58610</td>
</tr>
<tr>
<td>PbO 25%</td>
<td>1.173</td>
<td>10.3823</td>
<td>12.84733</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>10.5217</td>
<td>12.76536</td>
</tr>
</tbody>
</table>
CONCLUSION

The PbO 25% composite proved to be the most efficient in terms of the attenuation parameters $\mu$, H.V.L. and T.V.L. The experimental and theoretical calculations using WinXCom and MCNP5 for evaluating $\mu/\rho$ are within reasonable agreement. In addition the closely related parameters $Z_{\text{eff}}$ and $N_{\text{eff}}$ are almost constant and their variation is very modest. As samples density increase, both parameters increase. And, it is concluded that the investigated leaded glass composites acquire the potential for radiation shielding.

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REFERENCES

التوصيف العملي و النظرى لمتراكبات الزجاج المرصرص كموهف لأشعة الجاما

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تقوم هذه الدراسة بتعيين معدلات التوهين الخطي لمتراكبات مختلفة من الزجاج المرصرص عند الطاقات الجامية MeV و1.332 MeV و 1.173 MeV باستخدام قاعدة نفاة طاقة جاما في إطار هندي جيد. و في هذه القياسات تم استخدام تقاوم عند Co-60 والناخلة Na(Tl) مع إجراء نظام التوليد الكهربائي (μ/ρ) باستخدام قيم معدل التوهين الكثائي MCNP5 للحساب نظريًا. وكذلك أستخدم برنامج WinXCom و شفرة الحسابية (Zeff) MCNP5. أما مقدمة الرقم القياسي المثالي (Nel) العملية و نظرية.

و قد لوحظ أن الإنتاج العام لكل مفاعلات التدريب شهدت زيادة بزيادة تركيز PbO بالعينات. وقد تم مقارنة القيم المنتجة من القياسات العملية والمحاسبة نظرية حيث وجد تطابق كبير بين القيم المقارنة مما يدل على صحة الأساليب و الطرق المستخدمة سواء العملية أو النظرية.