INTERACTION STUDIES AND GAMMA-RAY PROPERTIES OF SOME LOW-Z MATERIALS

by

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In present work we use NaI(Tl) detector in narrow-beam good geometry set-up for the gamma ray attenuation studies of some low-Z materials. The parameters such as mass attenuation coefficients, effective atomic numbers and effective electron densities, atomic cross-sections, electronic cross-sections of materials for graphitic powder, polycarbonate, polyvinyl chloride, plaster of Paris, gypsum, and limestone were determined using gamma ray sources 57Co, 133Ba, 137Cs, 60Co, and 22Na at energies of 122, 356, 511, 662, 840, 1170, 1275, and 1330 keV. It was observed that the effective atomic numbers and effective electron densities initially decrease and tend to be almost constant as a function of gamma-ray energy. An attempt was done to check the availability of these low-Z materials at large scales and obtainable at low cost as gamma ray shielding materials. The investigated data are useful in electronic industry, plastic industry, building materials, and agriculture fields.

Key words: mass attenuation coefficient, atomic cross-section, effective atomic number, low-Z material

INTRODUCTION

The investigation of mass attenuation coefficient, effective atomic number, and electron density of materials are the most important in the study of radiation in many fields. Nuclear radiation consists of high-energetic photons. The interaction of gamma rays with matter is wide spread application in nuclear physics, electronic industry, material modification, medical science, coating, paint industry, agriculture industry, etc. The interaction process mainly depends upon the intensity and the type of absorbing material. The gamma rays have greater penetrating power and obey different absorption laws [1]. As the use of radiation is wider for different applications, it is very important to study the interaction and absorption of gamma radiations in materials. For the study of absorption and interaction the basic quantities are effective atomic number, electron density and mass attenuation coefficient [2]. The study of attenuation coefficient gives more importance to materials in the energy range 10-1500 keV. The gamma radiation in the energy region 200 keV to 1500 keV interacts with material mainly due to a dominance of photoelectric and Compton effect photon interaction processes. Mass attenuation coefficient ($\mu_m$) is the measure of the probability in gamma ray interaction with matter [3].

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composite materials are synthesized materials from one or more constituent materials. The composite materials are widely used in various fields such as naval, aerospace, automotive industry, and technology. This is due to their unique attributes such as non-existence of erosion, rust and high resistibility at high temperature. Owing to these advances the composite materials are popular in industrial applications [4].

Over the last 20 years of investigations infusion research all fusion devices have implemented low-Z carbon based materials as plasma facing materials, as they enhance the performance of these materials such as density, temperature and energy confinement [5]. The devices prepared from low-Z materials have the excellent thermo-mechanical properties and due to this will not melt at normal heat. The low-Z elements show the advanced properties when use carbon as dopants or coatings [6]. Developing new advanced materials in recent years for nuclear science has become increasingly critical to high demand on better shielding in extreme environments. Radiation shielding materials possess good mechanical properties long term reliability with suitable thermo-physical characteristics [7]. The correct values of mass attenuation coefficient are found of immense importance for various fields such as nuclear diagnosis, radiation protection, nuclear medicine, radiation dosimetry, radiation biophysics, etc. The mass attenuation coefficient data are
also used in penetration and energy deposition in shielding and other dosimetric materials. In composite materials the single number cannot represent the atomic number, the number for composite materials is termed “effective atomic number (Z_{eff})” and it varies with energy. The energy absorption will be calculated if certain constants are known i.e., effective atomic number (Z_{eff}) and electron density (N_{el}) of the materials, therefore the study of effective atomic number and electron density is very useful for many applications: in UV-sunlight protection, coatings, paints, electronic industry as well as medical field [8]. Recently few researchers in our laboratory investigated the values of mass attenuation coefficient, effective atomic numbers, electron densities, total atomic cross-section for dosimetric materials, fatty acid, minerals, amino acids, low-Z materials, etc. [9-12]. Many researchers investigated the extensive data on effective electron density, electron density, atomic cross-section, total cross-section for many materials [13-15].

The objective of the experimental work is to investigate gamma ray attenuation in these samples as low-Z materials are affordable as compared to high-Z materials such as lead, mercury which may not prove useful at large dimensions. Gamma ray attenuation study is very useful to check the feasibility of the materials. We have measured the mass attenuation coefficient (\(\mu_m\)) which was then used to calculate total attenuation cross-section (\(\sigma_t\)). The attenuation data for theoretical calculations is obtained from XCOM program using a PC [16, 17]. It shows good agreement with the experimental data for some low-Z materials.

**THEORY**

In present work the following equations were used to determine the mass attenuation coefficient, atomic cross-sections (\(\sigma_i\)), electronic cross-sections (\(\sigma_e\)), effective atomic numbers (\(Z_{eff}\)) and effective electron densities (\(N_{el}^{eff}\)) and molar extinction coefficient for low-Z materials.

When a beam of monochromatic gamma photons is incident on matter according to Lambert-Beer law:

\[
I = I_0 e^{-\mu t}
\]

where, \(I_0\) and \(I\) are the incident and transmitted photon intensities, respectively, \(\mu [cm^{-1}]\) represents linear attenuation coefficient of the material and \(t [cm]\) is the thickness of the target material/sample. Rearrangement of eq. (1) yields the following equation for the linear attenuation coefficient

\[
\mu = \frac{1}{t} \ln \left( \frac{I_0}{I} \right)
\]

(2)

The mass attenuation coefficients \(\mu_m\) of the sample should be calculated by using the equation

\[
\mu_m = \sum w_i (\mu_{m,i})
\]

(3)

where \(w_i\) is the weight fraction. The \(w_i\) can be defined as follows

\[
w_i = \frac{n_i A_i}{\sum n_i A_i}
\]

(4)

where \(A_i\) is the atomic weight of the sample and \(n_i\) the number of formula units.

The values of mass attenuation coefficients, eq. (3), were then used to determine the total attenuation cross-section (\(\sigma_{tot}\)) by the following relation

\[
\sigma_{tot} = \mu_m \left( \frac{N}{N_A} \right)
\]

(5)

where \(N = \sum n_i A_i\) is the atomic mass of the sample and \(N_A\) is the Avogadro’s number.

Similarly, effective electronic cross-section (\(\sigma_e\)) for the individual element is given by

\[
\sigma_e = \frac{1}{N_A} \sum f_i A_i \left( \mu_{m,i} \right) = \frac{\sigma_{tot}}{Z_{eff}^{eff}}
\]

(6)

where \(f_i\) is the fractional abundance of the sample and \(Z_{eff}^{eff}\) the effective electron number of the sample.

The total atomic cross-section and total electronic cross-section are related with the effective atomic number. Therefore the equation for \(Z_{eff}^{eff}\) can be defined as

\[
Z_{eff}^{eff} = \frac{\sigma_t}{\sigma_e}
\]

(7)

The equation for \(N_{eff}^{eff}\) can be defined as

\[
N_{eff}^{eff} = \frac{N}{N} Z_{eff}^{eff}
\]

(8)

**EXPERIMENTAL DETAILS**

Radioactive sources \(^{57}\text{Co}, \(^{133}\text{Ba}, \(^{137}\text{Cs}, \(^{54}\text{Mn}, \(^{60}\text{Co}, \) and \(^{22}\text{Na}\) emitting energies 122, 356, 511, 662, 840, 1170, 1275, and 1330 keV, respectively, were used for irradiation. The gamma ray photons were detected using NaI(Tl) detector with resolution of 0.101785 to 662 keV. A detailed experimental set-up of transmission experimental is shown in fig. 1. Signals from the detector were enlarged and analyzed with a 8K multichannel analyzer. The effectiveness of NaI(Tl) detector is higher at low source energy [18]. The uncertainty in determined experiment is found to be 1-4 % [19]. To make graphitic powder (c), polycarbonate (\(C_{15}H_{16}O_2\)), polyvinyl chloride (\(C_2H_2Cl\)), plaster of Paris (\(CaSO_4H_2O\)), gypsum (\(CaSO_4H_2O\)), and limestone (\(CaCO_3\)) as radiation target we used KBr press machine to prepare tablets having same thickness (0.13 g/cm²). Then we filled them in a cylindrical plastic container having the same diameter as that of sample tablets. To determine the diameters of these samples we used a traveling microscope. Transmission experiment was performed with the empty sample container and it was found that the
Table 1. The mean atomic numbers calculated from the chemical formula for low-Z materials

<table>
<thead>
<tr>
<th>Low-Z materials</th>
<th>Molar mass [g mol⁻¹]</th>
<th>Chemical formula</th>
<th>Mean atomic number, &lt;Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphitic powder</td>
<td>12.01</td>
<td>C</td>
<td>6</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>254.3</td>
<td>C₆H₅NO₂</td>
<td>3.6970</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>62.50</td>
<td>CH = CHCl</td>
<td>5.333</td>
</tr>
<tr>
<td>Plaster of Paris</td>
<td>77.94</td>
<td>Ca₃S₂O₄H₁₀</td>
<td>10.35</td>
</tr>
<tr>
<td>Gypsum</td>
<td>136.14</td>
<td>CaSO₄·2H₂O</td>
<td>7.333</td>
</tr>
<tr>
<td>Limestone</td>
<td>100.08</td>
<td>CaCO₃</td>
<td>10.00</td>
</tr>
</tbody>
</table>

Table 2. Mass attenuation coefficient, μₘ [cm²g⁻¹] of low-Z materials

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphitic powder</td>
<td></td>
<td>0.142</td>
<td>0.143</td>
<td>0.101</td>
<td>0.100</td>
<td>0.083</td>
<td>0.085</td>
<td>0.075</td>
<td>0.077</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td></td>
<td>0.152</td>
<td>0.153</td>
<td>0.105</td>
<td>0.107</td>
<td>0.091</td>
<td>0.092</td>
<td>0.082</td>
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<tr>
<td>Polyvinyl chloride</td>
<td></td>
<td>0.160</td>
<td>0.162</td>
<td>0.114</td>
<td>0.115</td>
<td>0.097</td>
<td>0.097</td>
<td>0.086</td>
<td>0.088</td>
</tr>
<tr>
<td>Plaster of Paris</td>
<td></td>
<td>0.170</td>
<td>0.171</td>
<td>0.102</td>
<td>0.102</td>
<td>0.084</td>
<td>0.086</td>
<td>0.077</td>
<td>0.078</td>
</tr>
<tr>
<td>Gypsum</td>
<td></td>
<td>0.17</td>
<td>0.17</td>
<td>0.104</td>
<td>0.104</td>
<td>0.086</td>
<td>0.087</td>
<td>0.079</td>
<td>0.080</td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
<td>0.280</td>
<td>0.282</td>
<td>0.105</td>
<td>0.107</td>
<td>0.081</td>
<td>0.082</td>
<td>0.073</td>
<td>0.074</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The values of mean atomic number calculated from chemical formula for graphitic powder, polycarbonate, polyvinyl chloride, plaster of Paris, gypsum, and limestone are described in tab. 1. It shows that the mean atomic number for all low-Z materials is different. The values of μₘ [cm²g⁻¹] for these low-Z materials at energies 122, 356, 511, 662, 840, 1170, 1275, and 1330 keV calculated experimentally using NaI(Tl) detector and theoretically using XCOM program are mentioned in tab. 2 and a typical plot displayed in fig. 2. Based on these values it can be seen that there is a small amount of variation in experimentally and theoretically calculated values i.e., it shows good agreement. The values for atomic cross-section (σᵣ) are displayed in tab. 3 and a typical plot is displayed in fig. 3.
It can be clearly seen from fig. 3 that there is a certain variation in atomic cross-section, but as the photon energy increases the values for atomic cross-section ($\sigma_t$) decreases and at a point they are constant.

The experimental and theoretical values calculated from XCOM for electronic cross-section ($\sigma_e$) of low-Z materials are displayed in tab. 4. They show good agreement with the experimental and theoretical values. Figure 4 shows that only the low-Z material i.e., polycarbonate which has the highest mass number shows more electronic cross-sections as compared to other low-Z materials at the same photon energy and remains constant at a certain point. The values for effective atomic number ($Z_{eff}$) are displayed in tab. 5 and a typical plot in fig. 5. It can be clearly seen both from the table and figure that the plaster of Paris and limestone which are having the mean atomic number near to 10 displays more effective atomic number.

### Table 3. Atomic cross-sections, $\sigma_t$ ($10^{-28}$ m$^2$ per molecule) of some low-Z materials

<table>
<thead>
<tr>
<th>Low-Z materials</th>
<th>Energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>122 Exp.</td>
</tr>
<tr>
<td>Graphitic powder</td>
<td>2.855</td>
</tr>
<tr>
<td>Poly carbonate</td>
<td>57.990</td>
</tr>
<tr>
<td>Plaster of Paris</td>
<td>82.300</td>
</tr>
</tbody>
</table>

### Table 4. Electronic cross-sections, $\sigma_e$ ($10^{-28}$ m$^2$ per molecule) of some low-Z materials

<table>
<thead>
<tr>
<th>Low-Z materials</th>
<th>Energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>122 Exp.</td>
</tr>
<tr>
<td>Graphitic powder</td>
<td>0.420</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>2.917</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.956</td>
</tr>
</tbody>
</table>

Figures: 2, 3, 4
at the same energy used for the all low-Z materials, and remains constant at the energy point.

The effective electron density (N_{eff}) for low-Z materials is displayed in tab. 6 and shows good agreement with the experimental and theoretical values. Figure 6 shows that the plaster of Paris and limestone shows more effective electron density as compared to the other low-Z materials; it decreases slightly and remains the same at the energy point. It is clear that Z_{eff} and N_{eff} are related to each other as values which initially decrease and then remain constant as photon energy increases.

CONCLUSIONS

The present experimental study has been undertaken to get information on mass attenuation coefficient (\mu_m) and related values of (Z_{eff}, N_{eff}, \sigma_e, and \sigma_p) for six low-Z materials. It is found that \mu_m is the main physical quantity to determine the values of N_{eff} and Z_{eff} for low-Z materials. It can be concluded from the present work that the low-Z materials used in this investigation are of use in dosimetry, radiation protection, etc. Present investigation should be useful in medical application as low-Z materials are composed of C, H, N, and O constituent elements. Also, low-Z materials doped with the high Z elements can be used as radiation shielding materials and are available at low cost. The values introduced in the present investigation can be used in many applications as electronics industry, construction, plastic industry, agriculture industry, etc., as a gamma ray shielding materials.
AUTHORS’ CONTRIBUTIONS

Theoretical and experimental work was carried out by R. R. Bhosale and D. K. Gaikwad. Experimental data was analyzed by P. P. Pawar and M. N. Rode. Whole manuscript was reviewed by all authors.

REFERENCES


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У истраживању коришћен је NaI(Tl) детектор и поставка геометрије уског снопа за проучавање особина слабљења гама зрачења материјала са ниским атомским бројем Z. За испитиване материјале, који су обухватали графитни прашак, поликарбонат, полиовинил хлорид, гипс из Париза, гипс и кречњак, одређени су следећи параметри: масени коефицијент слабљења, ефективни атомски број, ефективна густина електрона, атомски ефикасни пресек и електронски ефикасни пресек. Као извори гама зрачења коришћени су 57Co, 133Ba, 137Cs, 60Co и 22Na, на енергијама 122, 356, 511, 662, 840, 1170, 1275 и 1330 keV. Уочено је да ефективни атомски бројеви и ефективне густине електрона најпре опадају, а потом теже да задрже скоро константну вредност у зависности од енергије гама зрачења. Проверена је доступност ових материјала у великим количинама, као материјала ниских цена за заштиту од гама зрачења. Добијене подаци могу се употребити у електронској индустрији, индустрији пластике, производњи грађевинских материјала и у пољопривреди.

Кључне речи: масени коефицијент слабљења, атомски ефикасни пресек, ефективан атомски број, материјал са ниским атомским бројем Z.