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Studies on Gamma-Ray Shielding Parameters of Polymer Containing Lead Oxide Composites from 1 keV to 100 GeV

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Abstract: The gamma-ray shielding parameters of polymer composites containing different percentages of lead oxide (0%, 10%, 20%, 30%, 40% and 50%) were theoretically calculated using XCOM program. The characteristics of gamma-ray shielding parameters for the composite of different lead oxide were found to be dependent on energy regions. At low-energy region, the radiation shielding parameters show several discontinuous jumps correspond to photoelectric absorption edges. At medium-energy region, the radiation shielding parameters are almost constant and the effective atomic number is close to the mean atomic number, dominated by Compton scattering process. In high-energy regions, pair production becomes the main interaction process and tends to be constant over energy. The investigation was carried out to explore the advantages of the polymer composites in gamma-ray shielding applications. The obtained results were used to calculate effective atomic number and electron densities for the same range of energy.

Keywords: Polymer composites, Mass attenuation coefficient, Effective atomic number, Gamma-ray shielding.

INTRODUCTION

Gamma-ray sources are not only dangerous to human health but also are detrimental to sensitive laboratory equipments. Shielding is necessary to protect penetrative neutrons and gamma-rays. The intensity of gamma-rays is varied by three factors: time, distance and shielding. The most effective method for attenuation of radiation is shielding[1]. Filler-reinforced polymers have gained increasing attention from X-ray technologists in radiation shielding since polymers have great potential in many important applications by virtue of their unique properties, such as low density, the ability to form intricate shapes, optical transparency, low manufacturing cost and toughness. One of the filler-reinforced polymers commonly used for radiation shielding is lead acrylic. Moreover, some researchers have also tried to synthesize nano-sized filler-reinforced polymers for radiation shielding by virtue of the size effect in X-ray attenuation[2-4].

The mass attenuation coefficient, μ/ρ, is a measure of the average number of interactions between incident photons and matter that occur in a given mass-per-unit area thickness of the material encountered [5]. Accurate values of the mass attenuation coefficient, μ/ρ, are required in the nuclear diagnostics, radiation protection, nuclear medicine, radiation biophysics, radiation dosimetry to obtain essential data. The mass attenuation coefficients are also used to determine of photon penetration and energy deposition in the biological and other materials[6-8]. The mass attenuation coefficients can be obtained from different database[9] and XCom program[10]. Because of photon interaction cross-section for elements of the composite material, a single atomic number being a characteristic of element will not describe the atomic number of composite material in the all energy ranges. So a new number for composite materials is called to be effective atomic number, Z_{eff}, suggested by G. Hine[9] and it varies with energy. Determination of the effective atomic number, Z_{eff}, and the effective electron number per unit mass, Neff, which is another important parameter for composite materials is very important in the fields of many technological applications and nuclear medicine for the calculation of dose in radiation therapy and medical imaging [6,11] .

Since the effective atomic number, Z_{eff}, and the effective electron number per unit mass, N_{eff}, are widespread use, this study is focusing on calculating the mass attenuation coefficient, effective atomic number and effective electron density of polymer composites with different lead oxide percentages.

THEORETICAL CALCULATION

When a photon beam passes through a matter, its intensity progressively reduces as a consequence of interactions between photons and atoms. The mass attenuation coefficient μ/ρ, (cm^2/g) is a measure of the average number of interactions that occur between photons and matter and it is defined as the probability of a radiation interacting with a material per unit mass thickness (mass per unit area).

Consider first a chemical compound. The formulas will later be generalized to mixtures as well. The total photon interaction cross section, σ_m, per molecule can be written as following[12]:

$$\sigma_m = \sum_i n_i \sigma_i \qquad (1)$$

Where n_i is the number of atoms of the i^{th} constituent element, and ri is total photon interaction cross section per atom of element i. The total number, n, of atoms in the molecule is

$$n = \sum_i n_i \qquad (2)$$

Suppose that the cross section per molecule can be written in terms of an effective (average) cross section, σ_a, per atom and an effective (average) cross section, σ_e, per electron as follows:

$$\sigma_m = n\sigma_a = nZ_{eff}\sigma_e \qquad (3)$$

Eq. (3) can be regarded as the definition of the effective atomic number. Essentially, it assumes that the actual atoms of a given molecule can be replaced by an equal number of identical (average) atoms, each of which having Z_{eff} electrons.

It follows from the first equality of Eq. (3) that the effective (average) cross section per atom is given by:

$$\sigma_a = \frac{1}{n}\sum n_i\sigma_i \qquad (4)$$

Similarly, the effective (average) cross section per electron is given by:

$$\sigma_e = \frac{1}{n}\sum_i n_i \frac{\sigma_i}{Z_i} \qquad (5)$$

It follows from the last equality of Eq. (3) that the effective atomic number can be written as the ratio between the atomic and electronic cross sections[12]:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \qquad (6)$$

Many authors have used Eq. (6) for calculating Z_{eff}. However, it is instructive to go one step further and insert the expressions (4) and (5) for σ_a and σ_e:

$$Z_{eff} = \frac{\sum_i n_i\sigma_i}{\sum_j n_j \frac{\sigma_j}{Z_j}} \qquad (7)$$

Eq. (7) is then the basic relation for calculating the effective atomic number of a chemical compound, and it will be further elaborated in the following. It may be noted in passing that Eq. (7) can be rewritten as[12]:

$$\frac{1}{Z_{eff}} = \frac{\sum_j n_j \frac{\sigma_j}{Z_j}}{\sum_i n_i\sigma_i} \qquad (8)$$

Eq. (8) shows that $(1/Z_{eff})$ is the weighted arithmetic mean of $(1/Z_i)$, where the weighting factor associated with each element is $n_i\sigma_i$. For each of the different processes, by which photons can interact with matter, the weighting factor is different, because of the different Z dependence of the atomic cross section.

Eq. (7) has been derived for a chemical compound, assuming that each n_i is an integer. A more general expression for Z_{eff} can be obtained by introducing the molar fraction, fi (sometimes expressed in units of atomic percent, at. %). For a chemical compound one has

$$f_i = \frac{n_i}{\sum_j n_j} = \frac{n_i}{n} \qquad (9)$$

Where $\sum_i f_i = 1$. Rewriting Eq. (7) in terms of molar fractions gives the more general expression

$$Z_{eff} = \frac{\sum_i f_i \sigma_i}{\sum_j f_j \frac{\sigma_j}{Z_j}} \qquad (10)$$

Eq. (10) is then the basic relation for calculating the effective atomic number for all types of materials, compounds as well as mixtures.

The atomic cross section, σ_i, of the i^{th} constituent element is related to the corresponding mass attenuation coefficient, $(\mu/\rho)_i$, through the relation:

$$\sigma_i = \frac{A_i}{N_A}(\frac{\mu}{\rho})_i \qquad (11)$$

Where Ai is the atomic mass and NA is the Avogadro constant. Useful expressions in terms of the mass attenuation coefficient can be obtained by inserting expression (11) for σ_i in the equations of the previous section.

Consider first a chemical compound. Inserting the expression (11) for σ_i in Eq. (7) gives the following relation for Z_{eff} [12]:

$$Z_{eff} = \frac{\sum_i f_i A_i (\frac{\mu}{\rho})_i}{\sum_j f_j \frac{A_j}{Z_j}(\frac{\mu}{\rho})_j} \qquad (12)$$

Eq. (12) can be used for calculating the effective atomic number of both compounds and mixtures. Further simplifications can be made in limited Z-ranges, where the ratio, A/Z, between the atomic mass and the atomic number is approximately constant.

The effective atomic number, Z_{eff}, is closely related to the electron density, N_e, which is expressed in number of electrons per unit mass. For a chemical element, the electron density is given by $N_e = \frac{N_A Z}{A}$. This expression can be generalized to a compound, and one has

$$N_e = N_A \frac{nZ_{eff}}{\sum_i n_i A_i} = N_A \frac{Z_{eff}}{< A >} \qquad (13)$$

Where $< A >$ is the average atomic mass of the compound. It can be shown that the electron density also is given by

$$N_e = \frac{\mu/\rho}{\sigma_e} \qquad (14)$$

Where l/q is the total mass attenuation coefficient of the compound, and σ_e is the electronic cross section given by Eq. (5). In the case of Compton scattering, the Klein–Nishina cross section can be used for σ_e.

RESULTS AND DISCUSSION

In this study, the basic radiation parameters of polymer composites with different ratio of PbO were studies by the direct method over wide photon energy range from 1 keV to 100 GeV using XCom program. These parameters are the μ/ρ, Z_{eff}, and N_{eff}.

The Z_{eff} and N_{eff} values of Polymer composites are given in **Tables 1 and 2** only for total photon interaction. The tables present Z_{eff} and N_{eff} values in the energy range from 1 keV to 20 MeV, however the values for the energy range from 1 keV to 100 GeV are displayed in graphical results.

Table 1: Effective atomic number of polymer composites for total photon interaction (with coherent).

Energy (MeV)	0%	10%	20%	30%	40%	50%
0.001	6.50E+00	1.59E+01	3.64E+01	4.60E+01	5.35E+01	5.96E+01
0.0015	6.52E+00	1.91E+01	4.27E+01	5.22E+01	5.92E+01	6.45E+01
0.002	6.53E+00	2.16E+01	4.69E+01	5.61E+01	6.26E+01	6.73E+01
0.003	6.55E+00	3.21E+01	5.96E+01	6.67E+01	7.11E+01	7.40E+01
0.004	6.55E+00	5.78E+01	7.50E+01	7.76E+01	7.90E+01	7.99E+01
0.005	6.56E+00	6.93E+01	7.88E+01	8.01E+01	8.07E+01	8.11E+01
0.006	6.55E+00	7.52E+01	8.04E+01	8.10E+01	8.14E+01	8.15E+01
0.008	6.54E+00	7.96E+01	8.15E+01	8.17E+01	8.18E+01	8.18E+01
0.01	6.51E+00	8.04E+01	8.17E+01	8.18E+01	8.19E+01	8.19E+01
0.015	6.38E+00	8.14E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
0.02	6.21E+00	8.17E+01	8.19E+01	8.20E+01	8.20E+01	8.20E+01
0.03	5.94E+00	8.18E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.04	5.81E+00	8.18E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.05	5.74E+00	8.19E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.06	5.71E+00	8.18E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.08	5.68E+00	8.18E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.1	5.67E+00	8.19E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.15	5.66E+00	8.19E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.2	5.65E+00	8.18E+01	8.20E+01	8.20E+01	8.20E+01	8.20E+01
0.3	5.65E+00	8.17E+01	8.19E+01	8.20E+01	8.20E+01	8.20E+01

0.4	5.65E+00	8.15E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
0.5	5.65E+00	8.12E+01	8.18E+01	8.19E+01	8.19E+01	8.20E+01
0.6	5.65E+00	8.05E+01	8.17E+01	8.18E+01	8.19E+01	8.19E+01
0.8	5.65E+00	8.15E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
1	5.65E+00	8.13E+01	8.18E+01	8.19E+01	8.19E+01	8.20E+01
1.5	5.65E+00	8.15E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
2	5.66E+00	8.16E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
3	5.67E+00	8.15E+01	8.19E+01	8.19E+01	8.20E+01	8.20E+01
4	5.68E+00	8.08E+01	8.17E+01	8.18E+01	8.19E+01	8.19E+01
5	5.69E+00	7.97E+01	8.15E+01	8.17E+01	8.18E+01	8.19E+01
6	5.71E+00	7.84E+01	8.12E+01	8.15E+01	8.17E+01	8.18E+01
7	5.72E+00	7.68E+01	8.08E+01	8.13E+01	8.15E+01	8.17E+01
8	5.74E+00	7.24E+01	7.97E+01	8.06E+01	8.11E+01	8.14E+01
9	5.75E+00	7.08E+01	7.93E+01	8.04E+01	8.09E+01	8.13E+01
10	5.76E+00	7.90E+01	8.13E+01	8.16E+01	8.17E+01	8.18E+01
11	5.78E+00	7.80E+01	8.11E+01	8.15E+01	8.17E+01	8.18E+01
12	5.79E+00	7.23E+01	7.97E+01	8.06E+01	8.11E+01	8.14E+01
13	5.80E+00	6.51E+01	7.76E+01	7.93E+01	8.02E+01	8.08E+01
14	5.81E+00	5.09E+01	7.22E+01	7.59E+01	7.79E+01	7.91E+01
15	5.82E+00	4.09E+01	6.68E+01	7.22E+01	7.53E+01	7.73E+01
16	5.83E+00	3.46E+01	6.21E+01	6.88E+01	7.28E+01	7.55E+01
18	5.85E+00	3.07E+01	5.87E+01	6.62E+01	7.09E+01	7.40E+01
20	5.87E+00	2.58E+01	5.33E+01	6.19E+01	6.76E+01	7.15E+01

Table 2: Effective electron density of polymer composites for total photon interaction (with coherent).

Energy (MeV)	0%	10%	20%	30%	40%	50%
1.00E-03	7.54E+23	8.59E+23	1.97E+24	2.49E+24	2.90E+24	3.23E+24
0.0015	7.57E+23	1.03E+24	2.31E+24	2.83E+24	3.20E+24	3.49E+24
0.002	7.58E+23	1.17E+24	2.54E+24	3.04E+24	3.38E+24	3.64E+24
0.003	7.60E+23	1.74E+24	3.22E+24	3.61E+24	3.85E+24	4.01E+24
0.004	7.61E+23	3.13E+24	4.06E+24	4.20E+24	4.28E+24	4.32E+24
0.005	7.61E+23	3.75E+24	4.26E+24	4.33E+24	4.37E+24	4.39E+24
0.006	7.61E+23	4.07E+24	4.35E+24	4.38E+24	4.40E+24	4.41E+24
0.008	7.59E+23	4.31E+24	4.41E+24	4.42E+24	4.43E+24	4.43E+24
0.01	7.56E+23	4.35E+24	4.42E+24	4.43E+24	4.43E+24	4.43E+24
0.015	7.40E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.43E+24
0.02	7.21E+23	4.42E+24	4.43E+24	4.43E+24	4.44E+24	4.44E+24
0.03	6.89E+23	4.43E+24	4.43E+24	4.44E+24	4.44E+24	4.44E+24
0.04	6.74E+23	4.43E+24	4.43E+24	4.44E+24	4.44E+24	4.44E+24
0.05	6.66E+23	4.43E+24	4.44E+24	4.44E+24	4.44E+24	4.44E+24
0.06	6.63E+23	4.43E+24	4.44E+24	4.44E+24	4.44E+24	4.44E+24
0.08	6.59E+23	4.43E+24	4.44E+24	4.44E+24	4.44E+24	4.44E+24
0.1	6.58E+23	4.43E+24	4.44E+24	4.44E+24	4.44E+24	4.44E+24
0.15	6.57E+23	4.43E+24	4.44E+24	4.44E+24	4.44E+24	4.44E+24
0.2	6.56E+23	4.43E+24	4.43E+24	4.44E+24	4.44E+24	4.44E+24
0.3	6.56E+23	4.42E+24	4.43E+24	4.43E+24	4.44E+24	4.44E+24
0.4	6.56E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.44E+24
0.5	6.56E+23	4.39E+24	4.43E+24	4.43E+24	4.43E+24	4.43E+24
0.6	6.56E+23	4.36E+24	4.42E+24	4.43E+24	4.43E+24	4.43E+24
0.8	6.56E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.44E+24
1	6.56E+23	4.40E+24	4.43E+24	4.43E+24	4.43E+24	4.43E+24
1.5	6.56E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.44E+24
2	6.56E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.44E+24
3	6.57E+23	4.41E+24	4.43E+24	4.43E+24	4.43E+24	4.44E+24
4	6.59E+23	4.37E+24	4.42E+24	4.43E+24	4.43E+24	4.43E+24
5	6.61E+23	4.31E+24	4.41E+24	4.42E+24	4.43E+24	4.43E+24
6	6.62E+23	4.24E+24	4.39E+24	4.41E+24	4.42E+24	4.43E+24
7	6.64E+23	4.15E+24	4.37E+24	4.40E+24	4.41E+24	4.42E+24
8	6.66E+23	3.92E+24	4.31E+24	4.36E+24	4.39E+24	4.40E+24
9	6.67E+23	3.83E+24	4.29E+24	4.35E+24	4.38E+24	4.40E+24
10	6.69E+23	4.27E+24	4.40E+24	4.42E+24	4.42E+24	4.43E+24
11	6.70E+23	4.22E+24	4.39E+24	4.41E+24	4.42E+24	4.42E+24
12	6.72E+23	3.91E+24	4.31E+24	4.36E+24	4.39E+24	4.40E+24
13	6.73E+23	3.52E+24	4.20E+24	4.29E+24	4.34E+24	4.37E+24
14	6.74E+23	2.76E+24	3.91E+24	4.11E+24	4.21E+24	4.28E+24
15	6.76E+23	2.22E+24	3.61E+24	3.91E+24	4.07E+24	4.18E+24
16	6.77E+23	1.87E+24	3.36E+24	3.73E+24	3.94E+24	4.08E+24
18	6.79E+23	1.66E+24	3.18E+24	3.58E+24	3.84E+24	4.01E+24
20	6.81E+23	1.39E+24	2.88E+24	3.35E+24	3.66E+24	3.87E+24

Mass attenuation coefficients: The dependence of mass attenuation coefficient μ/ρ of polymer composites to photon energy is shown in **Fig. 1.** While in **Fig. 2** only results from the polymer composite with 20 % of PbO on the variations of the μ/ρ for total and partial photon interactions were shown. It is seen from figure that different dominant interaction processes on different energy regions. There are three energy ranges relative to the partial processes: photoelectric absorption at low energies, incoherent

(Compton) scattering at intermediate energies and pair production at high energies. In **Fig. 2**, the curve of Compton scattering is split up because it dependent on probability of photon interaction by incoherent scattering for each energy and can be explained by Klein–Nishina cross sections equation for the Compton Effect[13].

Effective Atomic Number, Z_{eff}: The variation of Z_{eff} of photon energy for total interaction processes in all polymer composites is shown in Fig. 3. Fig. 4 shows the variation of Z_{eff} of only polymer composite with 10 % PbO. From these figures, it can be seen that the minimum value of Z_{eff} is found around intermediate energies (0.4 > E > 16 MeV).For coherent (Rayleigh) scattering process, the variation of Z_{eff} with photon energy is shown in **Fig. 5.** From the figure it is clear that Z_{eff} increases with increasing of energy from 1 keV to 300 keV and then it remains constant thereafter. Similar results were also obtained by Manohara and Hanagodimath[6] for the case of amino acids.

For the incoherent (Compton) scattering process, the variation of Z_{eff} with photon energy is shown in **Fig. 6.** It can be seen that initially Z_{eff} decreases with increasing energy, minima at 20 keV, and then it increases with increasing energy up to 10 MeV. Finally it remains nearly constant even with further increase in energy.For the photoelectric absorption process, the variation of Z_{eff} with photon energy is shown in **Fig. 7**. The behavior of Z_{eff} with respect to energy shows discontinuous jumps in the intermediate energy range (E < 11MeV), decreases with increasing of photon energy up to 100 MeV and then it remains nearly constant thereafter. The variation of Z_{eff} with photon energy for pair production in nuclear field is shown in **Fig. 8.** The value of Z_{eff} is constant up to 50 MeV and then increases with further increasing of photon energy. **Fig. 9** shows the variation of Z_{eff} with photon energy for pair production in electric field. From the figure it is clear that Z_{eff} is independent of photon energy from 3 to 60 MeV. For E > 60 MeV, the value of Z_{eff} increases with increasing of photon energy.

Effective Electron Density, N_{eff}: The variation of N_{eff} of polymer composites with photon energy for total photon interaction is shown in **Fig. 10.** The total and partial interaction processes of N_{eff} values for the polymer composite containing 10% of PbO are shown in **Fig. 11.** It is observed that Ne shows similar trends to Z_{eff}.

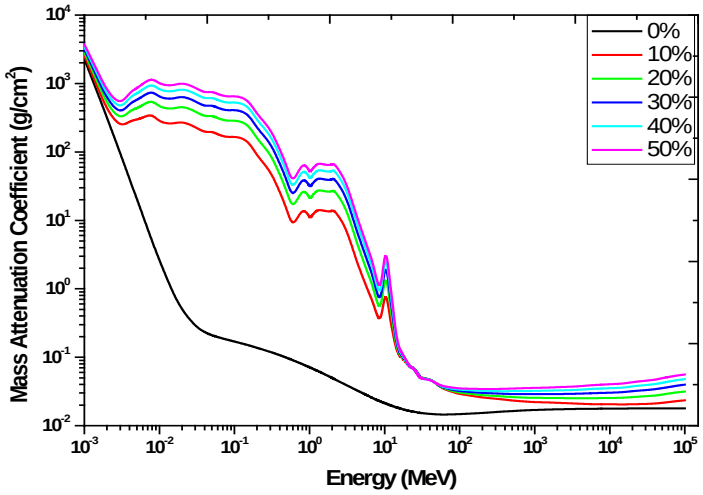

Fig. 1: The variation of mass attenuation coefficient of polymer composites with photon energy for total interaction (with coherent).

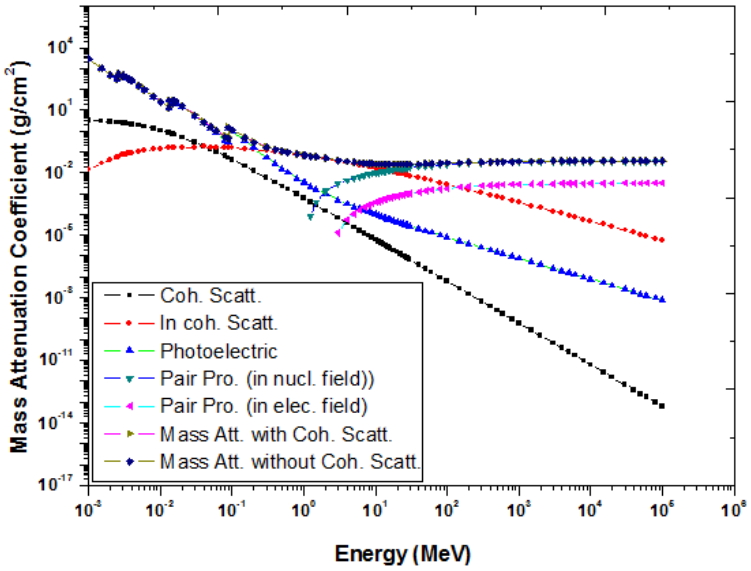

Fig. 2: The variation of mass attenuation coefficient of polymer composite with 20 % of PbO against photon energy for total and partial interactions.

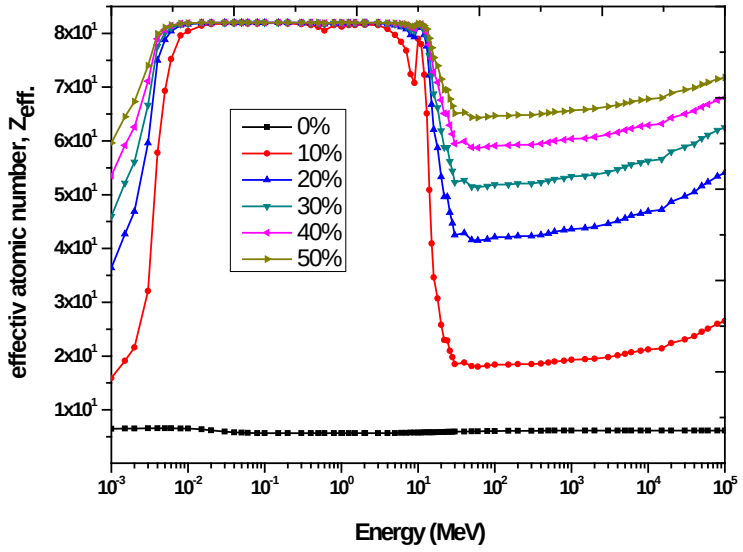

Fig. 3: The variation of effective atomic number of polymer composites with photon energy for total interaction (with coherent).

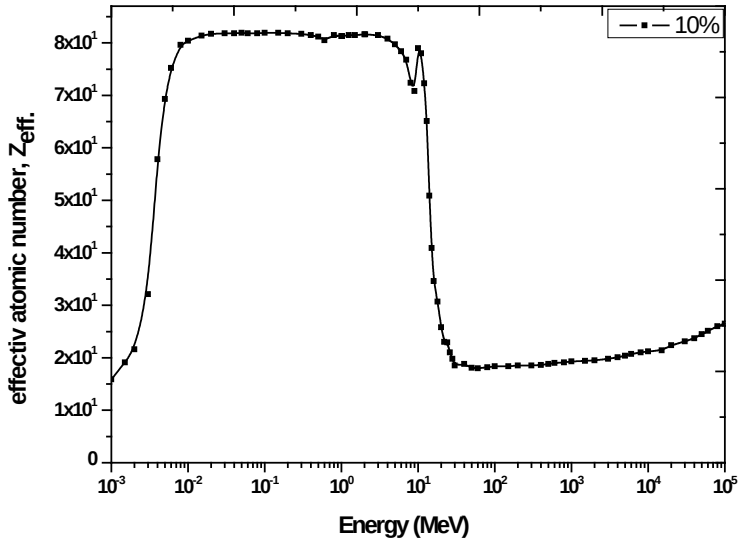

Fig. 4: The variation of effective atomic number of polymer composite with 10 % PbO against photon energy for total interaction (with coherent).

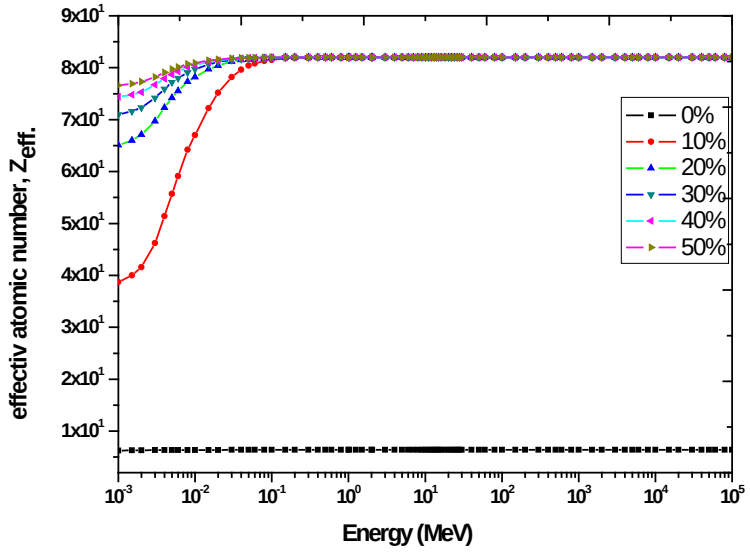

Fig. 5: The variation of effective atomic number of polymer composites with photon energy for coherent scattering.

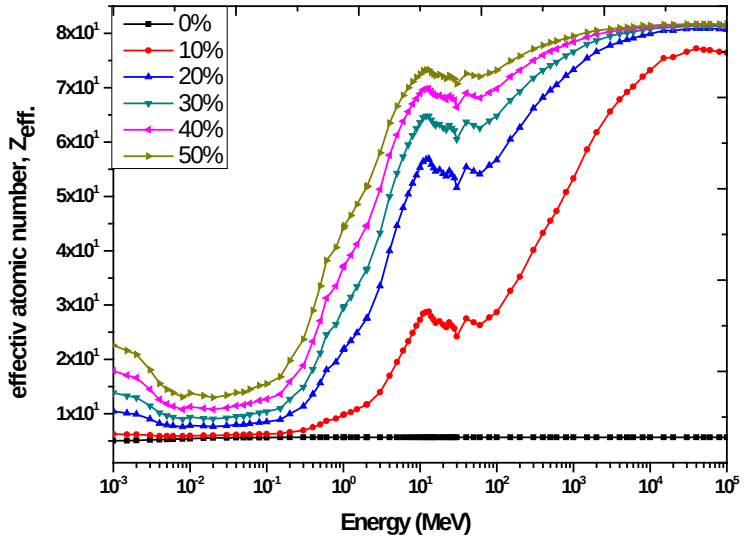

Fig. 6: The variation of effective atomic number of polymer composites with photon energy for incoherent scattering.

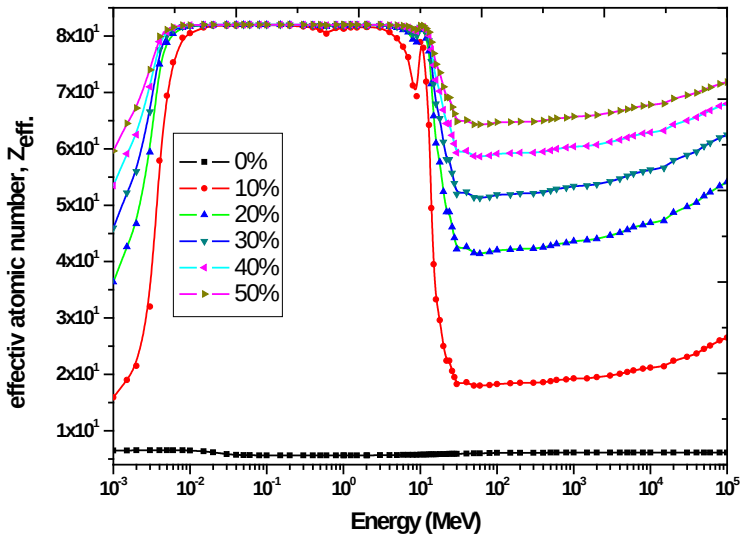

Fig. 7: The variation of effective atomic number of polymer composites with photon energy for photoelectric effect.

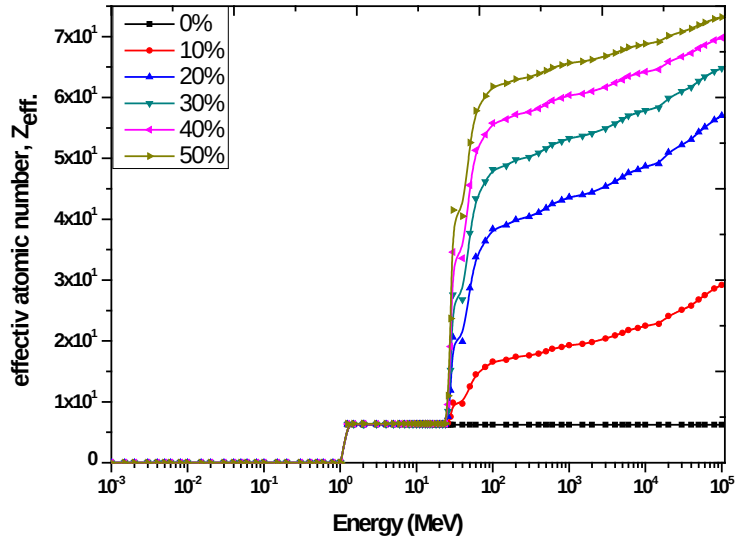

Fig. 8: The variation of effective atomic number of polymer composites with photon energy for pair production in nuclear field.

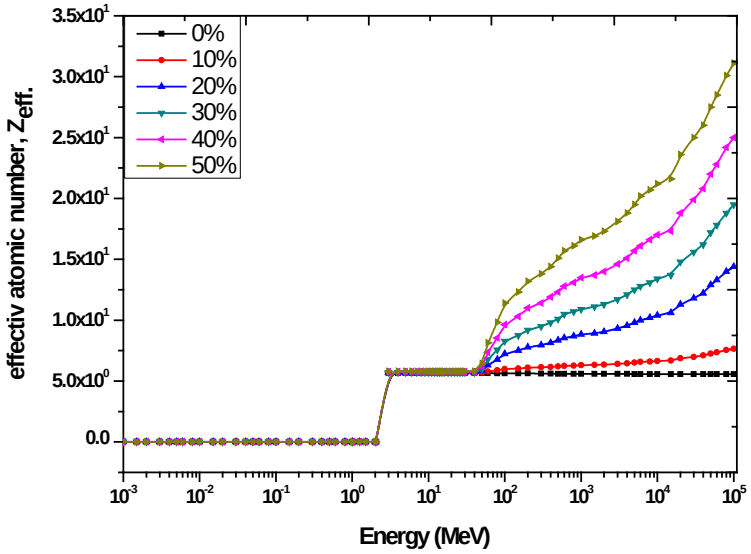

Fig. 9: The variation of effective atomic number of polymer composites with photon energy for pair production in nuclear field.

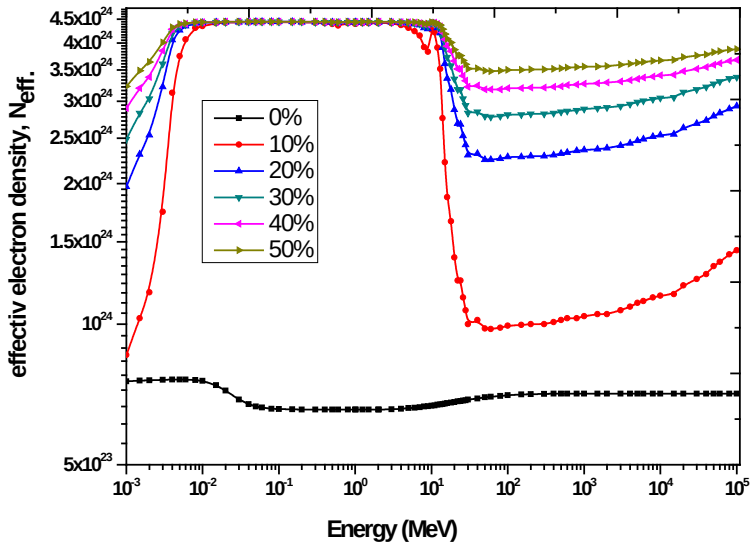

Fig. 10: The variation of effective electron density of polymer composites with photon energy for total interaction (with coherent).

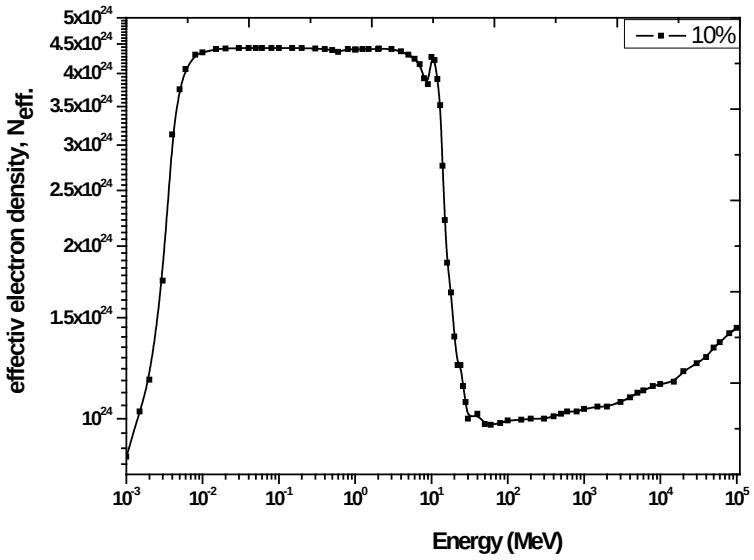

Fig. 11: The variation of effective electron density of polymer composite with 10% PbO aganist photon energy for total interaction (with coherent).

CONCLUSION

The present study gives the values for the gamma-rays mass attenuation coefficients, effective atomic numbers and effective electron densities of polymer composites reinforced with different percentages of

PbO (0% - 50%) over a wide range of photon energies from 1 keV to 100 GeV. The result of this study is helpful in understanding the interaction of γ-ray with polymer reinforced composites, which has been used in fabrication of a new shielding material. The obtained results show that Z_{eff} and N_{eff} parameters are dependent on photon energy, influenced by different interactions. In addition, the obtained results indicated that the polymer composites reinforced with different percentages of PbO are good shielding materials for gamma rays.

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