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Application of Gamma-Ray Attenuation in Studying Soil Properties

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The objective of this work is focused to calculate the total mass attenuation coefficients, effective atomic numbers and electron densities in some soil samples for total and partial photon interactions in the wide energy range (1 keV–100 GeV). The values of these parameters have been found varied with composition of soil and energy while their trend has been found to be with all energies. The variations of these parameters according to energy are shown for all possible photon interactions. WinXCOM code was used to calculate soil mass attenuation coefficients. The obtained data should be important for comparing radiation sensitivity and radiation detection of soil. The results of this work can be used for research in other soils with different textiles.

Keywords: Soil; mass attenuation coefficients; effective atomic number; effective electron number; WinXCOM.

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1. INTRODUCTION

Soil is important for supporting and helping growth of agricultural crops. The soil's natural cycles go a long way in ensuring that the soil can provide an adequate physical, chemical and biological medium for crop growth. Soil has to be attractive very much for future life not only due to the potential applications in the field of agriculture but also in other applications in constructions, electronics and energy efficient savers. So, it is useful to get accurate information about all possible interactions in the soil samples. The attenuation interaction parameters e.g. mass attenuation coefficients, effective atomic number, effective electron density, are used to study all possible photon interactions because they depend on the energy of incident photon and the composition type of the absorbing material.

Studying photon attenuation with matter for different compound materials have been discussing by several workers in different categories such as compounds, alloys, glass, minerals, and biology and so on [1-15]. The objective of this study is to calculate mass attenuation, effective atomic numbers and electron densities of some selected soil samples collected from different places in Egypt.

2. METHOD OF COMPUTATION AND THEORETICAL BASIS

When a material of thickness x is placed in the path of a beam of monoenergetic γ-ray or X-ray radiations, the intensity of the beam will be attenuated according to the Beer–Lambert's law,

$$\mathrm{I} = I_0 e^{-\mu x} \tag{1}$$

where I_0 and I are the incident and attenuated photon intensity, respectively, and μ (cm^{-1}) is the linear attenuation coefficient of the material. Mass attenuation coefficient is a density-independent and more accurately characterizing a given material. Mathematical rearrangement of Eq. (1) yields the following equation for the mass attenuation coefficient ($cm^2.g^{-1}$) [11-14]:

$$\frac{\mu}{\rho} = \frac{1}{\rho x} ln\left(\frac{I_0}{I}\right) \tag{2}$$

where ρ ($g.cm^{-3}$) is the measured density of the material. The total mass attenuation for a material composed of many elements can be calculated as the sum of the $(\mu/\rho)_i$ values of each element by the following formula [11-14]:

$$\left(\frac{\mu}{\rho}\right) = \sum_i c_i \left(\frac{\mu}{\rho}\right)_i \tag{3}$$

where c_i and $(\mu/\rho)_i$ are the fraction weight and the mass attenuation coefficient of the *i*-th element in the material, with that rule :

$$\sum_i c_i = 1 \tag{4}$$

For a chemical compounds the weight fraction is given by:

$$c_i = \frac{n_i A_i}{\sum_j n_j A_j} \tag{5}$$

The average atomic cross-section σ_a can be obtained as follow [11-14]:

$$\sigma_a = \sigma_m \frac{1}{\sum_i n_i} \tag{6}$$

Similarly, the average electronic cross-section σ_e can be obtained as follow:

$$\sigma_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i \tag{7}$$

where $f_i = \mathrm{n_i}/\sum_j n_j$ and Z_i are fractional abundance and atomic number of elements, respectively. n_j is the number of atoms of the constituent element, $\sum_j n_j = n$ is the can be obtained as follow [11-14]:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{8}$$

The number of electrons per unit mass (effective electron number), N_{el} of the material can be obtained as follow:

$$N_{el} = \frac{\left(\frac{\mu}{\rho}\right)}{\sigma_e} = \left(\frac{Z_{eff}}{M}\right) N_A \sum_i n_i \tag{9}$$

3. RESULTS AND DISCUSSION

The soil samples used in this study was taken from five different physical agricultural zones in Egypt with different fractions of sand, coarse silt, fine silt, coarse clay and fine clay with different concentrations. Concentration of chemical compounds in the investigated soil samples was determined by using set of chemical reactions and conventional methods as listed in Table 1. WinXCOM program was applied for calculating the mass attenuation coefficients of soil samples

[16]. The software can generate cross-sections and attenuation coefficients for elements, compounds or mixtures in the energy range between 1 keV and 100 GeV, in the form of total cross-sections and attenuation coefficients as well as partial cross-sections of the following processes: incoherent scattering, coherent scattering, photoelectric absorption and pair production in the field of the atomic nucleus and in the field of the atomic electrons. The code possesses a comprehensive database for all elements over a wide range of energies, constructed through the combination of photoelectric absorption, incoherent, coherent scattering, and pair production (nuclear and electric field) cross-sections. The partial and total mass interaction coefficients are also tabulated in the database of the code.

The photon attenuation coefficients (μ/ρ), Z_{eff} and N_{el} of all soil samples were calculated. The result of total mass attenuation coefficients of soil sample is shown in Fig. 1. The variation of (μ/ρ) is due to chemical composition of soil and the incident photon energy.

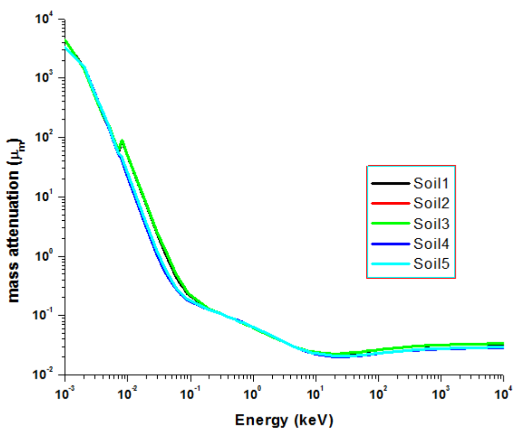

Fig. 1. Variation of photon mass attenuation coefficient of some soil samples with photon energy for total photon interaction

There three different regions for the distribution of mass attenuation against energy. The first region, which is defined as the photoelectric absorption region where mass attenuation coefficients have the highest maximum values proportional to atomic number Z^{4-5}. The second region, which is defined as the intermediate energy region, the incoherent scattering is the most effective. The third region, which is defined as the high energy region, mass attenuation coefficients increase, where the pair production is maximum effect and mass attenuation is proportional to the square of atomic number.

The behavior of Z_{eff} for photon total interaction reflects how it is important the partial photon interaction with the soil samples. The photon interaction processes play a significant role in this field, since the interactions occur at low energies, where photoelectric absorption is the most important interaction process.

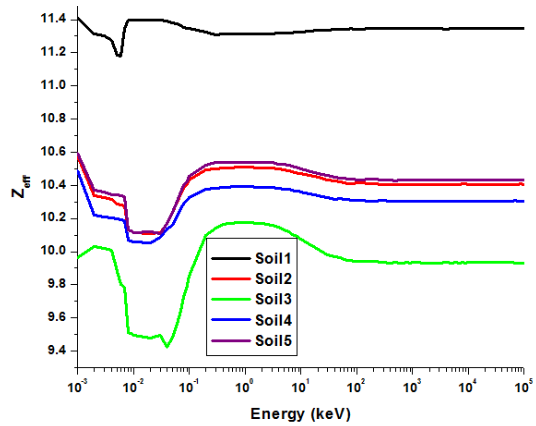

Fig. 2. Variation of Z_{eff} with photon energy of the soil samples for total photon interaction

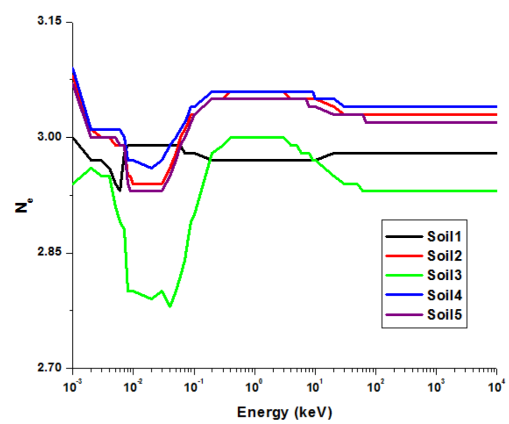

Fig. 3. Variation of N_e with photon energy of the soil samples for total photon interaction (with coherent)

The changes of Z_{eff} and N_{el} with photon energy are shown in Figs. 2 and 3. In all soil samples, the interaction of photons is related to effective atomic number values and the energy of photons which it can be negligible at high energies. From Fig. 2, it is clear Z_{eff} increased in the investigated soils and then decreased up to 10 MeV. Above 100 MeV, Z_{eff} will be constant. This because the effect of pair production in the region of high energy. The Z_{eff} of all soil samples is higher due to the exits of some high Z elements.

The behavior of Z_{eff} for total photon interaction indicates the importance of the partial photon interaction behavior. At lower energy (E < 0.01 MeV), the maximum value of Z_{eff} is exist. At middle (0.05 MeV < E < 5 MeV), where Compton scattering is the main response of photon interaction process, Z_{eff} is nearly equal to the mean of the atomic number which can be calculated according to the formula, $<Z>= \frac{1}{n}\sum_i n_i Z_i$. The third region is high energies, (E > 100 MeV), Z_{eff} is still constant but smaller than in the low-energy range. This is due to the effect of pair production process and the cross section which has Z^2 dependence. It is seen from Table 2, there is a better agreement in Compton scattering through the main photon interaction process of the matter.

The variations of N_{el} with photon energy for total interaction processes (Fig. 3) are the same as Z_{eff} and can be explained by the same way. It can be noticed that the value of N_{el} is found to extend within ($2.94–3.07\times10^{23}$electron.g^{-1}) as shown in Table 3. This can be explained on the similar way based on as for Z_{eff}. The calculation values of atomic numbers and electronic densities are shown in Figs. 4 and 5. Both of them are decreased to the range edge 10 MeV and then it is increased with the energies of photons.

Table 1. Chemical composition of the investigated soil samples

Soil type	Chemical components (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	Na_2O
Soil 1	67.10	11.11	8.11	3.32	2.12	1.00	4.67	2.10
Soil 2	79.30	4.77	3.58	1.66	1.89	0.97	4.40	3.22
Soil 3	52.37	18.44	14.35	4.36	2.66	0.90	3.44	2.33
Soil 4	60.18	16.55	13.70	3.73	1.43	0.91	3.33	2.35
Soil 5	45.17	19.31	18.18	3.41	2.76	1.00	3.26	3.39

Table 2. Effective atomic number (Z_{eff}) of investigated soils at different energy (MeV) for total photon interaction

Energy (MeV)	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
10^{-3}	11.20	10.57	9.96	10.49	10.59
10^{-2}	10.67	10.11	9.49	10.06	10.11
10^{-1}	11.15	10.43	9.85	10.32	10.45
10^{0}	11.38	10.50	10.18	10.39	10.54
10^{1}	11.28	10.47	10.07	10.36	10.50
10^{2}	11.14	10.14	9.94	10.31	10.44
10^{3}	11.14	10.40	9.93	10.30	10.34
10^{4}	11.13	10.40	9.93	10.30	10.34
10^{5}	11.13	10.40	9.93	10.30	10.34

Table 3. Effective electron number ($N_e \times 10^{23}$ electrons/g)) of investigated soil at different energy (MeV) for total photon interaction

Energy (MeV)	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
10^{-3}	2.94	3.08	2.94	3.09	3.07
10^{-2}	2.80	2.94	2.80	2.97	2.93
10^{-1}	2.93	3.03	2.91	3.04	3.03
10^{0}	2.99	3.06	3.00	3.06	3.05
10^{1}	2.96	3.05	2.97	3.05	3.04
10^{2}	2.92	3.03	2.93	3.04	3.02
10^{3}	2.92	3.03	2.93	3.04	3.02
10^{4}	2.92	3.03	2.93	3.04	3.02
10^{5}	2.92	3.03	2.93	3.04	3.02

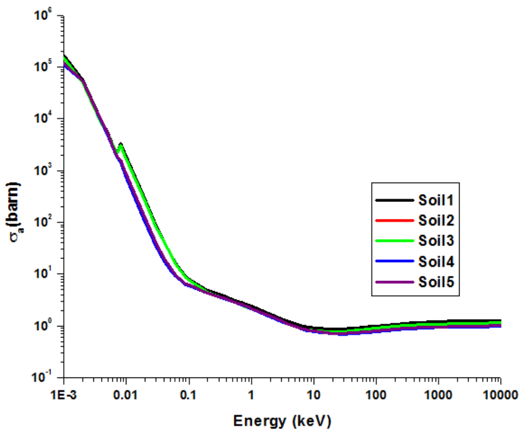

Fig. 4. Variation of atomic cross sections σ_a (b/atom) with photon energy

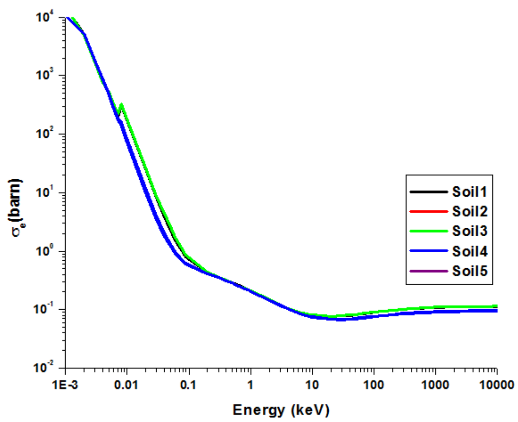

Fig. 5. Variation of atomic cross sections σ_e (b/atom) with photon energy

4. CONCLUSION

This study has been applied to study the effect of photons in soil by studying mass attenuation coefficients, photon interactions parameters, effective atomic numbers and electron density for different soil samples. The results can applied for other extended soil samples. In the interaction of photons with the soil, mass attenuations values are depending on the chemical structures of the samples. The obtained results of (μ/ρ) are varied with photon energy in the main three regions (photoelectric absorption, Compton scattering and pair production). Both of electron density and effective atomic number are closely related to each other and they are depending on energy. The dependence on the atomic number indicates that soil having high effective atomic numbers absorb strongly the incoming photons. The minimum value is found in the intermediate region, where Compton scattering is exist and Z_{eff} is approximately equal to the mean atomic number of the soil. The highest value of Z_{eff} is found at the low energy region, where photoelectric absorption is exist.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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