Experimental and Theoretical Investigation of Gamma Attenuation for Soil and Oil Soil Samples

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Abstract. The gamma rays attenuation is investigated experimentally and theoretically for soil and oil soil samples. The soil samples were collected from different locations of Kirkuk city in Iraq and the oil soil samples which are soil samples contaminated with oil were collected from different locations in surrounding areas of Kirkuk oil field. The experimental measurements have been investigated using gamma spectrometer multichannel analyzer MCA contains shielded NaI (Ti) detector. The collimator of aperture diameter 3 mm were used to ensure that the detector absorbs a narrow beam of gamma rays after passing through the test column. Samples were irradiated by gamma-rays emitted from point sources of $^{241}$Am, $^{133}$Ba, $^{137}$Cs and $^{60}$Co. The attenuation coefficients were also calculated theoretically using XCOM software and Monte Carlo simulation code Geant4. To evaluate the availability of the codes, the comparisons with the experiments are presented.

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1 Introduction

Radiations have today become an inseparable part of living environment, the workers and the public around must be protected or shielded from these radiation. When radiation passes through any material such as soil, its intensity gradually reduces as a result of a series of interactions. The linear attenuation coefficient ($\mu$), which is defined as the probability of a radiation interacting with a material per unit path length. The magnitude of attenuation coefficients depends on the incident photon energy, the atomic number and the density of the materials. Soil has chemical properties as on its compositions like Fe, Ca, Na, Mg, K, Al, S, etc. Gamma transmission measurements had been used to evaluate different properties of soil and soil-water diffusion processes.

Most of the obtained experimental results have been compared with the theoretical results by using the XCOM program and Monte Carlo simulation codes.
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Geant4. Geant4 is found an effective tool to calculate radiation interaction parameters in different types of mixtures. The impacts of various parameters on the mass attenuation coefficient of materials are discussed in many studies. Varied experimental and theoretical studies have been conducted on the effects of different factors on the mass attenuation coefficients of soil [1-28].

In this work, we have investigated the gamma attenuation experimentally and theoretically for many soil and oil soil samples for the photons of the energies 59.5, 356.5, 662, 1173, and 1332 keV. Experimentally, using gamma spectrometer multichannel analyzer MCA contains shielded NaI (Tl) detector, and theoretically by using XCOM code and Monte Carlo simulation code Geant4.

2 Gamma Attenuation

The mass attenuation coefficients of the soil samples calculation by the following equation based on the Beer-Lambert law [29]:

\[ I = I_0 e^{-\mu x}, \]  \hspace{1cm} (1)

where \( I_0 \) and \( I \) are the attenuated and incident photon intensities, respectively, \( x \) (cm) is the thickness of the material. The linear attenuation coefficient \( \mu \) of the material is an intrinsic property of each material, by taking the logarithm of both sides,

\[ \ln (I) = \ln (I_0) - \mu x. \]  \hspace{1cm} (2)

This equation is in the form of an equation for a straight line, \( y = a + bx \), where the slope of the line \( b = \mu \) (cm\(^{-1}\)) and \( x_m \) (cm) is the sample thickness. Equation (2) may be expressed using the mass attenuation coefficient \( \mu_m = \mu/\rho \) (cm\(^2\)/g) and the density \( \rho \) of the material.

The \( \mu_m \) values of soil samples were calculated by mixture rule

\[ \mu_m = \sum_{i}^{n} w_i (\mu_m)_i, \]  \hspace{1cm} (3)

where \( w_i \) is the fraction of the \( i^{th} \) element and the summation is over all components of the mixture.

3 Theoretical Calculations

Berger and Hubbell developed a software called XCOM. The idea behind XCOM software is saving time from manual work of interpolating tabulated values and using mixture rule. XCOM is a web-based that calculates photon interaction cross-section or mass attenuation coefficients for elements, compound or mixture at 1 keV to 100 GeV photon energies [30].
This XCOM software provides attenuation coefficients and total cross section as well as partial cross sections for the following processes: coherent scattering, incoherent scattering, photoelectric and pair production in the field of the atomic electrons and in the field of the nucleus for compounds. The total attenuation coefficients and interaction coefficients for mixtures or compounds are obtained as sums of the corresponding quantities for the atomic constituents. Below 30 keV energy, the uncertainties are as much as 5–10% because of correction to experiments for high-Z impurities and departure of correction to experiments for high-Z impurities and departure of Compton cross section from Klein-Nishina theory. Also above 100 MeV photon energy, uncertainties in \( \mu_m \) values may be 5–10% [31].

The Monte Carlo simulation code Geant4 is one of the most and largest ambitious open source codes in terms of the scope and size, and it is a modern object-oriented C++ code. The development of Geant4 has grown to become a large international collaboration of over (100) scientist, physicist programmers, and software energies from a number of institutions and universities participate in a broad range of research experiments in Europe, Canada, Japan, and United States. The application areas include high energy physics nuclear experiments, medical, accelerator and space physics as well as low energy physics in the newer versions.

The Geant4 code covers a wide energy range starting from 250 eV to 1 TeV [32,33]. It is simulation the photon attenuation through materials in flexibility computer environment, instead of performing an experimental determination of \( \mu \) values of different composite materials or mixtures. So for that the system model would be useful for further experiments where material and incident photon energy is being changed.

4 Experimental Procedures

The investigated soil samples were taken from different locations of Kirkuk city of Iraq and the oil soil samples were collected from some oil stations of Kirkuk city, and analyzed chemically by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The ICP-MS combines a high-temperature ICP (Inductively Coupled Plasma) source with a mass spectrometer. The ICP source converts the atoms of the elements in the sample to ions. These ions are then separated and detected by the mass spectrometer [34].

A 500 mm mesh was used to sieve the investigated samples, and the drying temperature was set to 110°C for 24 h to ensure that any significant moisture was removed. A cylindrical plastic container of internal diameter 3 cm and height 4 cm was placed between detector and sources. The collimator of aperture diameter 3 mm were used to ensure that the NaI(Tl) detector absorbs a narrow beam of gamma rays after passing through the test column. The whole system
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Figure 1. Experimental setup for measuring gamma attenuation coefficients.

was enclosed in lead shielding (5 cm lead, 0.5 cm copper, 0.5 steel) to reduce background counts. The experimental arrangement is as shown in Figure 1.

The gamma rays were 59.5 keV, 356.5 keV, 662 keV and (1173, 1332) keV photons emitted by $^{241}\text{Am}$, $^{133}\text{Ba}$, $^{137}\text{Cs}$ and $^{60}\text{Co}$ radioactive point sources, respectively. The number of counts $I_0$ of gamma particles for 1800 s using multichannel analyzer (MCA) was measured and the background contribution has been subtracted from the total counts. Then by inserting the soil samples in container 1 cm, 2 cm, etc., the number of counts $I$ of gamma particles for

<table>
<thead>
<tr>
<th>Sample</th>
<th>Chemical components (%)</th>
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<tbody>
<tr>
<td></td>
<td>Fe</td>
</tr>
<tr>
<td>Soil 1</td>
<td>3.79</td>
</tr>
<tr>
<td>Soil 2</td>
<td>2.30</td>
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<td>Soil 3</td>
<td>2.93</td>
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</tr>
<tr>
<td>Soil 9</td>
<td>2.42</td>
</tr>
<tr>
<td>Soil 10</td>
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<tr>
<td>Oil soil 5</td>
<td>1.94</td>
</tr>
<tr>
<td>Oil soil 6</td>
<td>1.47</td>
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</tbody>
</table>
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1800 s was measured for each path length. The graphs of intensity ln(I) versus thickness of soil sample are plotted, the slope of the absorption graph gives the experimental gamma-ray mass attenuation coefficient of the samples.

5 Result and Discussion

Table 1 shows the chemical components of the investigated soil and oil soil samples. Figures 2 and 3, show experimental results of linear attenuation curve of energies 59.5 keV, 356.5 keV, 662 keV, 1173 keV and 1332 keV for investigated soil and oil soil samples (soil contaminated with oil), respectively. The theroretical calculation of linear attenuation coefficients of soil and oil soil samples are
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Figure 4. The Geant4 simulation of electromagnetic interaction with Iron at: (a) 59.5 keV; (b) 356.5 keV; (c) 662 keV; (d) 1173 keV; and (e) 1332 keV.

Figure 5. The Geant4 simulation of electromagnetic interaction with Aluminum at: (a) 59.5 keV; (b) 356.5 keV; (c) 662 keV; (d) 1173 keV; and (e) 1332 keV.
carried out by Geant4 Monte Carlo simulation code and XCOM program at the above photon energies. The linear attenuation coefficient of Geant4 and XCOM is a function of the incident photon energy and the chemical composition. As an example, the Geant4 simulation of electromagnetic interaction with Iron and Aluminum at above energies is presented in Figures 4 and 5.

![Graphs of linear attenuation coefficients for different soils](image)

Figure 6. Calculated linear attenuation coefficients by Geant4 and XCOM with respect to experiment at: 59.5, 356.5, 662, 1173 and 1332 keV in Soil samples: (a) soil 1; (b) soil 2; (c) soil 3; (d) soil 4; (e) soil 5; and (f) soil 6.
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Geant4 Monte Carlo simulation code results of samples were compared with the theoretical results calculated by using XCOM program and to the experimental results. The results are shown in Figures 6–8. The values of the mass attenuation coefficients decrease sharply in the high-energy region. There is satisfactory agreement between experiment and theory at 59.5 keV, although the experimental results tend to be lower than the theoretical results. The overestimate of theoretical results at some energies reflect the effect of the chemical composition of the sample and the mixture-rule method. Geant4 Monte Carlo code is better than XCOM in comparison with the experimental results.

Figures 9 and 10 summarize the behavior of the theoretical and experimental mass attenuation coefficients vs. energy of the investigated soil and oil soil samples, respectively. It is observed that as the energy increase the mass attenuation coefficient will be decreased. The mass attenuation coefficient has a highest value in the energy region (1–100 keV), where the photoelectric absorption is significant. In the intermediate energy region (100 keV – 1 MeV), the Compton scattering is significant, and mass attenuation coefficient is found to be constant.

Figure 7. Calculated linear attenuation coefficients by Geant4 and XCOM with respect to experiment at 59.5, 356.5, 662, 1173 and 1332 keV in soil samples: (a) soil 7; (b) soil 8; (c) soil 9; and (d) soil 10.
Figure 8. Calculated linear attenuation coefficients by Geant4 and XCOM with respect to experiment at 59.5, 356.5, 662, 1173 and 1332 keV in oil soil samples: (a) oil soil 1; (b) oil soil 2; (c) oil soil 3; (d) oil soil 4; (e) oil soil 5; and (f) oil soil 6.

But in the high energy region (1–15 MeV), the mass attenuation coefficient has a lowest value as the pair production is dominant.
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Figure 9. Theoretical and experimental mass attenuation coefficients of the investigated soil samples.

Figure 10. Theoretical and experimental mass attenuation coefficients of the investigated oil soil samples.
6 Conclusion

The experimental measurements of attenuation coefficient are carried out for soil and oil soil samples of various chemical components. Only at 59.5 keV, we found a significant difference in the value of the attenuation coefficients between experimental measurements and theoretical calculations for soil and oil soil samples. Geant4 code is a powerful in studying interaction of photons in materials and it is better than XCOM in comparison with the experimental results. The overestimate results at some energies reflect the effect of the chemical components percentage of the samples and the mixture-rule method. The study has a particular importance to know the efficiency of the system by comparing the experimental results with theoretical results.

References

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