Calculation of Mass Attenuation Coefficients and Cross Sections for Different Elemental Metals

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Abstract

The Compton effect is studied with the measurement of a γ-ray energy spectrum using a scintillator, photomultiplier tube, and multichannel analyzer. The gamma rays interact with the detector, producing all three primary interaction processes, so that every phenomenon that is being studied in a sample is also taking place in the detector itself along with several other effects that mask the process of interest. The linear and mass attenuation coefficients are studied for the elements Ni, W, and Al and materials at different photon energies using a continuous spectrum from the ^{137}Cs source via standard collimated beam shielding. The linear and mass attenuation coefficients calculated with the Win X-COM program are in good agreement with the theoretical values. That the materials with high photon absorption cross-section may be used for changing the shape of the radiation spectrum. The increase in their thickness decreases the mass attenuation coefficient. The measurements were carried out using a 3"×3" NaI (Tl) detector system and an 8 mCi Cs-137 source.

1. Introduction

Nowadays the measurement of x-ray differential scattering cross-sections becomes a useful study in radiation attenuation, transport, and energy deposition and also plays an important role in medical physics, reactor shielding, and industrial radiography, in addition to x-ray crystallography. While the coherent (Rayleigh) scattering accounts for only a small fraction of the total cross section, which contributes at most 10% in heavy elements, just below the K-edge energy. Also, the incoherent (Compton) scattering accounts for the rest of the total cross section, where, for the low Z materials, this process dominates over most of the energy range [2]. Gamma-ray dosimetry is a non-destructive method for determining the density.The principle of gamma-ray tomography measurement is based on the absorption of gamma radiation in the tested material. The scanning is performed using a small radioactive source and a sensitive electronic detector. The source and detector are kept external to the pipe and positioned on opposite sides at a fixed distance apart. In the literature, a variety of experimental data relevant to the measurement of the mass attenuation coefficients of different samples are available. The aim of the present work is measuring and calculating the attenuation of photons in these materials in addition to comparing the results with the Win X-COM program.

2. Theory

A photon makes its way through matter; there is no way to predict precisely either how far it will travel before engaging in an interaction or the type of interaction it will engage in. In clinical applications we are generally not concerned with the fate of an individual photon, but rather with the collective interaction of the large number of photons [3]. In most instances, we are interested in the overall rate at which photons interact as they make their way through a specific material. The interactions, either photoelectric or Compton, remove some of the photons from the beam in a process known as attenuation. Under specific conditions, a certain percentage of the photons will interact, or be attenuated, in a 1-unit thickness of material [4]. When monoenergetic gamma rays are collimated into a narrow beam and allowed to strike a detector after passing through an absorber of variable thickness, the result should be a simple exponential attenuation of the gamma rays [5]. Each of the interaction processes removes the gamma-ray photon from the beam either by absorption or by scattering away from the detector direction and can be characterized by a fixed probability of occurrence per unit path length in the absorber. The sum of these

probabilities is simply the probability per unit path length that the gamma ray photon is removed from the bea [6]:

$$\mu = \tau_{photoelectric} + \sigma_{Compton} + k_{pair} \quad (1)$$

where μ is the linear attenuation coefficient.

The number of transmitted photons I is then given in terms of the number without an absorber (I_0) as:

$$\frac{I}{I_0} = e^{-\mu x} \quad (2)$$

where x is thickness of the absorber

The gamma-ray photons can also be characterized by their mean free path λ, defined as the average distance travelled in the absorber before an interaction takes place. Its value can be obtained from

$$\lambda = \frac{\int_0^\infty x e^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu} \quad (3)$$

and is simply the reciprocal of the linear attenuation coefficient. Typical values of λ range from a few mm to tens of cm in solids for common gamma ray energies .The use of the linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material is the same. Therefore, the mass attenuation coefficient is much more widely used and is defined as :

$$mass\ attenuation\ coefficient = \frac{\mu}{\rho} \quad (4)$$

where ρ represents the density of the medium

For a given gamma-ray energies. the mass attenuation coefficient does not change with the physical state of a given absorber. For example it is the same for water whether present in a liquid or a vapor form. The mass attenuation coefficient of a compound or mixture of elements can be calculated from:

$$\left(\frac{\mu}{\rho}\right)_{compound} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (5)$$

where the W_i factors represent the weight fraction of element i in the compound or mixture

As the radiation interacts with matter, its intensity will decrease. It is important to know how radiation intensity decreases as it passes through a substance. The degree of attenuation is dependent on the absorber material and the energy of the radiation. For all the absorbing materials, the attenuation of gamma radiations is exponential in character [7]. Two important physical spectroscopic parameters used for measuring the extent of attenuation of gamma rays as they pass through a given absorber are the linear attenuation coefficient and the mass attenuation coefficient [8].

3. Materials and Methods

In the present research, 3 pure metal elements were chosen to cover a wide range of atomic numbers from 13, 28, and 74 in order to study the attenuation of continuous energy gamma rays in high- and low-Z materials. The gamma detector used in this work was a 3"×3" NaI (Tl) scintillation detector. The system is portable and can be used in laboratories and fieldwork. It has a fully integrated multichannel analyzer (MCA) tube base that contains a high-voltage power supply and preamplifier, all supplied by Canberra Industries, USA. The source was cylindrical ^{137}Cs, 0.8 cm in diameter, whose activity was 8 mCi, giving collimated gamma rays at the exit of the lead collimator of the same dimension. Samples are located 15 cm after the radioactive source, and the measurement time was 15 minutes.

In order to compare our experimental data with the theoretical calculations the Win X-Com program was used. This software can calculate the various cross sections and attenuation coefficients for the elements, compounds or mixtures in the energy range between 1 keV and 100 GeV, or on selected energies, in the form of total cross-sections and attenuation coefficient as well as the 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. For compounds, the quantities tabulated are the partial and total mass interaction coefficients. The program possesses a comprehensive database for all elements over a wide range of energies, constructed through the combination of incoherent and coherent scattering cross-sections of, photoelectric absorption and pair production cross-sections.

4. Results and Discussion

In the present work, the different elements are taken to measure and calculate mass attenuation coefficients and cross-sections. From the measured values of I_0 and I, Eq. (2), the ratios I/I_0 are plotted against mass absorber thickness for the elements Ni, W, and Al, as shown in figures (1), (2) and (3). It is obvious that I/I_o decreases with the increase of the sample's mass thickness. Furthermore, a good agreement between the theoretical and the experimental results is obtained.
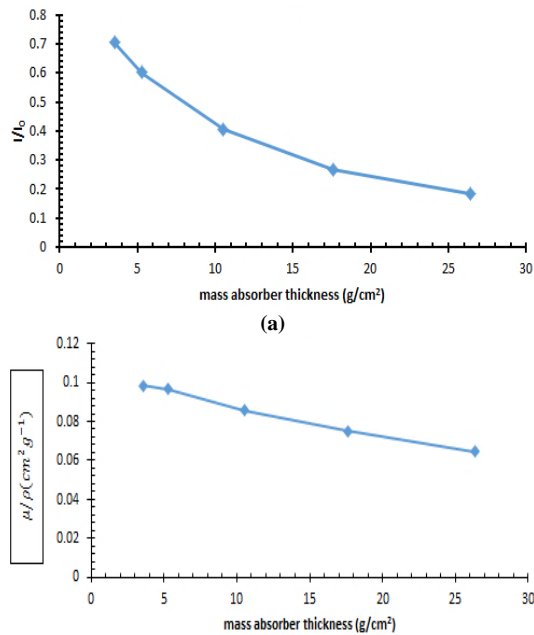
(a)

Fig. (1) (a) Transmitted-to-incident continuous energy gamma ray intensity vs. mass absorober thickness for Ni, (b) Plot of mass attenuation coefficient for continuous energy gamma ray vs. mass absorober thickness for Ni
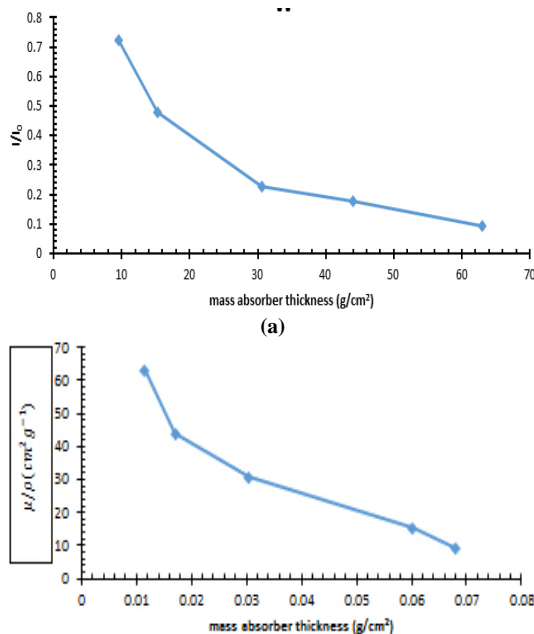

(a)

Fig. (2) (a) Transmitted-to-incident continuous energy gamma ray intensity vs. mass absorober thickness for W, (b) Plot of mass attenuation coefficient for continuous energy gamma ray vs. mass absorober thickness for W
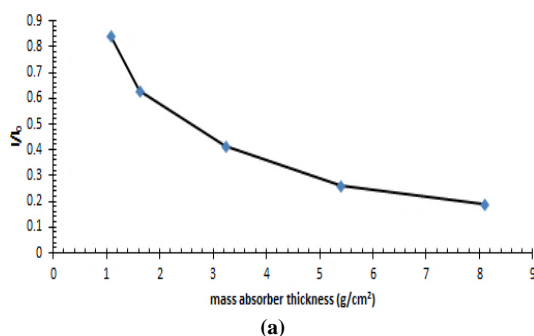

(a)

(b)

Fig. (3) (a) Transmitted-to-incident continuous energy gamma ray intensity vs. mass absorober thickness for Al, (b) Plot of mass attenuation coefficient for continuous energy gamma ray vs. mass absorober thickness for Al

The experimental values of μ/ρ of the continuous energy gamma-ray source for various elements are evaluated using Eq. (4) and depicted in figures (1), (2) and (3). Inspection of these curves reveals that the μ/ρ decreases with increasing the mass absorber thickness. This result may be attributed to the increase in the number of small-angle scattering and multiple scattering photons that reach the detector. This is unlike the mass attenuation of monoenergetic gamma rays, which is independent of mass absorber thickness [9,10]. This confirms that the attenuation of continuous energy gamma rays in an absorber does not conform to a single exponential law (Eq. 2), unlike the absorption of monoenergetic gamma rays. Rather, it is a combination of a large number of exponential terms. This is due to the continuous nature of the spectrum, which undergoes a change in its shape on passing through different mass absorber thicknesses.

At a particular mass thickness of each sample, the value of μ/ρ increases with the increase of the Z value of the absorber. The reason is that all three processes of absorption of gamma rays in matter increase as the atomic number Z increases.
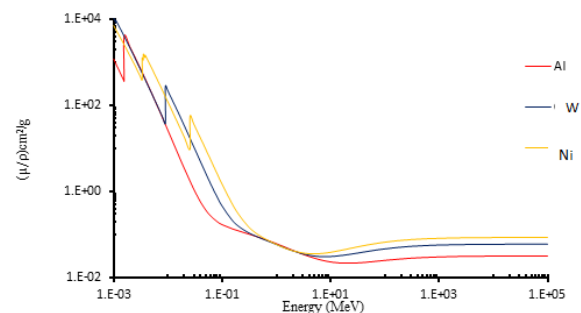

Fig. (4) variation of mass attenuation coefficient with photon energy for different elements

The values of the total mass attenuation coefficients for the element samples under study

as a function of the energy range from 0.001 to 10^5 MeV are shown in Fig. (4), which are calculated theoretically using the Win X-Com program and illustrated. The main effect observed was that as the atomic number of the attenuators increased, the calculated total μ/ρ increased.

The documented pattern is that attenuation due to photoelectric interactions varies with the cube of the target's atomic number because, as Z increases, more valence shells are filled and electrons within a given shell are bound more tightly to the atom [11]. The result would therefore be higher binding energies and a wider range of binding energies among the electrons within a given atom. This means that more electrons per unit area would be available for photoelectric interaction since more of them would have binding energies that approximate the energies of the photons from the incident continuous energy gamma-ray beam. While attenuation due to Compton scattering varies directly with electron density (or linear Z-dependence), pair production shows Z^2 dependence. In the low-energy region, overall attenuation is the sum of attenuation by Compton scattering and attenuation of the photoelectric effect. Therefore, as atomic number increases, overall attenuation increases greatly because the number of photoelectric interactions increases greatly, while the number of Compton scattering interactions increases only slightly. In the intermediate and high energy regions where the Compton and the pair production are the dominant reaction channels, the contribution of these reactions to the $(\mu/\rho)_{tot}$ in terms of Z is only slight.

5. Conclusions

In the interaction of photons with matter, μ/ρ values are dependent on the physical and chemical environments of the elements in the sample. The obtained μ/ρ values decrease with increasing photon energy. The results of this study will be helpful to understand μ/ρ change with variation of the atomic and electronic number of different alloy compositions. The calculated linear and mass attenuation coefficients are in good agreement with the theoretical values.

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