Cs-137 Material as a Source of Gamma Rays for Studding Compton Scattering and Photon Attenuation Using a Rotating NaI(Tl) Scintillation Crystal Spectrometer

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Abstract

Caesium (Cs) material of Group 1 of the periodic table the alkali metal group. Caesium-137 (^{137}Cs) are the most widely used sources of gamma radiation. It produces gamma rays with an energy of 0.662 MeV and has half-life of 30.1 years. A collimated ^{137}Cs source producing γ-rays and a rotating NaI(Tl) scintillation crystal spectrometer with a photon energy of 662 keV were used in this experiment to study Compton scattering and photon attenuation. The aim in this experiment is to verify relation for the energy of the scattered photons (gamma rays) given by the Compton scattering equation using special relativity. As well as the effects of Compton scattering, the variation in energy when the photon is scattered to an angle (θ) is studied. The attenuation of the gamma rays was shown to follow Beers law. In addition, the Compton scattering was determined to produce a linear relationship between the reciprocal of the scattered photon energy, $1/E^{-}\gamma$ as a function of (1-cosθ), where θ is the scattering angle. The differential scattering cross section, $d\sigma/d\Omega$ for photon scattering from electrons which measures the probability of the process occurring was also investigated.

Keywords: Caesium-137, materials, radiation detector, Gamma Rays, Photon Attenuation, Compton Scattering.

Introduction

Each material in the periodic table has special properties. In general the matter consists of atoms and the atom consists of nucleus enclosed by electrons that circuit around this nucleus. If gamma ray interacts with matter, it will interact with both nucleus and electrons.
As a fact there are two mechanisms, which gamma rays interact with matter, they are absorption and scattering. Despite these two mechanisms, include a big number of interactions for gamma rays with matter, only three major types are an important role in radiation measurements; Compton scattering, pair production and photoelectric effect.
Arthur H. Compton was the first to measure photon-electron scattering in 1922. Compton effect is the name used to explain the wavelength increase when the energy of gamma-ray photon interacts with matter [1].
The interest of this phenomenon is that gamma- ray photon can be treated such as particles when scatter from the electrons, they obey the same energy conservation law and an impetus. As it is shown in Figure 1, Compton scattering occurs when a photon hits an electron, the photon energy being communicate to the changed particle. Therefore, it measures the change in energy of a photon, for example, the scattering at variant angles [1,2].

Theory

As it indicated above, there are many types of gamma-rays interaction with matter, Compton scattering, pair production and photoelectric effect.

In this experiment, the Compton effect had been investigated and observe the interactions through the attenuation measurements. Firstly, the attenuation of photons in matter is described by Beers law [3]:

$$I = I_0 \exp(-\mu t) \tag{1}$$

Where, I is the transmitted photon intensity, I_0 is the incident photon intensity, μ is the liner attenuation coefficient and t is the thickness of the absorber.

As it is shown in Figure 1, the Compton effect is the elastic scattering of photons from electrons. As a reaction, the process is:

$\gamma + e \rightarrow \gamma^{-} + e$

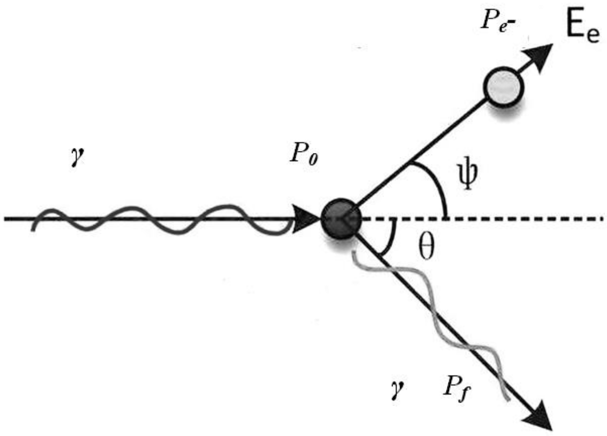

Figure 1 Schematic plot of Compton scattering process [4].

Since this is a two body elastic scattering process, the angle of the scattered photon is completely conflated with the energy of the scattered photon by energy and momentum conservation [5]. This relation is usually written as:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta) \tag{2}$$

where λ and λ' are the wavelengths of the incident and scattered photon respectively, and θ is the photon scattering angle. The energy of a photon is related to its frequency and wavelength as:

$$E = hv = \frac{hc}{\lambda} \tag{3}$$

where *c* is the velocity of light. Combining eqs. (2) and (3) the energy of the scattered photon is:

$$E\gamma' = \frac{E}{1 + \frac{E}{m_0 c^2}(1 - cos\theta)} \tag{4}$$

The kinetic energy of the recoil electron is:

$$\mathrm{Te} = E - E' = E\,\frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)} \qquad (5)$$

Where $\gamma = \frac{hv}{mc^2}$

The quantity *h/mc* in eq. (2) is called the Compton wavelength and has the value: *h/mc* = 2.426 x 10^{-10} cm : 0.02426 A^o. When *hv* << mc^2 the probability for Compton scattering can be regarded as a classical process and is given by the Thompson cross section which is the classical limit of the exact Compton scattering cross section formula.

$$\frac{d\sigma}{d\Omega}\Big|\ Thompson = r_0\left(\frac{1+cos\theta}{2}\right) \qquad (6)$$

Where $r_0 = \frac{e^2}{4\pi\epsilon_0 mc^2}$ is the classical electron radius and has the value, $r_0 = 2.818\mathrm{x}10^{-13}$ cm. When integrated over all scattering angles, eq. (6) yields the total Thompson cross section:

$$\sigma_r = \frac{8}{3}\pi r_0^2 \qquad (7)$$

This simple cross section has several failings:

1. It does not depend on the photon energy, a fact not supported by experiment.
2. The electron, although free, is assumed not to recoil.
3. The treatment is no relativistic.
4. Quantum effects are not taken into account.

The problem was solved by Klein and Nishina in 1928 giving the correct quantum mechanical calculation for Compton scattering, so called Klein-Nishina formula:

$$\frac{d\sigma}{d\Omega} = r_0^2\left(\frac{1+cos\theta}{2}\right)\frac{1}{(1+\gamma(1-cos\theta))^2}\times\left[\frac{\gamma^2(1-cos\theta)^2}{(1+cos^2\theta)\big(1+\gamma(1-cos\theta)\big)}+1\right] \qquad (8)$$

This result is for the cross section averaged over all incoming photon polarrzations. By integrating eq, (8) over all angles, the total cross section can be obtained. While the expression for the total cross section is a lengthy formula, two asymptotic expressions for the total cross section σ_c in the low energy and high energy case are simpler.

Equation (9) will be using to calculate the number of electrons in the scattering sample:

$$K=V\rho ZN_A/A \qquad (9)$$

where V is the volume of scattering, Z is the atomic number, ρ is the density and A is the atomic weight. While ΔΩ is defined as following equation:

$$\Delta\Omega= A/d2 \qquad (10)$$

where A is detector surface area and d is distance from scatterer to detector face. Equation (11) is the final one in the theory which is as below:

$$I = \text{Activity of the source (Bq)} / 4\pi r^2 \qquad (11)$$

where R is distance from the source to the centre of the sample.

Experimental method

Photon attenuation

The first part of the experiment was photon attenuation setup. Prior to calibrate the (MCA) program, an experiment must be run to determine the linear coefficient of lead and compare these results to the theoretical prediction.
The HpGe detector was calibrated by ^{152}Eu source with 200s as a live time then, the net counts was measured of γ-ray ROI's (121, 244, 344, 778, 964, 1112 and 1408) keV by using the amount of lead absorbers from 0.6 g/cm^2 to 35 g/cm^2.

Scattering energy

At the beginning of this experiment a calibration for the system was achieved, this was by placing a ^{137}Cs source with 661.64 keV into the plastic vial which placed onto the aluminium stub at the centre of rotation to create an energy spectrum. This happened by locating the detector at the right angle, then by replacing the ^{137}Cs source with a ^{133}Ba source, another energy spectrum was recorded over the ^{137}Cs spectrum.
The ^{137}Cs peak was used in addition to the peaks of ^{133}Ba that have the following energies of gamma ray (80.99 and 356.01) keV. 2.5cm of aluminium rod was placed on the centre of rotation followed by the removal of the plastic vial, the detector was rotated to an angle of 20^o and a spectrum was cumulated for a preset time of 300s.
This spectrum contains the scattering signal from bench and other locations, and then the effect of this unwanted scattered radiation was removed by removing the aluminium rod from its position. Here the second spectrum in subtract was made.
These measurements were repeated for scattering angle up to 100^o, the graph was plotted of scattering photon energy ($E^{-}\gamma$) versus scattering angle (θ) including both our measured and calculated data.

Differential scattering cross section

In this part of the experiment $\frac{d\sigma}{d\Omega}$ was calculated using the equation (8) and plotted the graph of $\frac{d\sigma}{d\Omega}$ versus θ.

Results and Discussion

Figure 2 below provides the linear attenuation of gamma rays, whereas the graph confirms that, the energy of gamma ray was decreased by the increase of the mass thicknesses of absorber.

Figure 3 shows both the calculated values of scattered photon energy from equation (4) and the measured values as a function of scattering angle.
Figure 4 provides that $\frac{1}{E'\gamma}$ against (1-cosθ) this straight relationship of Compton scattering for both measured values and calculated values, by using equation (8), it was found 1.586 for intercept, and gradient 2.071 of measured data. After calculation it found to be 1.956 and 1.51.

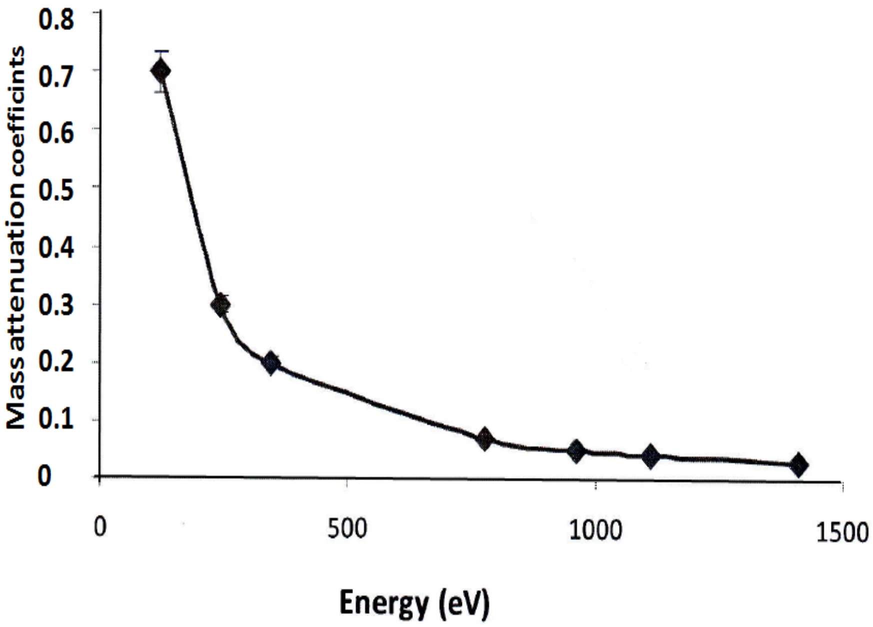

Figure 2 Attenuation of ^{137}Cs through aluminium

The error of the measurement is:
Deviation for a = $|1.586 - 1.51| / 1.51 \times 100\% = 5.03\%$
Deviation for a = $|2.071 - 1.956| / 1.956 \times 100\% = 5.87\%$

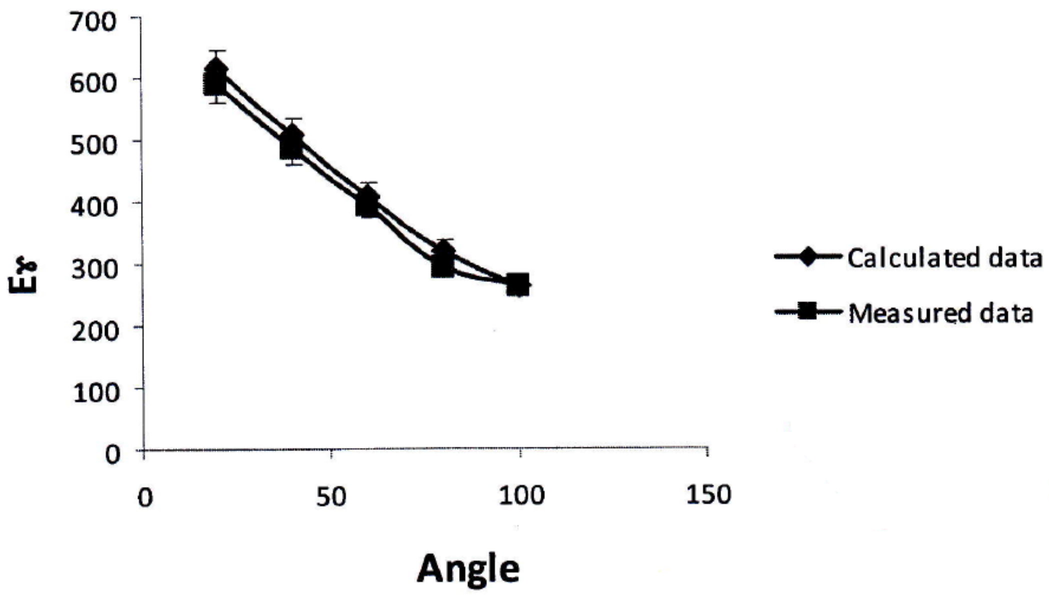

Figure 3 Scattering energy of ^{137}Cs as a function of angle

Figure 5 shows the calculated values for differential cross section for Compton scattering against the scattering angle.
As well as the measured values were found to be k= $3.08\times10^{7}\pm2.0\times10^{5}$ photons/m^2/s. by using the equations (9, 10, 11).
The Table 1 below shows the constant's values that were used to find these measurements.

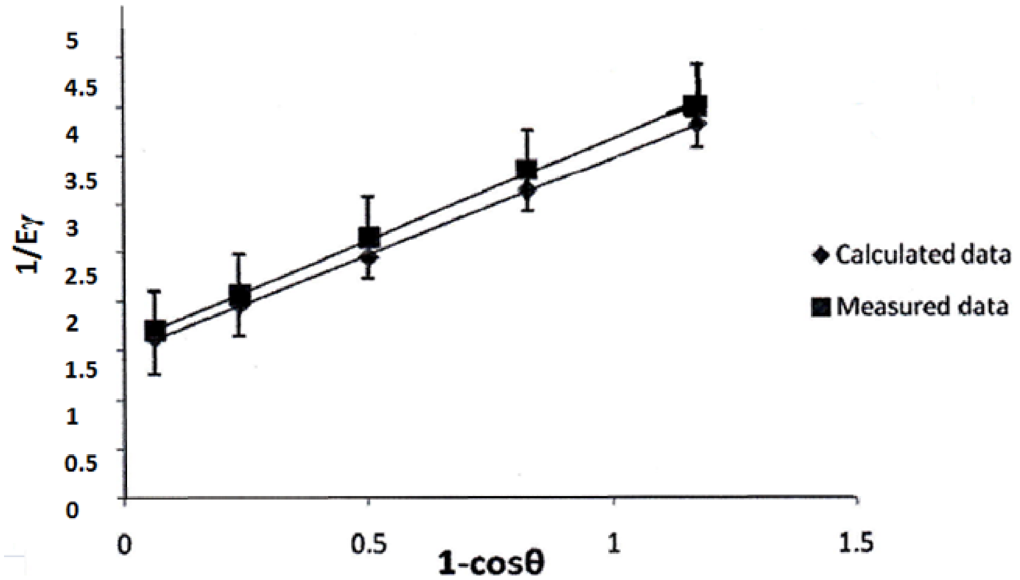

Figure 4 Compton scattering linear relationship

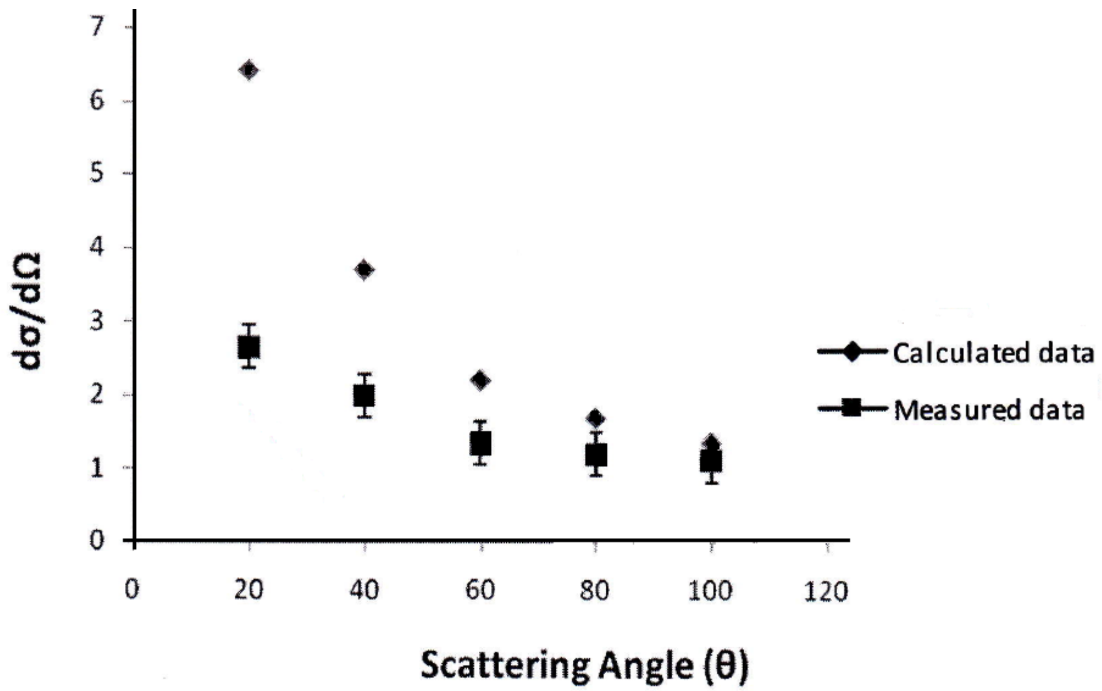

Figure 5 Deferential scattering cross section

Table 1 The constant's values that were used for the measurements [6,7].

Constants used	Rate
A	26.98g
Z	13
V	$3.93\times10^{-5}\pm1.1\times10^{-6}m^3$
ρ	2.7×106g/m3
N_A	6.022×10^{23}

Activity=$A_o e^{-\lambda t}$	$27.82\times10^{6}\pm1.0\times10^{4}$
t	30.02±0.002y
A_O	55.5×10^{6}Bq
d	0.35±0.001m
A=πr^2	$5.03\times10^{-3}\pm2\times10^{-4}$m
R	0.27±0.001m
$T_{1/2}$	30.15y
$\Lambda=\log_e 2/t_{1/2}$	$0.023y^{-1}$

Conclusion

This experiment used a NaI(Tl) scintillation crystal spectrometer and a collimated ^{137}Cs source to study some of the characteristics and interacting mechanisms of γ -rays.
In this experiment gamma ray attenuation was investigated by HpGe and ^{152}Eu source. The attenuation was due to several interactions when gamma ray was passing through an absorber of variable thickness and removes the gamma ray photon from the beam either by absorption or scattering. The scattered photons are detected by scintillation /photomultiplier arrangement produces an electrical pulse with a magnitude proportional to the energy absorbed in the scintillation. The detector can be rotated in order to make measurements as a function of scattering angle.
The scattered energy $E^- \gamma$, of the photons for Compton scattering as a function of scattering angle θ was then plotted in Figure 2, which showed a good fit between the theoretical and measured data. This shows that as the angle increases, the energy of the scattered γ-ray will decrease. By rearranging the Compton scattering equation 3, the Compton effect was explored further, producing a linear relationship between [$\frac{1}{E^{-}\gamma}$] and (1-cosθ). On the other hand, the differential cross section for Compton.
scattering was studied by using the Klein- Nishina formula. Both the measured and predicted results are of the same order of magnitude with a higher probability of forward scattering, and a decreasing cross section as a function of angle.

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