Compton Scattering

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Abstract

The purpose of this experiment is to investigate the phenomenon called Compton Scattering. This report goes into detail about the findings of energy and momentum conservation in photons, giving way for the discovery of photons behaving as wave-like particles. The experiment involves analyzing the scattering of high-energy photons (gamma rays) due to the interacts of electrons on a metallic target. By counting the amounts of photons scattered at different angles, ranging from 30 to 90°, the change in energy can be determined. Setting this change as a function of the angle, also for the calculation of the mass of an electron. In this report, the mass of an electron was determined to be $(7.967 \pm 0.706) \cdot 10^{-31}$ kg, which is an 11% error margin from the actual mass of an electron, being $9.1 \cdot 10^{-31}$ kg.

1 Introduction

This report provides an overview of the experiment done by Arthur Compton, discovering an important phenomenon in particle physics, explaining the behavior of light as wave-like particle. This discovery challenged the understanding of physics, and gave way to many new discoveries. In 1923, Arthur Compton measured the effects of high energy light scattering from solids. He found that the scattering due to the metal caused a change in frequency of the photon's wavelength. This observation was problematic at the time, because light was understood as a wave, however, this experiment showed that the change in energy meant that light is actually made up of particles, with wave-like behavior. These particles were later named photons by Albert Einstein. To find the different effects of scattering, a radiation detector measures the amount photon counts scattered at different angles ranging from 0 to 90°. This report's purpose is to investigate this experiment and reexplaining Compton's finding, which is now known as Compton Scattering.

2 Background Information

If a beam of gamma ray photons is sent towards a metallic target, those photons interact with the electrons causing the electrons to also scatter. It was found that the photons have a change in frequency. This change in frequency is analogous to a change in energy which is given to the free electron. The change in frequency can be observed to have a relation to the angle of the source with the detector. Using this information, the mass of an electron can be calculated.

3 Theory

When a photon interacts with the free electron, the photon loses some of its energy. Due to the energy and momentum conservation, that energy is displaced into the electron. This shift in energy creates a shift in frequency of the photon. A simple analysis of kinematics gives this shift in frequency:

$$\lambda' - \lambda = \lambda_c(1 - cos\theta) \tag{1}$$

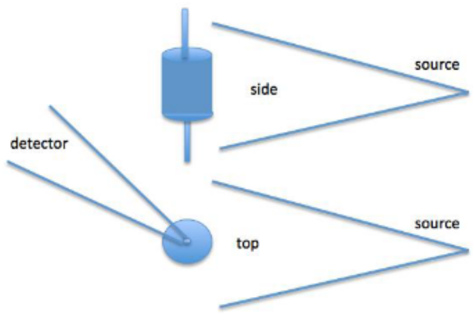
where $\lambda_c = h/mc\ 2.4pm$ is the Compton wavelength. Using this equation, the change in energy can be derived giving the following equation:

$$\frac{E'}{E} = \frac{1}{(1 + E/mc^2)(1 - cos\theta)} \tag{2}$$

E' represents the shifted energy for at the angle θ, E represents the original energy of the gamma ray source mc^2 is the electron's energy, where c is the speed of light. By measuring the change in energy of the Caesium source at different angles, this equation can rearranged to calculate the mass of an electron.

4 Experimental Procedure

To determine the effects of scattering, a beam of photons is obtained by utilizing the gamma radiation from a $^{137}C_s$ (Caesium) source. The source is placed in a container, called a collimator, with a hole of 0.75cm diameter, allowing the beam of photons to exit. The energy of a $^{137}C_s$ source has an energy of 661.7keV and a half life of 30.1 years. This energy is not high enough to induce radioactivity in the measuring apparatus, which is necessary for data acquisition[2]. An aluminum cylindrical target is located 15.5cm away from the detector, with a diameter of 1.8cm and a height of 1.9cm. This target is then located 51.3cm away from the radiation detector (C12137). This detector has a diameter of 4cm. When aligned, the source and detector are 35.8cm apart. The following diagram shows the general geometry of this experimental setup:



Top and side views of scattering geometry of cylindrical target

Figure 1: General Set Up Diagram

To avoid inconsistencies in the data, the radiation was measured with no source or aluminum target, for a time period of 30 seconds, twice and then averaged out. This measurement will be removed from all further data acquisitions. Next, the absolute activity of the source when directly aligned was measured (without Al target). To do so, a small Pb plate was located in front of the detector, minimizing the detector to a diameter of 1.2cm. Once absolute activity, was measured for a known energy, a ^{133}Ba (Barium) source, which a peak radiation energy of 356 keV was added for a two-point energy calibration.

Once measurement for calibration was complete, the scattering measurement can commence. The aluminum target is placed as stated earlier and measurements were made at a 30°, 50°, 70°, and 90°angle. The each set of data acquisition was done for 10 minutes and done 2-3 times and averaged out. The aluminum target was then removed and the process was once again done, removing background radiation and giving more accurate measurement.

5 Results

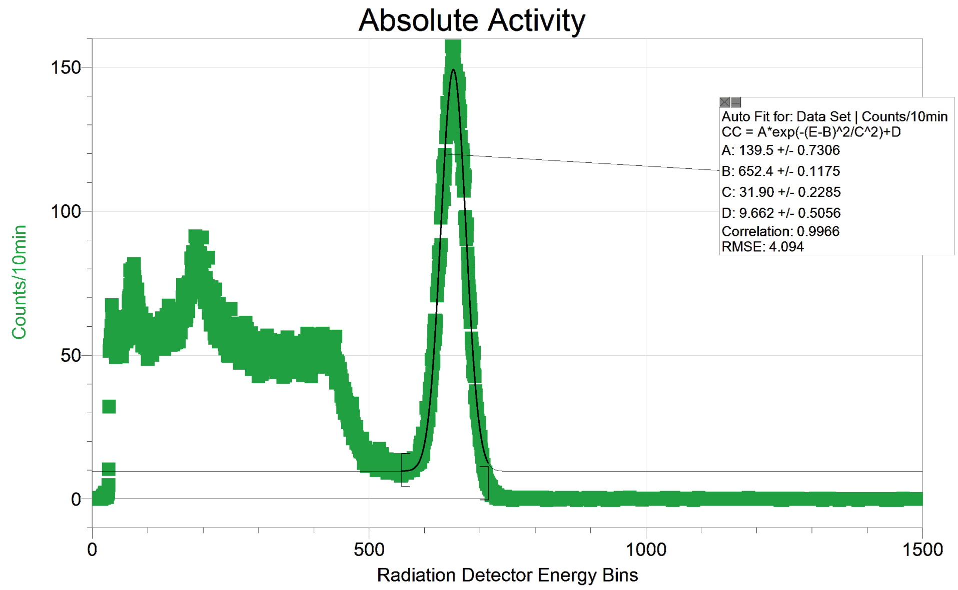


Figure 2: Absolute Activity of ^{137}Cs Source

Figure 2 shows the distribution of the absolute activity of the ^{137}Cs source, with a Gaussian Fit of $(139.5 \pm 0.7306)e^{-(x-(652.4 \pm 0.1775))^2/(31.9 \pm 0.2285)^2)} + (9.662 \pm 0.5056)$ Using these parameters, the intensity of the source can be calculated $I = \int_{-\infty}^{\infty}(139.5 \pm 0.7306)e^{-(x-(652.4 \pm 0.1775))^2/(31.9 \pm 0.2285)^2)}/tdx = 13.145 \pm 0.116$. This, however is the intensity through, just the detector. To get the source intensity, this needs to be integrated over a sphere, giving: $\frac{13.145}{\pi(D/2)^2}\frac{3}{4}\pi R^3 = 65732$ photons per second. Using this, the absolute activity can be calculated, using the approximate efficiency of the detector being $0.01\mu Ci = 1000 counts/min$. This gives an absolute activity of $3.94\mu Ci$.

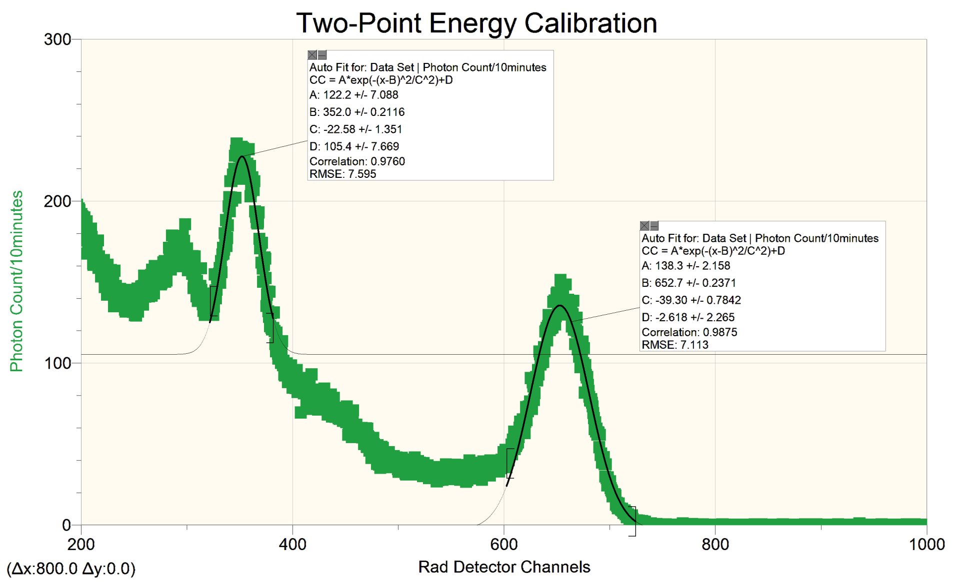


Figure 3: Calibration of Energy and Intensity

Figure 3 shows the count of photons in the span of 10 minutes in respect to the energy given by the radiation detector of the two radiation sources. A Gaussian fit was applied to the peak of the different radiation energy, with the first one being from the ^{133}Ba, at 352.0 ± 0.2116 and the second from ^{137}Cs, at 653.7 ± 0.2371. Using their respective peak energy, the calibration can be done using the following equation:

$$E(keV) = a + b \times E_{\text{rad dec}} \tag{3}$$

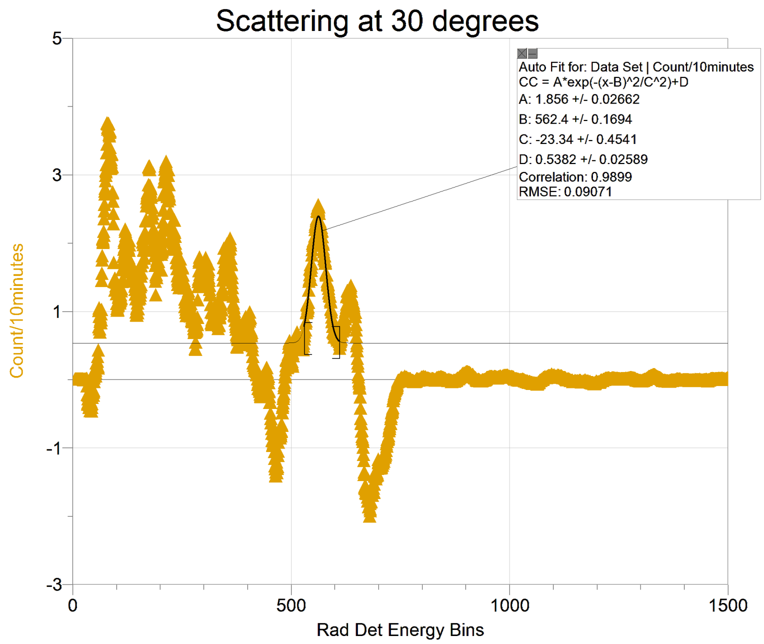
$$^{137}\text{Cs: } 661.7keV = a + b(652.7keV) \tag{4}$$

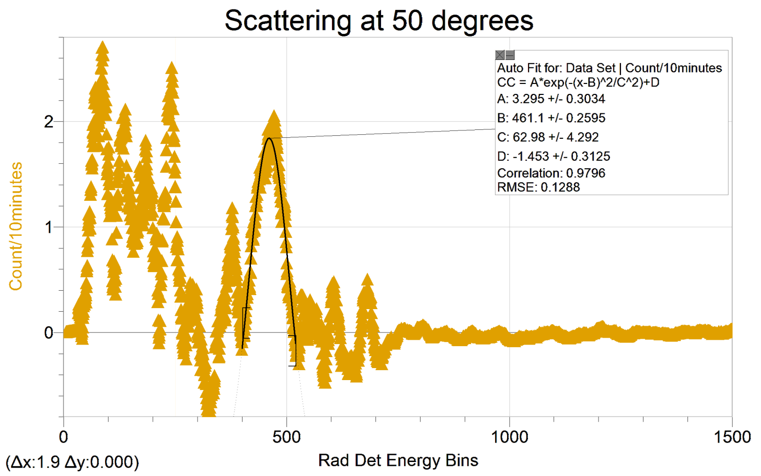
$$^{133}\text{Ba: } 356keV = a + b(352keV) \tag{5}$$

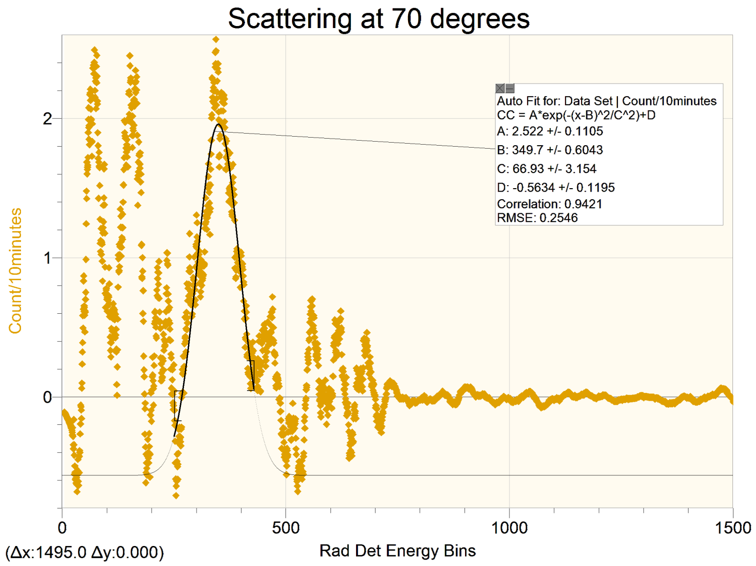
$$a = -1.853keV, \;\; b = 1.017keV/bin \tag{6}$$

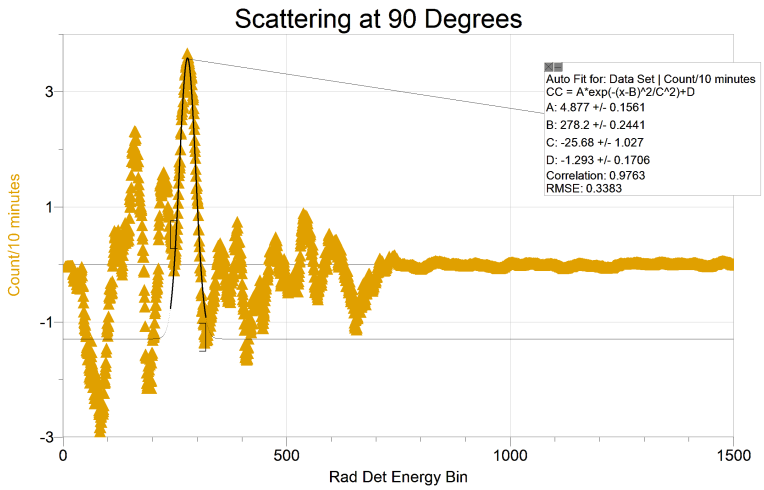
Additionally, the intensity of the ^{137}Cs can be determined as done earlier giving a total intensity of 7225.52 photons per second. This value is much smaller because the detector was not covered by the pB plate and thus has a much bigger surface area but still counted the same amount of photons.

Once having calibrated the detector for the proper displacement in energy measurement, the measuring of angle dependent scattering can begin. Starting from 30 degrees and going to 90 degrees.









The figures above represent the count of photons as a function of the radiation detector energy bins for different scattering angles. When the gamma rays hit the aluminum target, the photons come in contact with electrons, transferring some of its energy to that electron, causing the both the electron and photon to scatter.

Angular Dependence Gaussian Fit:				
Angle	**Peak Photon Count (A)**	**Energy Bin (B)**	**Gaussian Width (C)**	**Photon Count Offset (D)**
30°	1.856 ± 0.02662	562.4 ± 0.1694	-23.34 ± 0.4541	0.5382 ± 0.02589
50°	3.295 ± 0.30342	461.1 ± 0.2595	62.98 ± 4.292	-1.453 ± 0.3125
70°	2.522 ± 0.1105	349.7 ± 0.6043	66.93 ± 3.154	-0.5634 ± 0.1195
90°	$4.877 \pm 0.0.1561$	278.2 ± 0.2441	-25.68 ± 1.027	-1.293 ± 0.1706

Table 1: Gaussian fit parameters of angle dependent scattering

Using this the angle and peak energy bin(the B parameter from Table 1), a linearization can be done, as explained in the theory, giving a slope which relates to the mass of an electron. Doing so gives the following plot:

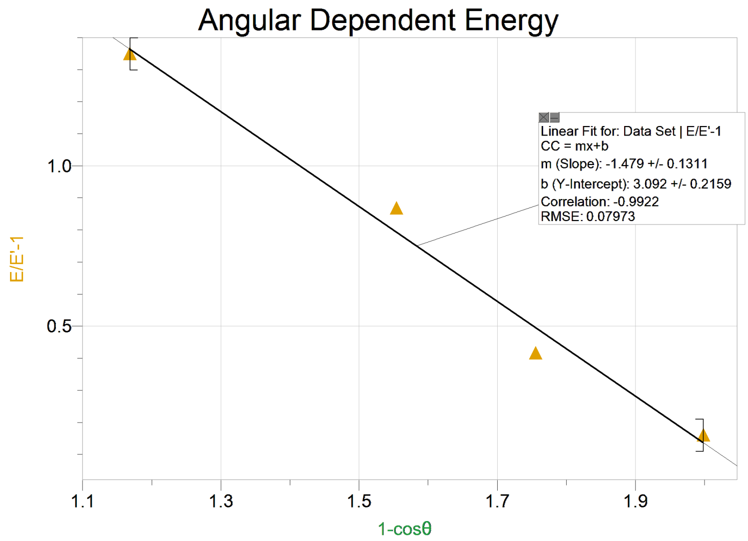


Figure 4: Angular Dependence on Relative Energy

Figure 4 shows the relationship between the angle in which the ^{137}Cs is located, in terms of $1 - cos\theta$, with respect to the energy the peak photon count was found, in terms of E/E'-1. E relates to the known peak frequency of ^{137}Cs, and E' being the energy bin from Table 1, but converted with the calibration parameters calculated in equation (6). Using equation (2) derived in the theory section, the slope of this graph, which was calculated to be -1.479 ± 0.1311, is directly related to the mass of an electron.

$$m = \frac{E}{(-1.479 \pm 0.1311)c^2} \tag{7}$$

$$m = (7.967 \pm 0.706) \cdot 10^{-31} \text{ kg} \tag{8}$$

6 Discussion

From the analysis of the data acquired for different scattering angles, a value was calculated for the mass of an electron. This value, being $(7.967 \pm 0.706) \cdot 10^{-31}$ kg, had an 11% error from the known $9.1 \cdot 10^{-31}$kg. In terms of energy, the electron was calculated to be 447.6 ± 39.6 keV, compared to the known 511.0 keV.This error margin comes from the values used for the peak frequency on the angle dependent. Due to using a Gaussian fit for a set range of points a deviation and error margin is given in each point causing all points to be skewed. Furthermore, the laboratory set up was not a closed system, giving accessibility to outside photons and energy to be counted, giving a deviation in background noise for each experiment.

7 Conclusion

In conclusion, this experiment investigating Compton Scattering proved to be successful in demonstrating the phenomenon of photon scattering and existence of photon-electron interactions, providing a means to calculate the mass of an electron. Through calibration, data acquisition, and analysis, the relationship between the scattering angle and shift in photon energy was confirmed. This shift in photon energy is crucial for the development of particle physics and the behavior of photons as wave-like particles. The calculated mass of the electron came out to $(7.967 \pm 0.706) \cdot 10^{-31}$ kg, exhibiting an 11% error margin from the known value of $9.1 \cdot 10^{-31}$ kg. This discrepancy can be attributed to various factors including measurement inaccuracies, background noise, and limitations within the experimental setup.

8 References

[1] Melissinos, Adrian C., and James Napolitano. Experiments in Modern Physics. Academic Press, 2015.

[2] Poul Bjerregaard, et al. “Cesium 137.” *Cesium 137 - an Overview — ScienceDirect Topics*