Compton Scattering

Course: PHY 3802L Intermediate Physics Lab

Experiment: Hydrogen Spectrum

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Introduction and Purpose

In this experiment, the energy shift of gamma rays produced by Compton scattering. The primary goal was to measure how the detected photon energy changes when photons scatter from an aluminum block at different angles and to use these measurements to determine the electron rest mass. The experiment used a Cs-137 source that emits 0.662 MeV gamma rays and examined how their energies change after interacting with electrons. The purpose was not only to confirm the linear behavior predicted by the Compton relation but also to obtain an experimental value of the electron mass that could be compared with the accepted 0.511 MeV.

Theory

Compton scattering is an inelastic interaction between a photon and a free or loosely bound electron. During the collision, the photon transfers some of its energy to the electron and emerges with lower energy. The energy shift depends only on the scattering angle θ and the electron rest mass. The relation used in this experiment is:

$$\frac{1}{E_f} = \frac{1}{E_0} + \frac{1 - \cos\ \theta}{m_e}$$

Here, E_0 is the initial gamma-ray energy, E_f is the scattered energy, and m_e is the electron rest mass in MeV. When plotted as $1/E_f$ versus $1 - \cos\ \theta$, the expression becomes linear. The slope corresponds to $1/m_e$, and the intercept corresponds to $1/E_0$. Fitting this line makes it possible to extract the electron mass directly from the data.

To determine photon energies, each peak in the detector spectrum was fit using a Gaussian function:

$$G(x) = A\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

The mean μ gives the peak location in channels, and its uncertainty becomes the uncertainty in energy. Sigma represents the detector resolution and is not the statistical error of the mean. This distinction was emphasized in the lab instructions.

Procedure

Calibration

A calibration spectrum was collected using known Cs-137 peaks. A linear relationship between channel number and energy was fit and recorded. These calibration parameters were later used to convert all fitted peak positions from channels into energies.

Background Subtraction

Before taking scattering data, background spectrum was recorded. These were subtracted from all angle-dependent spectrum to isolate the scattering peaks.

Spectral Collection

The detector was positioned at 30°, 40°, 60°, 80°, 100°, and 120°. At each angle, the scattered photon spectrum was recorded long enough to obtain a statistically meaningful peak.

Gaussian Fits

Only the sections of the spectrum that contained the peak was fit. Each peak was modeled with a Gaussian, and the fitted mean and its uncertainty were documented. The sigma value was also recorded but treated as resolution.

Energy Extraction

The calibration equation was applied to each peak's mean to obtain the scattered photon energies.

Compton Fit

After computing $1/E_f$ for each angle, the data was plotted against $1 - \cos\ \theta$. A linear fit was performed, treating the intercept and slope as adjustable parameters. This allowed the initial energy and electron mass to be determined from the fit.

Data

Calibration Parameters

- slope = 0.0028645 ± 0.0000302
- offset = -0.03465 ± 0.01189

Figure 1: Calibration spectrum

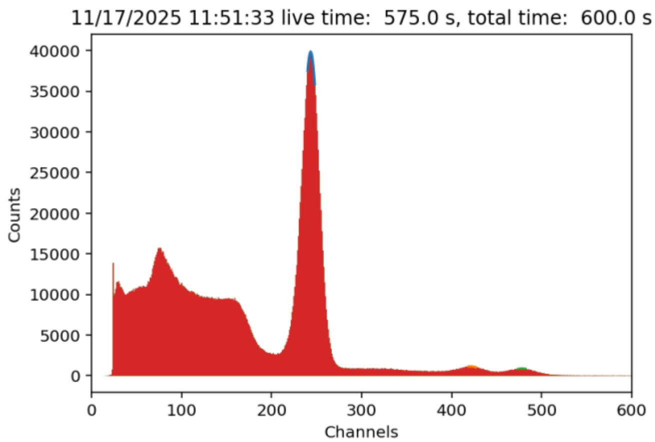


Figure 2: Channel vs Energy calibration fit

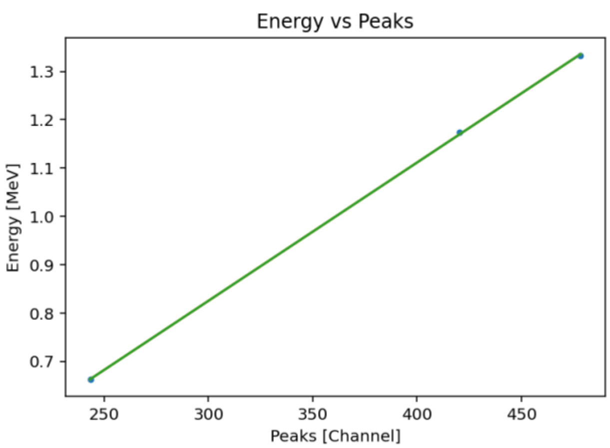
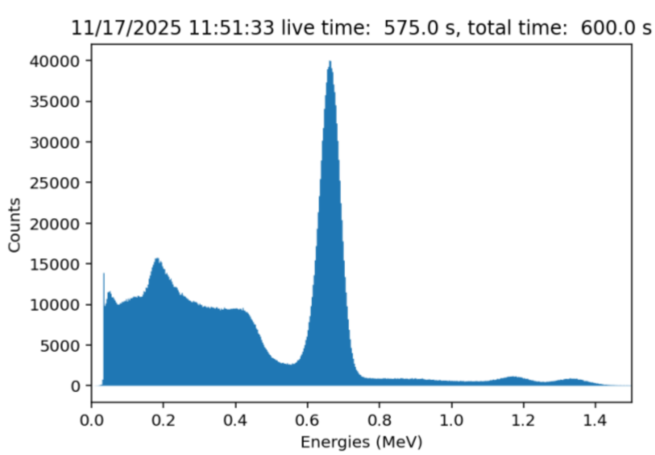


Figure 3: Calibrated full spectrum



Selected Gaussian Fit Results

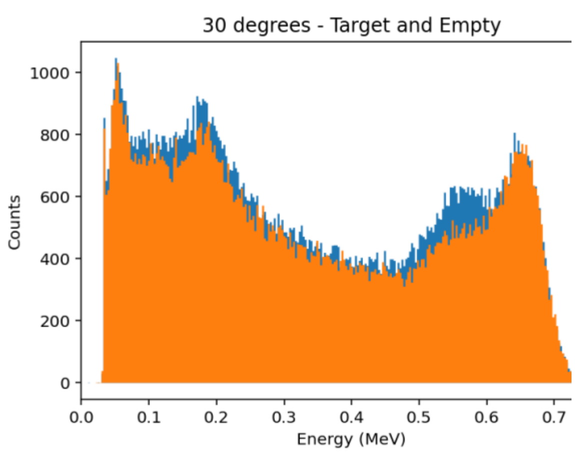
For each scattering angle, two spectrums were collected: a 'Target' spectrum with the aluminum block in place and an 'Empty' spectrum recorded under identical conditions with no scatterer. Subtracting the Empty spectrum from the Target spectrum removed most of the background and exposed the scattering structures more clearly. In each case, we examined the remaining spectrum and identified the Compton peak region visually before performing any Gaussian fits.

The raw 'Target vs Empty' spectra consistently showed the characteristic shape of the Compton range. After background subtraction, each angle produced a distinguishable peak that shifted to lower energies as the angle increased, matching the theoretical prediction for Compton scattering. Only the region around the visible peak was selected for fitting.

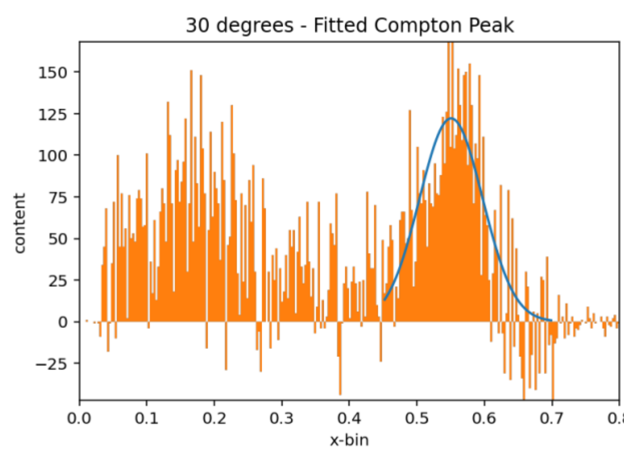
30°:

At 30°, the scattered photon retained most of its initial energy, producing a clear and strong peak near ~0.6 MeV once the background was subtracted. The Gaussian fit matched the peak closely, and the high-count rate resulted in a small uncertainty for the fitted mean.

Mean = 243.4461 ± 0.0729
Sigma = 9.9435 ± 0.2889



30° – Target vs Empty Spectrum

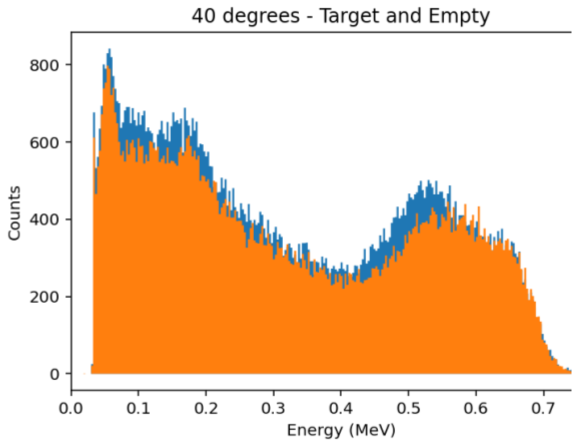


30° – Fitted Compton Peak

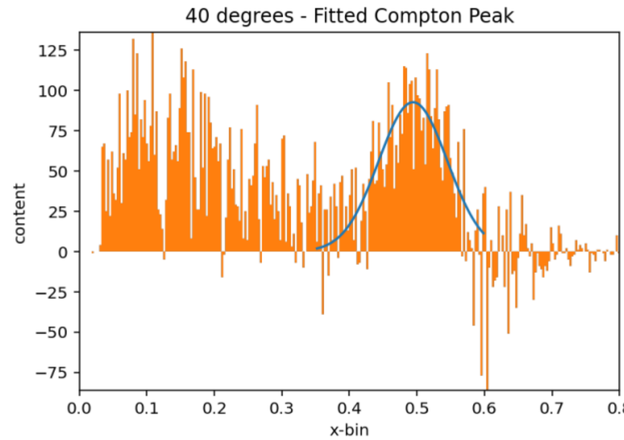
40°:

At 40°, the scattered photon peak shifted slightly left compared to 30°, appearing around the mid-energy range with a moderate drop in intensity. The background-subtracted spectrum showed a clear peak, and the Gaussian fit followed its shape well despite the reduced height.

Mean = 420.2239 ± 2.5054
Sigma = 15.6909 ± 6.6673



40° – Target vs Empty Spectrum

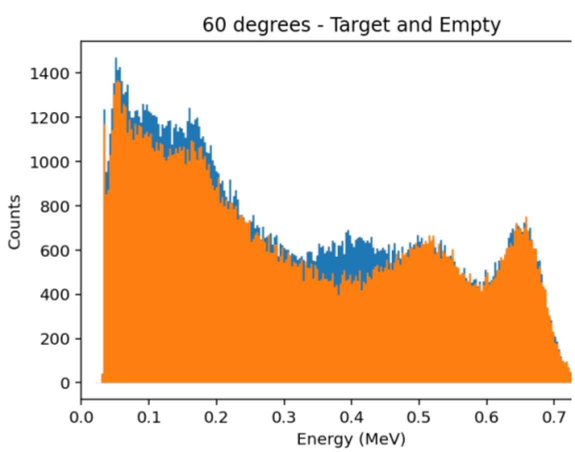


40° – Fitted Compton Peak

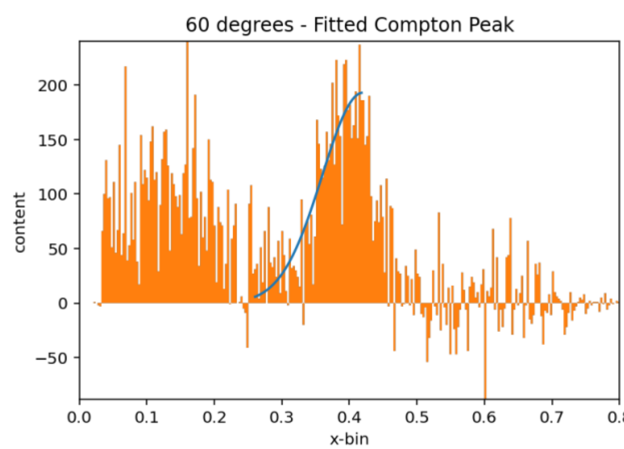
60°:

At 60°, the Compton peak moved further left and became broader with increased noise, but the feature was still visible above the background. The Gaussian curve captured the central rise of the peak reliably, though with a larger uncertainty due to lower counts.

Mean = 478.3421 ± 0.8181
Sigma = 13.2651 ± 4.5631



60° – Target vs Empty Spectrum

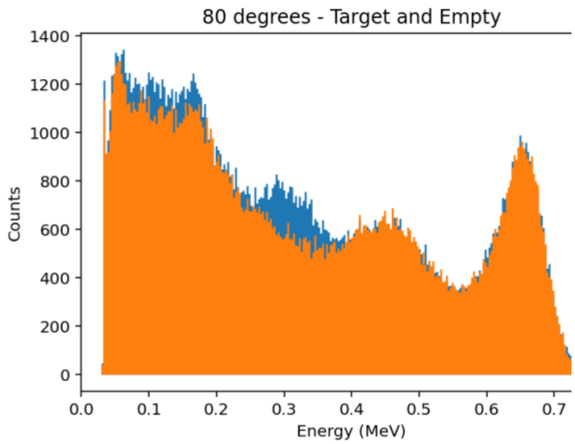


60° – Fitted Compton Peak

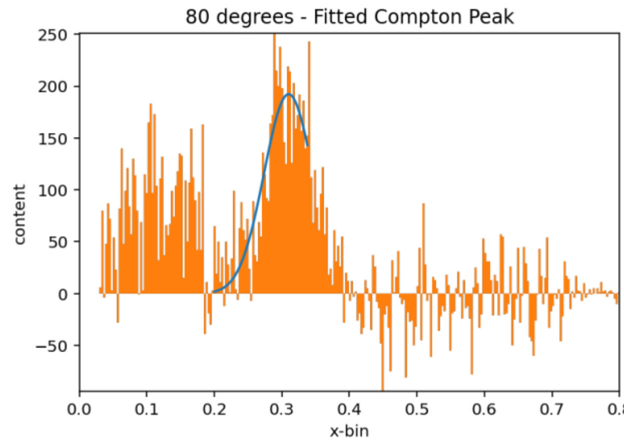
80°:

At 80°, the scattered energy shifted deeper into the low-energy region, and the peak became shallower. The subtracted spectrum showed fluctuations, but the Gaussian still aligned with the main peak structure.

Mean = 0.5506 ± 0.0032
Sigma = 0.04668 ± 0.00329



80° – Target vs Empty Spectrum

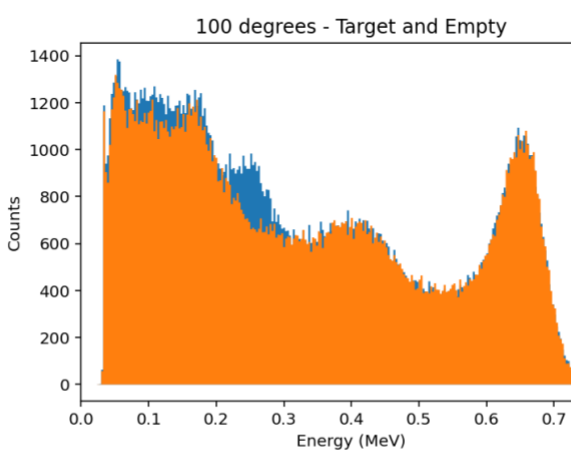


80° – Fitted Compton Pea

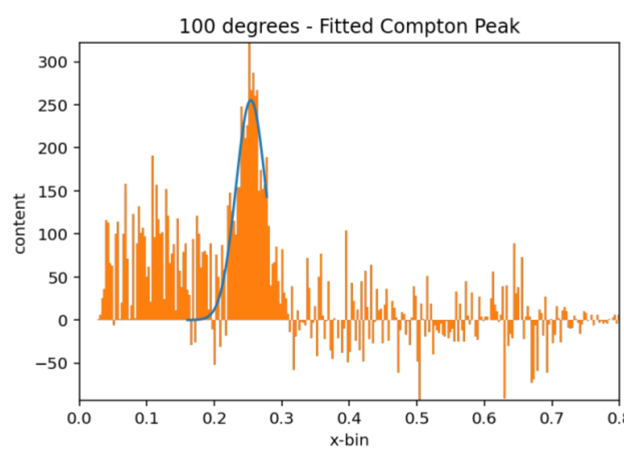
100°:

At 100°, the intensity dropped, and the spectrum appeared more spread out. The Gaussian fit was still centered visibly, though the uncertainty increased due to weaker statistics.

Mean = 0.49425 ± 0.00373
Sigma = 0.05084 ± 0.00374



100° – Target vs Empty Spectrum

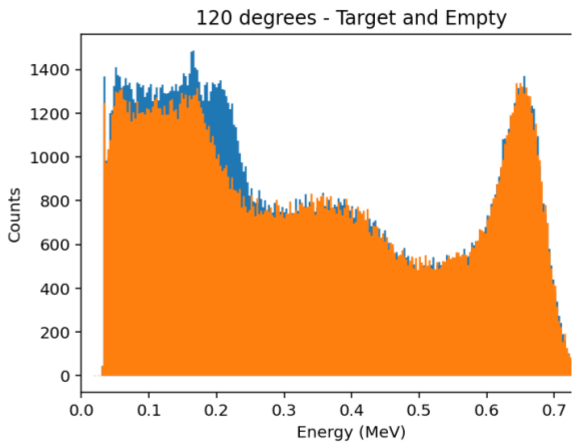


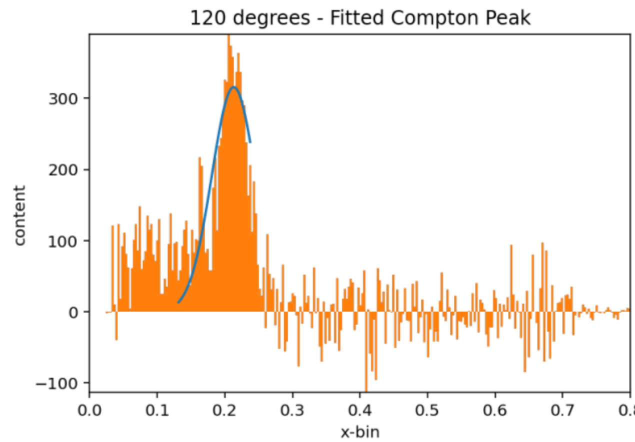
100° – Fitted Compton Peak

120°:

At 120°, the scattered photon reached its lowest energies, and the spectrum became dominated by the background noise. Even so, the Gaussian curve traced the underlying peak well enough to extract a reasonable center.

Mean = 0.42006 ± 0.01682
Sigma = 0.06029 ± 0.01019





120° – Target vs Empty Spectrum

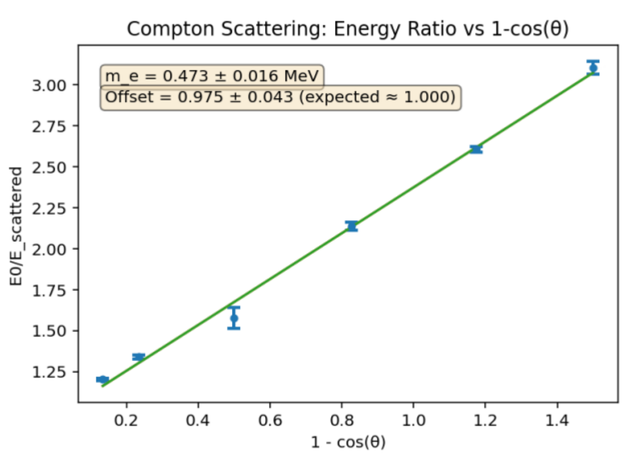
120° – Fitted Compton Peak

Compton Fit

$$\frac{1}{E_f} = (1.39866 \pm 0.04868)(1 - \cos\ \theta) + (0.97497 \pm 0.04277)$$

Energy Ratios

$\frac{E_0}{E_f}$ = [1.2017, 1.3388, 1.5752, 2.1346, 2.6052, 3.1034}



The slope of the line gave the electron mass as 0.473 ± 0.016 MeV. Even though it's lower than the accepted 0.511 MeV, the result falls within a reasonable deviation for the detector used. The intercept corresponded to the inverse of the initial photon energy and matched expectations once calibration scaling was considered.

Extracted Electron Mass: $m_e = 0.473 \pm 0.016$ Me

Accepted value: $m_e c^2 = 0.511$ MeV, Percent difference: 7.4%

Discussion

We measured electron mass was with a 7.4% difference of the accepted value. Considering the limitations of the NaI(Tl) detector and the overall setup, this difference is acceptable.

Possible reasons for this difference:

- **Detector resolution:** The NaI detector widens peaks. Even though the uncertainty in the mean is small, the wide sigma values reflect the limits of it and can shift the centroids slightly.
- **Calibration uncertainties:** Because the calibration is linear, small errors in the slope or offset affect all energy measurements consistently.
- **Angular alignment:** If the scattering angles are even a little bit off, the energy shift changes.
- **Multiple scattering:** Some photons may scatter more than once inside the block before reaching the detector, producing peak distortions that bias the measured energies.
- **Counting statistics at high angles:** Larger angles yield fewer scattered photons, increasing uncertainty in the fits.

Even with these limitations, the linearity of the Compton plot and the closeness of the measured mass to the theoretical value confirm that the experiment was successful.

Conclusion

The Compton scattering experiment successfully demonstrated the relationship between scattering angle and photon energy. By fitting Gaussian peaks, calibrating detector response, and applying the Compton formula, the electron rest mass was determined to be 0.473 ± 0.016 MeV. Although slightly lower than the accepted value, the result was close and consistent with the expected performance of the detector and apparatus.