# Compton Scattering and Rest Mass of the Electron v1.1

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**Background.** The Compton Effect (1922) demonstrates that massless photons possess momentum as well as quantized energy. Photon momentum and energy can be transferred to a stationary electron of mass $m$ in an inelastic collision. Special relativity and quantum mechanics are essential to explain the change in frequency (equivalently wavelength) of the scattered photon and the motion of the electron.

Compton scattering is derived using conservation of energy and momentum, where the energy and momentum of a photon of frequency $\nu$ are taken as $h\nu$ and $h\nu/c$, respectively. The rest energy of the electron is $mc^2$ and it is assumed to have zero momentum prior to its interaction with the photon.

The photon scatters off an electron at angle $\theta$ and with a smaller energy $h\nu'$:

$$h\nu' = h\nu \left[ \frac{1}{1 + (h\nu/mc^2)(1 - \cos\theta)} \right] \tag{1}$$

The electron acquires the lost photon energy as additional kinetic energy:

$$\Delta E = h\nu - h\nu' \tag{2}$$

To observe the effect, photons with energies comparable to the electron rest energy $mc^2$ are required. The needed high energy photons are found in the gamma-ray portion of the electromagnetic spectrum. A variety of radioactive isotopes spontaneously emit the appropriate gamma-rays and are used in this experiment.

Because their energy is so high, it is difficult to detect gamma-rays directly. Indirect detection is used here through a process called *scintillation*. A scintillator is a special material – in this case a sodium iodide (NaI) crystal – that converts high-energy photons such as gamma-rays into visible photons that can be detected. The NaI scintillation crystal is directly attached to a photo-multiplier tube (PMT) that is sensitive enough to resolve very few visible photons. Detected photons appear as voltage pulses at the output of the PMT. The height of the voltage pulse is directly proportional to the energy of the gamma-ray that created it. A multi-channel analyzer (MCA) measures the distribution of the PMT voltage pulses. By mapping the height of each pulse into a corresponding bin (x-axis on its display), the MCA produces a spectrum of the gamma-ray photons that strike the scintillator. The combination of scintillation, PMT, and MCA forms a gamma-ray spectrometer.

There are many possible interactions that occur when gamma-rays collide with a scintillator, but the two most relevant for this experiment are photo-electric absorption and Compton scattering. In photo-electric absorption, a gamma-ray liberates a bound electron from the scintillator crystal. This highly energetic electron travels through the NaI giving up its kinetic energy in collisions with other atoms along the path. These excitations relax back to the ground state by emitting visible photons. The more kinetic energy the electron possesses, the further it travels, the more photons are emitted, and the larger the voltage pulse at the output of the PMT. Although many visible photons are emitted, each voltage pulse corresponds to a single gamma-ray event. The gamma-rays irradiate the scintillator at a low enough rate that they can be individually distinguished. It is important to understand that the PMT cannot detect gamma-ray photons. It only detects *visible* photons that result from the dissipation of kinetic energy of fast moving electrons in the scintillator.

Although multiple visible photons are produced by a single-gamma ray, the detected photon count can vary even though the gamma-ray photon energy does not change. This results in a statistical (Gaussian) distribution in the spectrometer bins. The spectrometer does not display a $\delta$-function, but a broad peak having a width that reflects this distribution.

The primary difference between Compton scattering and photo-electric absorption is in the amount of energy transferred. In the photo-electric interaction, an electron is ionized with kinetic energy almost identical to the gamma-ray. In Compton scattering, there is a continuum of energies that can be exchanged, ranging from 0 to 100% of the incident gamma-ray energy. This arises from the angle-dependence in Equation (1). Energy is partitioned between the electron that is struck and the scattered photon. The maximum energy an electron can acquire in Compton scattering occurs at $\theta = 180°$, in which it directly recoils from a head-on collision. This produces the *minimum* possible scattered photon energy:

$$h\nu' = h\nu \left[\frac{1}{1 + 2h\nu/mc^2}\right] \tag{3}$$

and the the *maximum* possible electron energy:

$$\Delta E_{max} = h\nu \left[1 - \frac{1}{1 + 2h\nu/mc^2}\right] = h\nu \left[\frac{1}{1 + mc^2/2h\nu}\right] \tag{4}$$

known as the Compton edge.

In photo-electric absorption, the MCA gives a direct measure of the gamma-ray photon energy. In Compton scattering, the MCA measures the energy of the recoiling electron, not the incident or scattered photon.

**Experiment.** The MCA x-axis is calibrated with a known radioactive source such as Cs-137. Characteristic features can be identified in the spectrum. A prominent peak at 662 keV appears due to direct electron ionization by a Cs-137 gamma-ray. This interaction is entirely due to photo-electric absorption and produces the photo-peak.

Compton scattering results in a smooth continuum of energy counts ranging from 0 eV to $\Delta E_{max}$. The maximum energy from Compton scattering (the Compton edge) is due to the recoil of electrons involved in head-on collisions. The photons emitted by these recoiling electrons must have lower energy than the photo-peak according to Equation (4). The Compton edge can be difficult to distinguish in the spectrum. It is taken as the halfway point between the rolloff shoulder and noise floor. It can be used to find the electron rest mass energy with Equation (4).

The Compton edge is associated with a minimum scattered photon energy as given by Equation (3). This backscattered photon cannot be directly detected by the PMT because its energy is too high, but it can interact with the scintillator by photo-electric absorption. The scattered photon generates a trail of electron ionization in the scintillator, the emission of many visible photons, and a prominent low energy peak in the MCA spectrum called the backscatter peak. Because this peak is produced by photo-electric absorption, the scattered gamma-ray photon energy is measured. The backscatter peak is superimposed on the Compton scattering continuum. Unlike the high-energy photo-peak which involves no Compton scattering, the backscatter peak is from a photon produced in a head-on Compton scattering event. The energy of the backscatter peak can be used to solve for the electron rest energy through Equation (3).

The Compton edge and backscatter peak provide two independent determinations of the electron rest energy through Equations (3) and (4). Different gamma-ray sources have different energies $h\nu$ resulting in different spectra and additional data.

**Equipment and Setup.** To get clean data, the PMT/scintillator and radioactive source must be shielded inside a lead brick enclosure. Use caution when moving the bricks as they are very heavy. Radioactive sources are stored in a locked box. Ask the instructor for access.

The MCA is a model UCS30 with accompanying GUI software and user manual. Referring to the user manual will make setup and data taking easier. The most critical aspect of setup is the PMT high-voltage setting. The polarity and maximum voltage will be marked on the PMT (typically +1200V). Please have your setup confirmed by an instructor before enabling high-voltage.

The MCA communicates with a host PC via USB. It biases the PMT using a special BNC cable with high voltage connectors. Never force a BNC cable onto a non-mating connector. A second BNC cable feeds the output of the PMT to the MCA, where pulses are appropriately amplified, conditioned, and counted.

Place a 1 $\mu$Ci Cs-137 source next to the scintillator. You may have to experiment with its height and orientation to get the best data.

Quick-start for the UCS-30 is as follows. From the menu bar, select Spectrum: Connect to Device and Mode: Pulse Height Analysis (Preamp-in). In the main menu, set the High Voltage to 600V and click the OFF button to turn the HV ON. Under Settings select Amp/HV/ADC. Set Conversion Gain at 1024; Coarse Gain: 8; Fine Gain: 1. Press the run button. You should start getting counts; adjust the HV to put the photo-peak in the approximate middle of the display. You will have to clear the display each time you make changes to the settings. When setup is adjusted to your satisfaction, record the bin corresponding to the Cs-137 photo-peak. Keyboard arrows can help in fine positioning of the cursor.

Replace the Cs-137 with the other available sources and record the bin numbers associated with their photo-peaks. Calibration data for several radioactive sources can be found in this table:

| | | |
|---|---|---|
| Cs-137 | 662 keV | 30.2 yr half-life |
| Co-60 | 1.173 MeV; 1.33 MeV | 5.3 yr half-life |
| Na-22 | 511 keV; 1.275 MeV | 2.6 yr half-life |
| Ba-133 | 356 keV | 10.5 yr half-life |
| Mn-54 | 835 keV | 303 day half-life |
| Cd-109 | 88 keV | 453 day half-life |
| Co-57 | 122 keV | 270 day half-life |

You may also get sum peaks at higher energies. Plot the photo-peak energy vs the bin number and attempt to make a linear, least-squares fit. This line will be your calibration curve; do not use the auto-calibrate function of the spectrometer.

Replace the Cs-137 source and measure the full-width, half-maximum of the photo-peak. Report this value in energy using the calibration curve.

Measure the Compton edge and backscatter peak for as many sources as possible. Use these to calculate the electron rest energy and rest mass. Be sure to include the uncertainties in your reported values.

Is the half-height energy the best estimate for the Compton edge? Which of the two peaks produce better results and why?

Why do backscatter photons produce a peak instead of a much broader continuum?