Physics PHYS 275
Experimental Physics Lab

Compton Scattering

I. Introduction

According to the classical wave theory for electromagnetic radiation, which is based on Maxwell's equations of electromagnetism, light waves, when they scatter from a charged particle such as an electron, should have the same wavelength after they scatter as before. In the early 1900's, however, several experiments were performed which began to cast doubt on the classical wave model. Observations of such phenomena as the photoelectric effect and the spectrum of electromagnetic radiation from blackbodies seemed to indicate that, at least sometimes, light behaves as a particle with energy $E = hf$, where $h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}$. The experiments that were performed beginning in 1920 by Arthur Compton further supported this conclusion by demonstrating the wavelength shift of light as it scatters from an electron.

II. Theory

A detailed derivation of the theoretical prediction for the Compton scattering experiment was presented in class. Only a brief outline will be given here.

Consider the classical explanation of the scattering of light (or electromagnetic radiation in general) from an electron, illustrated in Figure 1. When the incident electromagnetic wave strikes the electron, the oscillating electric field causes the electron to oscillate. In these oscillations the electron accelerates, and thereby produces "secondary" waves which are emitted in all directions. Of course, the frequency of these waves is identical to the original wave, or $f = f_0$, and $\lambda = \lambda_0$.

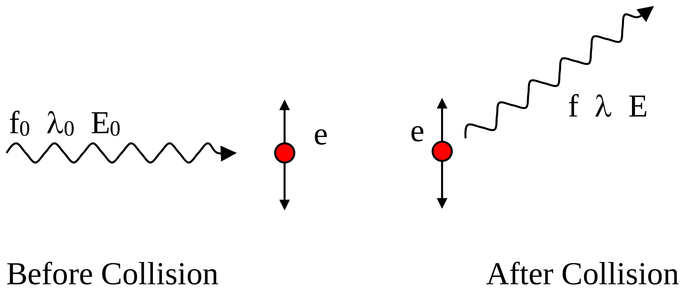

Figure 1 –A schematic diagram of an electromagnetic wave interacting with an electron in the classical model.

In the quantum model, light can behave like a particle, which is called a photon. These "packets" of electromagnetic radiation have energy $E = hf$, and scatter from an electron as illustrated schematically in Figure 2. Initially the photon has the energy $E = hf$. After the collision, some of the energy has been transferred to the electron, so that the final energy of the photon is reduced. Therefore $E < E_0$ so $f < f_0$ and $\lambda > \lambda_0$.

In this model, we showed that the wavelength difference is given by

$$\Delta\lambda = \lambda - \lambda_0 = \frac{h}{m_e c}\left(1 - \cos\theta\right)$$

and therefore the final photon energy is

$$E = \frac{E_0}{1 + \frac{E_0}{m_e c^2}\left(1 - \cos\theta\right)}. \quad \textbf{(1)}$$

In this experiment we will be comparing these two predictions, from the classical and quantum models, to measurements of the final photon energy.

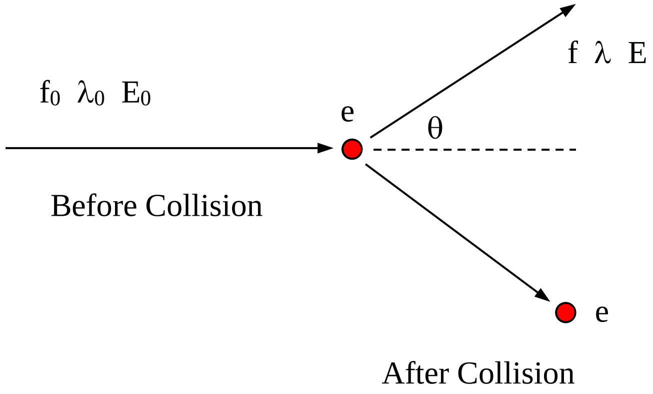

Figure 2 – A schematic diagram showing scattering of a photon by an electron in the quantum model.

III. Experimental Apparatus

The apparatus consists of a source of high energy gamma rays, ^{137}Cs, an active scattering target, and a detector for the scattered gamma rays. Figure 3 shows the overall design of the experiment while Figure 4 is a photograph of the apparatus.

The ^{137}Cs produces monoenergetic gamma rays of 662 keV energy (well, there are also some 32 keV x-rays, too, but let's ignore that for now). It is attached to a movable arm which allows the angle of the source relative to the two detectors to be adjusted. The scattering angle may be read from the angle markings on the table. The distance between the source and the active target may also be adjusted.

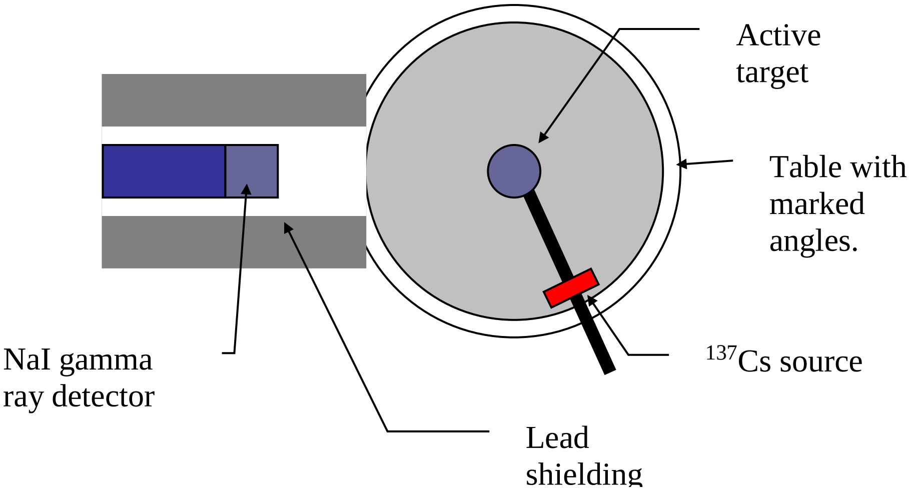

Figure 3—A top-view schematic diagram of the layout for the experiment. The scattering angle may be adjusted by moving the arm to which the ^{137}Cs source is attached.

Figure 4 Photographs of the experimental apparatus showing (left) the gamma source attached to the movable arm, the NaI crystal active target, and the lead shielding which is surrounding the NaI detector for the scattered gamma rays, and (right) the NIM electronics and multichannel analyzer.

Both active target and the scattered-gamma detector are cylindrical sodium iodide (NaI) crystals. The scattered gamma detector crystal is 1.5 inches in diameter and 1.5 inch thick, while the target detector is 2 inches in diameter and 1 inch thick. This type of crystal emits light when a gamma ray enters the material and interacts with the atomic electrons. The amount of light emitted is proportional to the energy of the gamma ray, assuming that none of the energy escapes. This light is collected in a photomultiplier tube (PMT), which converts the signal to a small current pulse which can be electronically monitored. Therefore, the gamma energy may be determined from the size of the pulse coming from the photomultiplier tube.

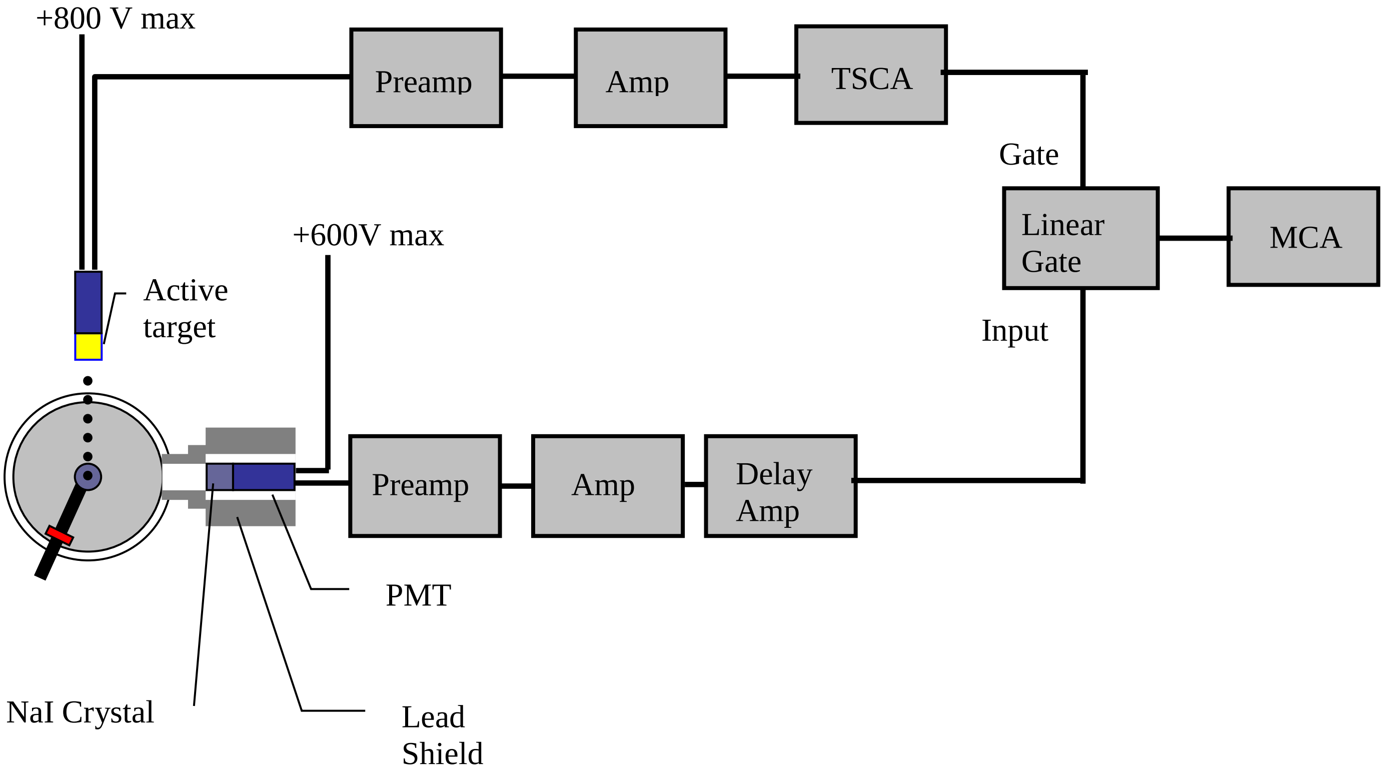

Figure 5 – Schematic diagram of the electronics for the Compton Scattering experiment.

The electronics setup for the experiment is shown in Figure 5. Pulses from the NaI "active target" scintillator are shaped and amplified by the preamp, then shaped into gaussian pulses and amplified further by the spectroscopy amplifier. The timing single channel analyzer (TSCA) is used to produce a logic pulse (fast negative NIM) whenever the input pulse height is above the threshold voltage. These pulses are then delayed and made the appropriate width by the gate generator. Slow positive NIM (0 V, +5 V) are output from the gate generator into the linear gate in order to "open" the linear gate for the correct amount of time to allow the pulses from the other detector to be digitized whenever there is a simultaneous pulse from the active target.

The signals from the scattered gamma NaI detector is also processed by a preamplifier and a spectroscopy amplifier. The pulses from the amplifier are delayed by a delay amplifier which is used to adjust the relative timing between the analog pulses and the logic gate pulses from the gate generator. The linear gate allows the analog pulses to be input the multichannel analyzer only when a logic pulse is present at the gate.

The SPECTECH UCS30 multichannel analyzer produces a histogram of pulse height versus number of events with that pulse height. This histogram may be read out into a computer using the USB port.

The high voltage required by the active target is produced by a HV NIM power supply; the HV for the scattered gamma detector comes from the UCS30.

IV. Experimental Procedure

A rough outline of the procedure is as follows.

1. Put the ^{22}Na source next to the active target scintillator. Turn on the high voltage – do not go over about +800 V. Make sure the pulses from the phototube and preamplifier are present and look appropriate. Look at the pulses from each amplifier. See if you can see the 511 keV "band" from positron annihilation. Adjust the amplifier gains and phototube voltage to put the peak of this band at about 7 volts.
2. Put the ^{22}Na source next to the scattered gamma ray detector. Turn on the high voltage – do not go over about +600 V. Make sure the pulses from the phototube and preamplifier are present and look appropriate. Look at the pulses from each amplifier. See if you can see the 511 keV "band" from positron annihilation. Adjust the amplifier gains and phototube voltage to put the peak of this band at about 7 volts.
3. Switch the linear gate to "pulse inhibit" or "off". This will allow basically all of the input pulses to "pass". Using the ^{22}Na, ^{137}Cs and ^{133}Ba sources calibrate the energy scale on the MCA. Use the table below.

Isotope	Gamma Ray Energy (keV)
^{22}Na	511 (back-to-back)
	1027
^{137}Cs	32
	662
^{133}Ba	30.6, 31.0
	34.9, 35.8
	53.2
	79.6, 81.0
	276.4
	302.9
	356.0,
	383.8

4. Adjust the TSCA so that pulses with pulse heights above about 0.2 V but less than the 511 keV band triggers a logic pulse.
5. Put the ^{22}Na source directly between the two detectors. This source emits back-to-back 511 keV gamma rays. Set up an oscilloscope with the gamma detector analog pulses in channel one and the active target TSCA logic pulses in channel two. Set the scope to trigger on the logic pulses, and adjust the delay amplifier and gate generator so that the peak of the analog pulse falls after the gate "opens", but at least 1 μs before it closes.
6. Now remove the ^{22}Na source,. Return the detectors, and place the ^{137}Cs back on the moveable arm. Adjust the lead shielding. Set the scattering angle, and collect the energy spectrum from the gated NaI detector. Save the spectrum to disk.
7. Repeat step 6 for at least five different angle settings°.

V. Data Analysis

1. For each energy spectrum (taken at each angle) determine the energy of the center of the Compton peak, and determine the uncertainty in this energy.
2. Make a plot of the energy versus scattering angle θ. Be sure to include error bars on your plot. Compare the predictions of Eq. (2) to your measurement.

VI. Laboratory Report

1. In your laboratory report be sure to include a detailed description of how you made your measurement -- describe the apparatus and the procedure you used to make the measurement.
2. You definitely should include a schematic diagram of the experiment as it actually was (i.e. don't count on it being exactly what is in this lab handout.)
3. You should have plots of each energy spectrum at each angle, as well as a plot of the scattered gamma energy as a function of θ. Be sure to include the theory prediction on your plot.
4. You should you should discuss the uncertainties present in your measurement.

VII. Questions to ponder

1. Do any gamma rays make it directly from the ^{137}Cs source into the NaI detector? Does this affect the result?
2. What is the best distance for the detector? For the source? Why?
3. Why is the "active" target used? Why not just scatter from a piece of aluminum? (I tried this and it doesn't work – why?)
4. What is the best placement for the lead shielding?
5. Does it matter what the target material is?
6. How well do you know the energy? How do you know this?
7. How is the uncertainty in the peak energy to be determined?