EXPERIMENT 32
COMPTON SCATTERING

Table of Contents

A- INTRODUCTION ..................................................2

B- THE EXPERIMENT ..............................................3
   1- Experimental setup ........................................3
   2- Electronics ...............................................4
   3- Software ..................................................6

C- PRELAB PROBLEMS ...........................................7

D- EXPERIMENTAL PROCEDURE .................................10
A- INTRODUCTION.

In Exp. 30 you were introduced to Compton scattering. What you learned is summarized below. Please read and understand General Appendix A sec. 2.

The energy of the scattered photon $k$ is given by

$$ k = \frac{k_0}{1 + \frac{k_0}{m} (1 - \cos \theta)} $$

(1)

and, by using conservation of energy, the kinetic energy of the recoil electron is given by

$$ T_e = k_0 - k $$

(2)

The differential cross section (see General Appendix B for the definition of differential cross section) is given by

$$ \frac{d \sigma}{d \Omega} = \frac{r_e^2}{2} \left( \frac{k}{k_0} \right)^2 \left[ \frac{k}{k_0} + \frac{k_0}{k} - \sin^2 \theta \right] $$

(3)

Where $k_0$ and $k$ are the energies of the incident and scattered photons respectively, $\theta$ is the scattering angle, $m$ is the electron's mass in energy units, and $r_e$ the "classical electron radius"

$$ r_e = \frac{e^2}{m} \text{ (cgs)} = 2.82 \times 10^{-13} \text{ cm} $$

The cross section given by Eq. 3 is known as the Klein-Nishina cross section.
The purposes of this experiment are:

a- To verify that the scattered photon energy is given by Eq. 1, and the recoil electron energy is given by Eq. 2.

b- To verify the angular dependence of the differential cross section given by Eq. 3.

This experiment was set up by a Caltech undergraduate, Kevin Ruddell, for his senior thesis. The instrumentation you will use is a small scale version of what is now common-place in nuclear and elementary particle physics.

B- THE EXPERIMENT.

1. Experimental setup. The plan view of the experimental set-up is shown in Fig. 2. A collimated beam of 0.662 MeV γ-rays from the decay of $^{137}$Cs is incident on a plastic scintillator detector. This scintillator is used both as the target to scatter the incident beam, and also to measure the energy of the recoil electrons. The scattered photons are detected and their energies measured by the NaI detector. (For details about scintillator detectors, again, see Exp. 30.) A plastic scintillator was chosen for the target for the following reason. Plastic is composed of low Z elements, mainly Hydrogen and Carbon, thus the absorption photon cross section at 0.662 MeV is entirely due to Compton scattering (See Figure 8B Exp. 30). As you learned in Exp. 30, NaI scintillator counters are more efficient at detecting photons in the energy range of this...
experiment and much better to determine their energies than are plastic scintillators, for this reason a NaI scintillator was chosen as the scattered photon detector.

2- **Electronics.** Fig. 3 shows the block diagram of the electronics used in this experiment. A summary of its operation follows. There are two distinct paths:

**Analog.** The scintillator signals are fed directly to the MCA's to have their output integrated and digitized. This works in the same manner as explained under Exp. 30. The triggers are generated by the **logic** section.

**Logic.** The logic section is necessary in this experiment for the following reason. If we were to analyze every event that produces a signal in either the plastic counter or the NaI counter, only an extremely small fraction of these events would correspond to Compton scattering events, let's see why. If all the events in the plastic counter were Compton scatters, only a very small number of the scattered photons would go into the NaI counter, why? For this reason we can not analyze **all** the plastic scintillator events. How about if we analyze **all** the NaI events? Most of these events are background events due to room background and photons from the beam scattered at the collimator and other places. You can convince yourself that this is the case by observing the NaI events with and without the plastic scintillator in the beam. For these reasons, to collect a rich sample of Compton scattered events, we must require that both the plastic and NaI counters produce "simultaneously" outputs above some preselected thresholds. This is accomplish in the following manner. The suitably amplified outputs of both counters are applied to two discriminators, these discriminators produce standard outputs (both in amplitude and time duration) if their inputs exceed some manually set threshold. The output of these discriminators are subsequently applied to the coincidence module. This module is the one that decides if the two scintillator outputs occurred "simultaneously": if there is any time overlap between its two inputs this module produces an output which is used to trigger the two qVT's. The signals from two simultaneous events in the two counters must arrive at the same time at the coincidence module, this has been arranged for you by adjusting the lengths of the coaxial signal cables between the photomultipliers and the amplifiers.
Figure 3
Electronics block diagram.

- Computer
- MCA's
- Gate in
- q
- qV's
- Pedestal
- Delay
- LOGIC UNIT
- Threshold
- 100 ns
- 100 ns
- Coincidence
- Discriminators
- Amplifier
- ×10
- NaI
- PI
- 200-400 mV
- 10-20 mV
- ×100
- 10-20 mV
Some additional remarks.

The \( qV \)'s. The analog input is plugged into the \( q \) input and the mode switch is set to the \( q \) mode. The output of the Coincidence module is plugged into the Gate inputs and the trigger switch is set to Ext. Trig. The appropriate thresholds are set in the discriminator module \( \text{(not, in the } qV \text{ thresholds).} \) The Pedestal will shift the entire spectrum \( \text{(Do Not Assume it is set the same as last time).} \) The 10-20 mV analog signals (\( q \) inputs) must arrive at the \( qV \) at's at least \( 30 \) ns after the Gate signal arrives from the Coincidence module. This is due to a 20 ns delay between the arrival of the Gate signal and the start of the \( qV \)'s internal integration time. Since it takes time (around 50 ns) for the signals to propagate through the logic units (amplifier, discriminator and the coincidence module) the analog signals must be delayed, this is the reason for the two delay modules between the amplifiers and the pedestal unit.

The coincidence module. Let's assume that the NaI scintillator signal is connected to the \( A \) input and the plastic scintillator to the \( B \) input. By using the push buttons in this module you can set the trigger so it is produced by the \( A \) or the \( B \) inputs only, or by the coincidence of the two inputs. This is very useful, for example, if you wish to setup the NaI counter (pedestal, threshold, gain and calibration) you want to look at the NaI counter without requiring a count in the plastic scintillator. In this case you set the module to trigger with the \( A \) input only and the program to look at the \( y \) histogram. The MCA threshold adjustment is the one at the NaI discriminator and not at the External. Discriminator unit.

3. Software. The program that controls this experiment, named COMPTON, is capable of making histograms of the number of counts in each of 1024 energy bins (viewed 1/2 at a time 0-511 or 512-1023) from either the plastic scintillator (called the \( x \) counter by the program) or the NaI scintillator (called the \( y \) counter). In addition you can make scatter plots of the counts in the NaI scintillator (\( y \) axis) versus those in the plastic scintillator (\( x \) axis).
C. PRELAB PROBLEMS.

1. The non-relativistic photon scattering cross section from free electrons, Thompson’s cross section, is given by

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} (1 + \cos^2 \theta)$$

Show that this cross section is the limit for the Klein-Nishina cross section as \(k_0/m \to 0\). Try to understand the origin of the terms 1 and \(\cos^2 \theta\).

2. Plot the scattered \(\gamma\)-ray energy and recoil electron energy as a function of angle, for an incident \(\gamma\)-ray beam of 0.662 MeV.

3. Assuming the minimum detectable recoil electron energy is 50 keV and the minimum \(\gamma\)-ray energy is 60 keV, what range of Compton scattering angles is accessible in this experiment?

4. Assume that the plastic scintillator is 2" long in the beam direction, and the NaI scintillator is a 2" diameter cylinder with its round end facing the plastic scintillator. The finite counter sizes result in counting the scattered \(\gamma\)-rays over a range of angles. Estimate approximately how far away from the plastic scintillator to locate the NaI scintillator in order that the angular resolution is \(\pm 5^\circ\). Use this result to help guide you in selecting the location of the NaI counter.

Do the following problem after the first week lab work.

5. The raw data to confirm the angular dependence of the Klein-Nishina cross section must be corrected for several effects.
   
   (a) The major correction is due to the strong energy dependence of the mass attenuation coefficient, that is, you must correct for the fraction of the scattered \(\gamma\)-rays that do not interact in the NaI counter using Fig. 5 in Exp. 30. What is this fraction at \(\theta = 30^\circ\)? Remember that the fraction that does interact is given by

$$\frac{N_I}{N_0} = 1 - e^{-\mu L}$$

where \(L\) is the thickness of the NaI counter. \(L = 2\) in.
(b) The second correction is due to the absorption of the scattered \( \gamma \)-rays in the plastic (target) counter which depends on the scattering angle, as shown in Fig. 4. A pretty good approximation to do the following calculations is the one shown in the figure, that is, that all the scattering takes place along the center line of the plastic (target) scintillator. Why is this a good approximation? The mass interaction coefficient for plastic scintillator over the range 0.1 to 0.6 MeV is \( \approx 0.1 \text{ cm}^2/\text{gm} \). What fraction escapes at angles \( \theta = 30^\circ, 90^\circ, 120^\circ \)? The density of plastic scintillator is around 1 gm/cm\(^3\).

![Figure 4](image)

The geometry to calculate the absorption of the scattered photons in the target.

6. Figs. 5a and 5b shows two different events that produce coincidences between the NaI counter and the plastic scintillator counter. State the area of the scatter plot shown in Fig. 6 which corresponds to the events shown in Fig. 5a and in Fig. 5b.

![Figure 5a](image)

![Figure 5b](image)
Figure 6
A typical scatter plot.
D- EXPERIMENTAL PROCEDURE

1. Familiarize yourself with the equipment. Compare all the electrical connections with those in Fig. 3.

2. Turn on the high voltage to the scintillators. Following the procedure explained under "the coincidence module" set up the electronics and the software to observe the NaI scintillator spectrum independently from the plastic scintillator. Check the gate lengths, the thresholds, and/or the pedestals and call the TA if adjustment is necessary. Adjust the NaI photomultiplier high voltage until the $^{137}\text{Cs}$ 0.662 MeV $\gamma$-ray's full energy peak is centered at around bin 440 (why?). Do the same with the plastic scintillator but adjust the plastic scintillator photomultiplier high voltage until the Compton edge from the $^{137}\text{Cs}$ 0.662 MeV $\gamma$-rays is at approximately bin 440 (why?). Set the threshold in the NaI counter as low as possible but excluding all the noise. Do a calibration check on each detector using the full energy peaks for the NaI detector and the Compton edges for the plastic scintillator produced by the various principal $\gamma$-rays from the sources in the calibration $\gamma$-ray set. Estimate the bin corresponding to zero energy using the technique suggested under "Some additional remarks" (p 32-6). Use the channels above 512 for $\gamma$-rays greater than 0.662 MeV.

3. Verify Eqs. 1 and 2. Start at a reasonable angle (e.g., 30°) and find the Compton group on the scatter plot. Estimate the electron and photon energies from the $x$ and $y$ histograms.

4. Verify the angular dependence of Eq. 3. Obtain counting rates at various angles. You may wish to follow this procedure: take a short run to decide the electron energy limits. Set these limits generously, but do not set limits to the $\gamma$-ray energy in the NaI (why?). Take a fairly long run observing the $\gamma$-ray energy histogram and the electron energy histogram ($x$ histogram). At the end of the run obtain the total number of counts by using the integrate command on the appropriate histogram. Remember to record the time duration of each run. Estimate the uncertainty in your counting rate.

** Corrections to your data: ** Factors that contribute to the efficiency of detecting $\gamma$-rays which depend on the $\gamma$-ray energy or the scattering angle must be considered. There are two important corrections.
a) Detection efficiency. First you must calculate the absorption probability using the data in Exp. 30 Fig. 5 (the NaI scintillator used in this experiment is a cylinder 2" in diameter and 1-3/4" thick).

b) Absorption of the scattered photons in the target. The average path length in the target is a function of the scattering angle, and, therefore, the absorption in the target of the scattered photons depends on the scattering angle (see pre-lab problem 5(b)).

5. (Optional) The following experiment is a lot of fun. The study of the $^{207}\text{Bi}$ decay scheme. To do this turn off the $^{137}\text{Cs}$ beam with a lead brick and using the cables connected to the target scintillator connect the plastic scintillator with the $^{207}\text{Bi}$ embedded inside it (DO NOT REMOVE THE TARGET SCINTILLATOR). Place this scintillator next to the NaI scintillator as shown in Fig. 8.

![Figure 8](image)

Set up to study the decay scheme of $^{207}\text{Bi}$.

Observe the energy spectra in each counter as well as the coincidence scatter plot which are very rich in structure. Relate your observations to the decay diagrams for $^{207}\text{Bi}$ shown in Figs. 9 and 10.
Figure 9
Decay scheme of $^{207}\text{Bi}$.

If we ignore the 7% decay into the 2.341 MeV excited state and the 10% into the 0.57 MeV we get the simplified diagram shown in Fig 10.

Figure 10
Simplified decay scheme of $^{207}\text{Bi}$. 