Compton Scattering

In this experiment we will scatter a gamma ray in a plastic scintillator detector (target) and detect the outgoing scattered gamma ray in a sodium iodide (NaI) detector. The apparatus allows you to rotate the NaI detector around the target position and measure energy of the scattered gamma ray $E_{\gamma'}$ as a function of the scattering angle θ. You will compare your measured $E_{\gamma'}(\theta)$ with the distribution expected form Compton scattering theory. This is a double scattering arrangement similar to what shown in Leo, Fig. 2-22, and Fig. 1 below.

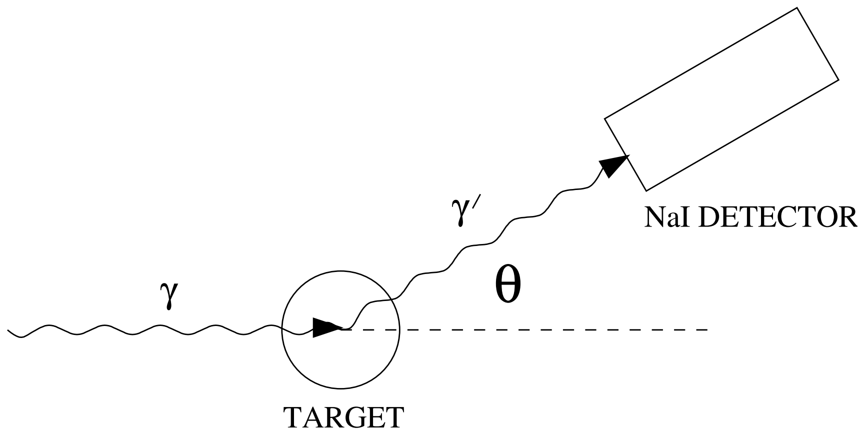

Figure 1: Schematic of Compton scattering experiment.

Compton scattering occurs when the photon interacts with a (free) electron and scatters through an angle θ defined by the position of the NaI detector. The recoil electron will deposit its energy in the target (here a plastic scintillator) and the recoil photon will be absorbed by the NaI detector.

The pulse heights from the NaI detector are recorded in the Multichannel Analyzer (MCA) for each detected scatter. In order to reduce background counts, we use coincident signals from the plastic and NaI detectors.

Apparatus

In this experiment a plastic scintillating counter is used as a target and an NaI scintillation counter as a detector of the scattered gamma ray. The source is placed in a lead tube that collimates the gamma rays that strike the target. The apparatus is mounted on a table that allows one to set different scattering angles between the incident and scattered gamma ray. A photograph of one of the two set-ups is shown in Fig. 2. The NaI detector is mounted on the arm which rotates while the plastic target is mounted at the pivot point of the NaI detector that is near the exit of the collimator and is stationary.

A discriminator and a dual gate generator are used to generate a delay between the pulse that signals a scattering event in the plastic scintillator and the pulse from the NaI detector. The delay is necessary because of the much slower rise and decay time of NaI signal following the scattering event. The procedure for setting up the delay is described below and shown schematically in Fig. 3. The output of the NaI is sent to an amplifier that provides the shaped positive pulse required by

Figure 2: Scattering table used for Compton scattering. NaI detector is mounted on a movable arm. The target is a plastic scintillator detector suspended vertically over the table's center. The source is behind the lead bricks inside a lead-wrapped tube.

the multichannel analyzer. For this experiment we use the Norland MCA for which instructions available on the physics 433 web page. The Norland MCA allows one to "gate" whether pulses are measured or not via a TTL-level input on the back of the unit.

Setup procedure and calibration

It is very important to set up the gating electronics and begin taking data as quickly as possible. Typically a counting of 10 minutes or longer is needed for each scattering angle; data taking needs to begin early in order to measure angles as possible during the lab period.

In the instructions that follow, a coincidence gate for the MCA is established by placing the ^{22}Na source between the plastic and NaI detectors. The logic units that are needed to set up the delay are a discriminator and a dual gate generator (one unit with 2 gate generators). The pulse from the plastic scintillator is first sent to a discriminator; the output of the discriminator becomes the input to the first gate generator. The pulse width of the NIM output of the gate generator should be adjusted to the expected delay between the scintillator and NaI pulse, which is typically 700–800 ns. The output of this first gate generator is sent to the input of the second gate generator. The pulse of the second generator is set so that it is long enough to encompass the duration of the positive part of the NaI pulse from the pulse-shaping amplifier. We then send the TTL-level signal from the second gate generator to the "COINC" input on the back of the Norland MCA.(See Fig. 3 for a timing diagram.)

Following the procedure described below, the data taking time can be optimized. Three important items need to be accomplished before data taking begins.

Part 1: Check out detector operation

1. Obtain a ^{22}Na source, mount it in the finger clamp, and position it so that it is directly between the NaI detector and the plastic scintillator. It should be at least 10 cm from the front of either detector.

2. While looking at the 50Ω terminated signals from each detector on the scope, bring up the high voltage on each detector. Use +1000V for the NaI detector and whatever is specified on

the plastic detector (typically +750 to +850V).

3. Once signals have been confirmed, route the signal from the NaI detector to the Ortec 113 preamp and then to the Ortec 575A pulse-shaping amplifier. Confirm that you see well-shaped pulses coming out of the 575A, and set the gain of that amplifier to give positive going pulses, with the .511 MeV annihilation line at about 7 volts peak height. (Do not use a 50Ω terminator when looking at the output of the 575A amplifier.)

4. Increase the vertical sensitivity on the scope, and adjust the "Pole-zero" screw on the 575A to minimize the over/undershoot as seen on the scope. ***Important: Placing the source too close to the NaI detector can result in baseline shifts from "pile-up" events.***

5. After setting up the NaI detector, route the signal from the 575A to the front input on the Norland MCA. Use a TEE to also continue looking at this signal on the scope.

6. Run the signal from the plastic detector into the discriminator. Connect the output from the discriminator to an oscilloscope channel, and terminate it with 50Ω.

7. Use the DMM to set the discriminator level to 30 mV. Confirm that you can see the signal from the discriminator.

8. Set the discriminator's pulse width to about 50 ns.

Part 2: Set up MCA triggering pulse

Establishing coincidence between plastic scintillators and NaI scintillators requires care because the time response of the two types of detectors is very different. Do you remember which gives the fastest response? Yes, it is the plastic scintillator.

The compliment NIM, $\overline{\text{NIM}}$, from the first gate generator is the input to the second gate generator. The second gate generator will be triggered by the falling edge of the $\overline{\text{NIM}}$ pulse and the TTL (+5 V) output is adjusted to encompass the NaI amplified pulse. The timing diagram is shown in Fig. 3. Proceed as follows:

1. Disconnect the output of the discriminator from the scope and connect it to the START input of the top gate generator channel. (You will want to use a short LEMO cable.)

2. Connect the $\overline{\text{NIM}}$ output from this first channel into the START input of the second channel with another short LEMO cable.

3. Connect the NIM output from the second channel into a different channel on the scope, and set the scope to trigger on the leading (i.e., falling) edge of this signal. Your scope should now have two inputs: one from the output of the 575A amplifier (with NO 50Ω terminator) and another from the NIM output of the second gate generator (WITH a 50Ω terminator).

4. If everything is correctly set, you should see the output of the 575A on one channel, and a NIM pulse on the second channel, similar to the top line and the second from the bottom line in Fig. 3.

5. Now comes the fun part: Use a screwdriver to adjust the *second* gate-generator channel so that its pulse is just long enough to "cover" the main part of the 575A pulse, and adjust the *first* gate generator to scoot the pulse back and forth so that it is centered within the (now long) NIM pulse. (Why does this operation seem to cause the 575A pulse to move?)

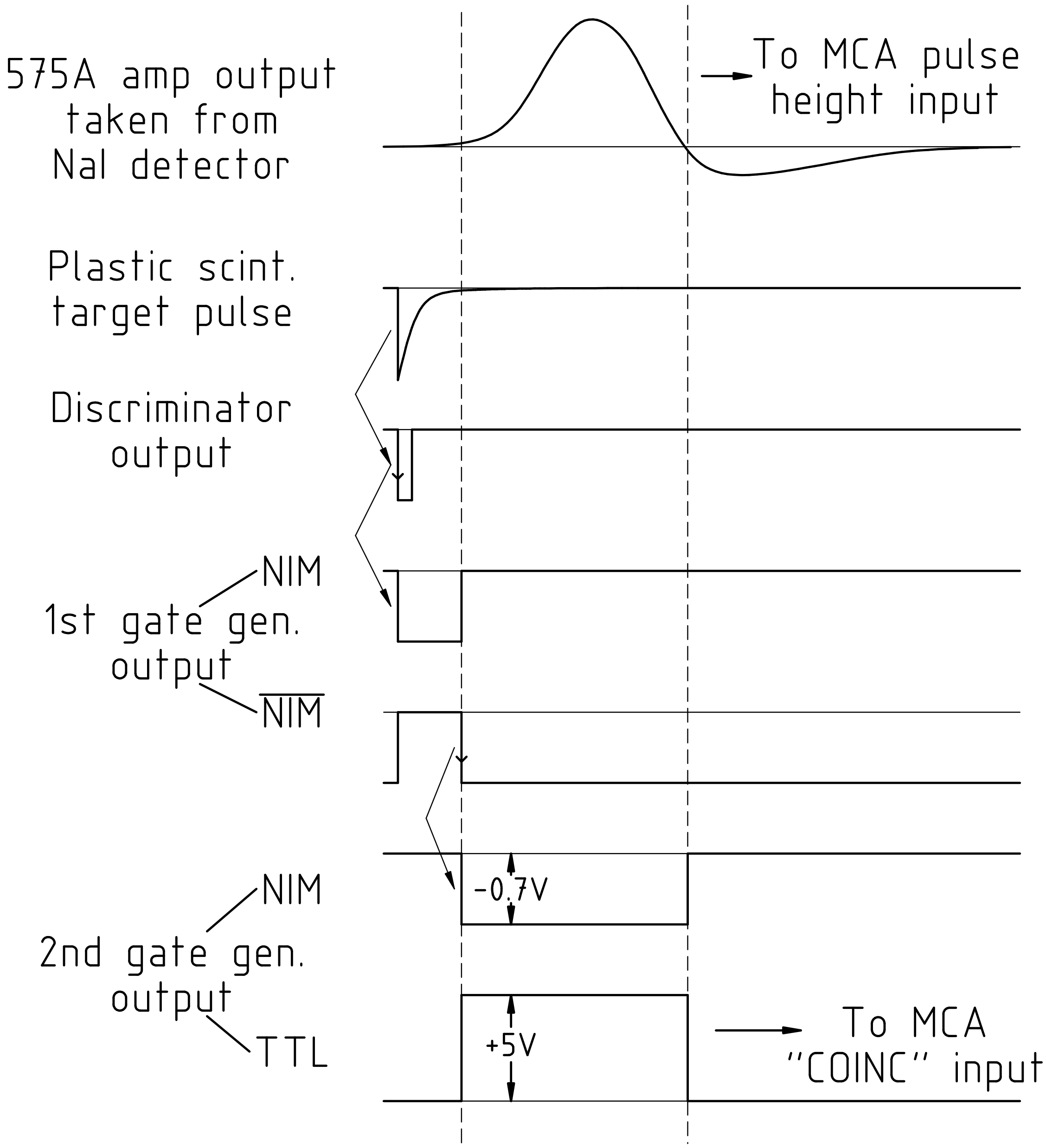

Figure 3: Pulse timing diagram for setting up coincident gating for the Norland MCA.

6. Connect a cable from the TTL output of the second gate generator to the MCA's "COINC" input on the back of the unit. Leave the other lines connected to the scope.

Part 3: Calibrate the MCA

A good gamma ray source to use for this experiment is ^{137}Cs, since it has one dominant gamma ray emission.

Exercise 1 *(For your report.) What would be the advantages and disadvantages of using a ^{60}Co source in this experiment?*

Calibrating the MCA so that you can measure the energy of the scattered γ ray is critical in this experiment. Photo-peaks from ^{22}Na, ^{137}Cs and ^{133}Ba sources give well defined energies for your calibration curve.

1. The coincidence logic must not be active during the calibration. (Discuss with your lab partners why this is true.) Remove the connection between the TTL output (on the gate generator) and the COINC input on the MCA. When this is disconnected, the MCA is always active: TTL inputs "float high".

2. Obtain the ^{137}Cs source, and place it in front of the NaI detector in such a way that the detector is not swamped by too many counts. (You want to optimize the energy resolution.)

3. Use the oscilloscope to set the gain on the 575A pulse shaping amplifier to put the photopeak from this source near 8.5 volts. Then run pulse height analysis for about a minute and see where the photopeak falls. It should be near the upper limit of the screen, but not so high that you do not get a full peak. Adjust the gain on the 575A if necessary, and retake the spectrum until the photopeak is properly positioned.

4. ***Important: once the gain of the 575A is set, it must not be changed.*** Note in your lab note book the settings, including the Ortec 113 capacitance setting.

5. Repeat the pulse height spectra with the ^{22}Na source and the ^{133}Ba source. **Do NOT change the amplifier gain.** ***None of the calibration spectra need to be run for more than a minute.*** (If you happen to have the weaker of the two barium sources, position the source closer to the NaI detector.) Save *but do not analyze* the data files; you will have plenty of time for analysis when the counting begins.

6. Reestablish the connection between the MCA COINC input and the gate generator.

Data collection

With the coincidence logic setup and calibration spectra data taken and saved, the experiment can begin.

Obtain the ^{137}Cs source and place its ***source end (the black tip) at the front of the tube, so that it faces the target*** in the lead-wrapped tube behind the stack of bricks.

Measure the distance between the source and the target, and the distance between the target and the face of the NaI detector (tape measure available). These distances should be about 20 cm each.

In order to cover as wide a range of angles as possible, make a first set of measurements with large differences in the scattering angle, and if time permits do angles between these measurements.

Suggested procedure: Set the arm at the 80° marker, and begin taking data. The count rate will be low; you will need to wait a few minutes before you see a peak in the middle of the screen. *You will probably need to count for 10 or more minutes in order to obtain acceptable statistics.*

Check that the coincidence electronics is behaving properly. If the trigger is set up properly, you should see very little of the ^{137}Cs photopeak and a notable photopeak much lower in energy. With some luck it may be possible to see the coincident counts on the oscilloscope too.

While the data is being collected, the calibration data can be fit to obtain a calibration curve for your spectrometer.

After obtaining your 80° data, save the data set, and immediately begin counting at another angle. A suggested sequence of angles: 80°, 20°, 140°, 60°, 120°, 40°, 100°. The 0° data is the calibration data already taken. Count rates tend to be a little higher for large scattering angles than for small. (Discuss in your lab report why this is the case (Hint: how much energy is deposited in the *target* at small scattering angles?)

As you acquire the data in the MCA you should make a quick calculation of the channel number vs. energy of the photo-peaks that are expected from the Compton scattering formula. Use this calculation to check the peak locations as the data are coming in. You could use the cursor function on the MCA to test your predictions: park the cursor on the channel where you think a peak will appear, then see if you are right!

While data are being collected there is sufficient time to fit the photopeaks of the previous angles. Obtain the peak positions and widths, and convert these to energy MeV energy units. Using a spreadsheet make a plot of the data. The more basic analysis done during data taking, the less work you will be needed later when writing the lab report. See the comments in "Analysis of results" below.

While the data are being collected, make a careful sketch of the scattering table, noting all relevant distances, target and detector sizes, the opening of the hole in the lead brick, etc. You will need this data for the description of apparatus, analysis and discussion of your results.

Exercise 2 *Can you make a rough estimate of the counting rate to expect? Consider the following items: The activity of the source and how many counts should the target see, based upon its solid angle from the source? What fraction of these counts should the detector pick up from the target? Estimate the solid angles involved from the scattering geometry.*

Scattering cross section

The second part of the experiment is a measurement of the γ–e interaction cross section. Several plastic slabs are provided for this purpose. This plastic is similar in composition to the scintillator plastic used in the target.

For this measurement, remove the plastic scintillator and use only the NaI detector. Set-up the

NaI detector at 0°. Disconnect the gate-generator to MCA-COINC link to disable the coincidence gating.

Set up the MCA to count for a specific length of time. Three to four minutes is usually sufficient. Use this time interval for the rest of the measurements.

Place a few plastic slabs in front to the hole in the lead brick, and take PHA data. ***Make sure to measure the thickness of the slabs.***

Repeat the above measurements for as wide a range of slab thicknesses as you have time for, including no slabs at all. Save the raw data, and restart the measurement as soon as possible in each case. You can analyze the data sets while collecting the data or later if necessary.

Analysis of results

Scattering angle versus energy

Much of this analysis can and should be done while taking data. Plot the measured energy $E_{\gamma'}$ versus the angle of scattering θ and compare with the prediction of the Compton formula. The graph should show both the prediction (as a line) and the data (as points).

Be aware of both statistical and systematic uncertainties. What are some of the sources of systematic error? Are the results dominated by statistical or systematic errors? What is the effect of the acceptance angle of each detector and the energy resolution? What additional data, if any, would be needed in order to address these questions. Discuss these questions in your lab report.

In the lab report, discuss how well your data agree with the expected Compton scattering distributions. Be sure to include your estimate of the errors of your measured data points.

Scattering Cross section

The transmission of γ rays through a slab of material of thickness x is given by

$$I(x) = I_0 \, e^{-x/\lambda} \, , \tag{1}$$

where $I(x)$ is the transmitted rate, I_0 is the incident rate, λ is the mean free path of the scattered photon ($1/\lambda$ is the probability per unit length of a scattering event), and x the thickness of the material. If n_e is the number of free electrons per cm^3 in the target, then the total Compton scattering cross section σ_C will be given by

$$\sigma_C = \frac{1}{\lambda n_e} \, . \tag{2}$$

In order to carry out the analysis of the scattering cross section, you will need to find the *integrated intensity* under the photopeak. The easiest way to do this is to fit the photopeak to a Gaussian and use the fit parameters along with a formula for the integrated area of a Gaussian peak. Plot (on appropriate axes–which would these be?) the intensity $I(x)$ versus the thickness of the plastic x. Fit the data to determine λ. You will need to look up data for the plastic (Lucite) in order to estimate n_e from the chemical composition of the plastic and its density.

From these results, calculate σ_C, and compare your result to the results of theory given in section 2.7 of Leo. (See equation 2.108 and the related graph. A "zero-order" approximation is given by equation 2.115.)

Optional: Analysis of peak widths

Plot the *widths* of the angle vs. energy photopeaks versus scattering angle θ. Compare this plot with the plot of peak locations versus angle. Is there a relationship? (Hint: what is the slope of the Compton scattering formula?)

By convolving the uncertainty in the scattering angle, which is due to the finite acceptance angles of the target and detector, with the uncertainty in the energy resolution of the detector itself, studied in the "Energy Measurements" experiment, a fairly good model of the peak widths as a function of angle can be obtained.

To do this, work out the error propagation formula for the uncertainty in the scattered energy given an uncertainty in the scattering angle. Work from the basic error propagation formula (i.e., sums of squares of partial derivatives times uncertainties; see eq. 4.64 in Leo.)

If the dependence of resolution of the detector on energy is known, the resolution in terms of the scattering angle can be determined. These two "uncertainties" will add as the sum of the squares.

Prepared by H. Lubatti and D. Pengra
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