# Phys 471 – MODERN EXPERIMENTAL PHYSICS II

## Lab 2 – Compton Scattering

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**I. INTRODUCTION**

In this lab, the behaviour of gamma rays scattered angularly by an aluminum target will be observed and studied. The cross sections of interaction at various angles of scattering will also be observed and compared to theoretical frameworks.

Radioactive sources will be utilized for calibration purposes, as well as for the focus of this experiment. A NaI/PMT particle detector will be utilized, as well as associated electronics such as a pre-amp, amplifier, and MCA. The student will become familiar with the operation of this equipment in obtaining the highest quality of data they can. The radioactive sources will be used efficiently and in accordance with the safety regulations of the Department. Lead shielding will be used both for the safety of the experimenter and public as well as to enhance the quality of data.

The relationship between the energy of a scattered gamma ray and the angle of scattering will be determined experimentally by the student. The relationship between the cross section and scattering angle will also be experimentally explored. Each of these relationships will be quantified and compared to a variety of theoretical frameworks for these interactions. For the first relationship, the theories of Thomson and Compton can be compared or contrasted with experimental results. For the second relationship, experimental data can be measured against the predications of Thompson and Klein-Nishina.

## II. SETUP

This experiment will be developed using a variety of equipment. A variety of small sealed disk radiation sources will be utilized to calibrate the energy range and efficiency of the particle detector. A number of Sodium Iodide (NaI) – Photomultiplier Tube (PMT) combinations are available. It is strongly suggested that the student use the Saint-Gobain/Bicron/ORTEC NaI crystal and 2” PMT combination, as they are newer and have better noise and resolution characteristics. There are two older detectors labelled "RCA" which have been tested extensively and are acceptable. There is one labelled "Toshiba" which is problematically noisy and should be avoided.

A number of relatively weak radioactive sources will be used for calibration. These include Ba-133, Co-57, Cs-137, and Na-22. When determining the efficiency of the detector at different energies it is important to know which gamma rays are emitted at which intensities from each source, as well as the activity of each. A particularly potent Cs-137 source will be obtained for the main data-taking period of this experiment. This source will be placed into the ~50kg lead collimator by a radiation professional who will instruct you on the safe and proper handling of it.

PMT power supplies **must** be set to output a positive voltage when using NaI PMT's. Failure to do so will damage the device. The voltage range of 500-900V is recommended, with no excursions above 1000V. Voltages higher than 1000V risk permanent damage to the PMT.

The PMT will need to be coupled to a pre-amplifier and amplifier to amplify and shape the detected signals for the MCA to analyse them. It is strongly urged to use the ORTEC Model 113 pre-amplifier as it is newer. The pre-amplifier needs to be powered by one of the connectors on the back of an amplifier in the electronics stack. Check the pre-amplifier manual to see if any particular output impedance is specified, and choose the output cable type (e.g. RG-62,59,58) accordingly. Study the signal after pre-amplification using the oscilloscope to observe the characteristics of the output signal, i.e. polarity, uni-polar or bi-polar. The signal should be cleanly shaped and free of distortions.

The next step is to optimize the amplifier settings. It is recommended to try the ORTEC Model 575A amplifier, as its operation seems the most compatible with the MCA data acquisition. Note that the MCA accepts a positively polarized signal by default. Both the Linear Amplifier Gain and other options warrant experimentation. A number of the settings directly affect the shaping of the PMT signals. After reading how the MCA obtains data from this signal you will have a better idea of what shaping of the signal will lead to improved MCA data acquisition. After some experimentation, we have found the bipolar output with a gain of 4-5 to work reasonably well.

The post-amplifier signal will next be fed into the MCA8000 using the ADC input. The rest of the signal and data manipulation can be performed in software. The Multi-channel Analyser (MCA) integrates the amount of energy represented in a PMT pulse and represents the aggregate of many counts in a histogram. The bins or channels further to the right on a MCA histogram graph represent the acquisition of a higher energy pulse than channels further to the left.

## III. DATA ACQUISITION

- Ensure that the MCA 8000 is turned on.
- Turn on the laptop, and under the Start Menu open the connection software HWSuper.
  - Ensure one of the Serial Port, PGT/ANS COM, and at least one of the COM ports should be selected.
  - Click Update.
  - You should be informed that communication has been verified, and the Serial Com light on the MCA should turn on for a second.
- Use the Start Menu to open the spectrum analysis software QtmMCA.
  - Click on the picture button third from the left on the top until a tab labelled Presets is available at the bottom right.

Using the presets you can tell the machine how long to acquire data before automatically stopping. This is critical because the software Stop button will often not respond while data is being acquired and stopping an acquisition cycle becomes very difficult. Select a short time period such as 60 seconds to test the software. If it is not running properly, restart the laptop and reattempt connection until successful.

While learning how to use the software, you will want to place a small sealed Cs-137 source on the face of the detector. If you have the strong Cs-137 source already in the collimator, this can also be used. This will provide a known radionuclide profile to study while fine-tuning the software and hardware settings, as well as your own understanding of the software.

The other setting in these tabs you may find useful is the ADC LLD (Analog-to-Digital Converter Low Level Discriminator) which allows the user to select how much of the bottom set of channels to be ignored. This is useful for excluding a large build up of noise in the lower channels that may make the useful data hard to see as it is acquired.

Data can be acquired by clicking the Start/Stop Acquisition button (shaped like a start/stop light). Once clicked, the software will take data until the Preset Live Time (LT) is achieved. It is recommended that LT is used rather than real time (RT) as LT takes into account the time that the machine can not acquire data during medium to high counting rates, known as dead time (DT).

As with scaling a graph, you will want your data to fill as many channels as is reasonable. The high (611 keV) peak of a Cs-137 spectrum is the highest energy that you will need to display in this experiment, so scale accordingly. The scaling of bins across the histogram can be achieved by adjusting the Course and Fine Gain on the amplifier.

Once desirable scaling is achieved, the amplifier settings should be recorded and should not be adjusted, or future calibration will be affected. Doing so may nullify the usability of old data, as new data may not be comparable to data before these settings were altered.

Use Right click & drag to select an area of the histogram to zoom in on.

-Background acquisition

Remove the source from the face of the detector and place it within or behind a lead shield, relative to the detector. In the case of the strong source, place the steel plug in the collimator hole. Note that even with the steel plug in, you will get a skewed spectrum if the detector is near or in line with the collimation hole. Use the software to acquire a data set composed of background radiation only. You may find it useful to make use of a longer acquisition period for this, due to the inherently lower background radiation rate. This may be required to build up an adequate picture of the background radiation spectrum.

-Subtraction

You may wish to subtract a background spectrum from a whole spectrum to obtain a spectrum with only the radiation not due to background sources. This can be done by Analysis Tools -> Spectrum Calc. Choose a spectrum slot for the new spectrum to be placed in. If your two data sets had different LT, you may have to multiply or divide one of the spectra so that the counts are comparable in terms of LT.

-Saving a spectrum

File -> Save as Spectrum

-Saving & loading an energy calibration

File -> Save/Load System Configuration

-Using ROI detail to find centre, how to adjust ROI.

Hold control and select a region of interest (ROI) by left clicking and dragging. ROI can manipulated or removed using the controls at the bottom right of the screen. The details of an ROI can be viewed by going to Analysis Tools -> ROI Detail. The centre is the mathematical central peak of the distribution, while the centroid is something else. The associated error with a spectral peak analyzed using the ROI tool is the FWHM value (full width at half maximum).

**Actions that cause bad things to happen:**

**As with much specialized software, QtmMCA is not particularly user-friendly.**

-Not setting an active preset live time.

If a preset for stopping the software is not set, it becomes notoriously hard to stop. If you have the misfortune of wishing to stop a data acquisition, but it would take more time to retake the data, you will have to click the stop acquisition (stop sign) button periodically until it chooses to stop. This can take from minutes up to nearly an hour, so take this into account when deciding whether attempt a manual stop or abandon a data acquisition by restarting the computer. Restarting the software will not stop a data acquisition, as the hardware has taken over at this point.

-Trying to manipulate or analyze data while an acquisition is occurring.

The software does not respond swiftly to any UI interaction while data is being acquired. It is nearly impossibly slow to attempt to manipulate or analyze data while a new set is being acquired. It is recommended that you plan your time accordingly, such that you have something other than QtmMCA work to do during this time, be it data analysis, homework, word processing or graphical work.

-Attempting an automatic software energy calibration.

The QuantumMCA software seems to be ill suited to perform an auto calibration, and much time and ingenuity was expended attempted to allow the software to auto calibrate. The failed attempts suggest that either the auto calibration is not suited to NaI detectors, or the software is simply incomplete. A manual calibration using "Energy By ROI Centroids" is recommended.

**-**Performing energy calibration in QtmMCA

A manual calibration is best performed using Setup -> Manual Calibrate -> Energy By ROI Centroids. To do this, one must first take a number of spectra of a variety of elements. Research which of the available isotopes are suitable to calibrate a range energies below and including the peak gamma ray of Cs-137. Have your instructor sign out the strongest available disk source of each of these isotopes. Produce a spectrum for each isotope, taking as much time as it takes for each peak pertinent to calibration to develop. Save each of these spectra in turn, ensuring that they are well labelled for later access. Next, utilize a blank spectrum to produce a set of ROI matching up with each pertinent calibration peak of the isotopes previously analyzed. After doing this, you should have a spectra containing all of the properly aligned ROI that are needed for a full energy calibration. Next, select Energy By ROI Centroids and input the actual energy of each calibration peak. Once done, select Linear Calibration and Execute. To archive this calibration, select File -> Save System Configuration. It may be wise to find and record (View -> Setups) the calibration equation produced by the software for future or external reference.

-Collecting detection efficiency data.

The previously mentioned energy calibration will assist the student in testing the theories of Thompson and Compton scattering, but more information is needed to calculate the scattering cross-sections. The detector does not have an equal probability of detecting gamma rays of different energies. It must be known how efficient the detector is at a variety of calibrated energy levels in order to estimate the actual cross-sections.

The sources used for the energy calibration will be utilized for this, as well as a few sources with energies above and below this range, so as to give the student a more thorough idea of the efficiency curve of the particle detector in use. The source activities, as well as the intensity and energies of the emitted gamma rays prominent enough to be used for calibration will be useful for determining the shape of detector efficiency. For ease and accuracy of calculation it is recommended that the disk sources are placed at the position of the scattering target while this data is taken.

In comparing the efficiencies at different energies, the key data to be measured from the histogram is the rate at the peak channel of a spectral peak. This can be found by creating an ROI composing a small central section of the Gaussian plateau of a peak, and using Analysis Tools -> ROI Details to determining the number of counts in that region, the number of channels it is composed of, and the amount of time those counts were acquired over. This information will help lay down the basis for determining the relative efficiency of detection at various energies.

## IV. BASIC EXPERIMENTAL INTRUCTIONS

Be sure to closely study the provided 22-Na, 57-Co, 60-Co, 133-Ba, 137-Cs energy level schemes and sample decay spectra. Alternatively, you may find it useful to have an easily accessible resource for determining the scientifically accepted gamma ray energies and intensities of a variety of sources.
**http://www.nndc.bnl.gov/chart** was very useful during the development of this lab. Find and select your favourite isotope, then select the link titled "decay radiation" near the bottom of the page. You will likely be most interested in the section titled "Gamma and X-ray radiation".

Following the instructions in Melissinos & Napolitano, thoroughly document your energy and efficiency calibrations, including enough information in your logbook so that your most important results could be later reconstructed from your notes, if needed. These notes should also enable the quality of the calibrations to be inspected, such as including a graph/function describing the relationship between detection efficiency and energy. Where applicable, the student may estimate relevant systematic as well as statistical errors in these calibrations.

**Only after your energy and efficiency calibrations have been performed and quantified, should you proceed with your main data collection and analysis. You will need the strong Cs-137 source. It is absolutely essential that the student follows all of the distributed nuclear safety regulations (e.g. ALARA principles) when using this source.**

Using the equipment available, the student should align the apparatus such that the collimated gamma beam lies in a plane that will pass through the centre of the detector and through the middle of a chosen mounted scattering target. Ensure that small sealed disk sources can be raised to also lie on this plane when propped upright on the target mount with one face directed toward the detector. Keep in mind that the beam does not remain perfectly collimated, and that the detector should be placed along the rotatable platform far enough from the target that it is relatively equally distant from the target as the source within the collimator is. The student is free to choose the parameters of this alignment, but should be aware that some positions will make data acquisition at a range of angles difficult or inaccurate, and that these positions should remain fixed and stable once data acquisition and calibration begin. A lead mount and shield is recommended to increase the stability of the detector. This will also attenuate background radiation from the environment which increases the difficulty of quality data acquisition.

Place a target in the scattering target mount. Ensure that the steel stopper is in place on the strong source before manipulating objects in or near the path of the radiation column. Position the detector to detect scattered gamma rays at 90 degrees of deflection. Acquire one data set with the scattering target in, and one with the target removed. Subtract one from the other such that you have a data set containing only the detected gamma rays due to the scattering target. Utilize the software tools available to extract the data you may need, such as the peak position (in keV) and peak rate. Obtain as many meaningful data points as is reasonable, at 10 to 15 degree increments. At the smallest angles of deflection (40 degrees downward) it may be possible to use a lead brick to shield the detector from the widening gamma column but not from radiation scattered from the target. This may reduce the amount of time required to obtain meaningful data. It will be useful to take data at zero deflection both with and without a target to determine the maximal peak energy of the Cs-137 gamma ray.

If time permits, the student should consider taking “No Target” runs for every angle, to enable background sources to be identified and subtracted. Is the yield ratio of "No Target"/"Target" large or small and does it vary with angle? How might this affect the quality of your measurement?

The careful estimation of the detector efficiency for each angle setting is vital for the differential cross section measurement. This includes not only the energy response of the NaI detector, but also the peak/total yield ratio for each setting. See the instructions in Melissinos & Napolitano. What are the origins of the most important features of the observed energy spectra and how do they vary with angle?

Results:

- Compare predictions of scattering theories (Thompson and Compton) to your measurements.
- Calculate the scattering cross-section at a number of tested angles and compare these data to the predictions of the Thompson and Klein-Nishina scattering theories.

**V. REFERENCES**

W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, 2$^{nd}$ Edition, 1994, Springer-Verlag.

A.C. Melissinos, J. Napolitano, *Experiments in Modern Physics*, 2$^{nd}$ Edition, 2003, Academic Press.