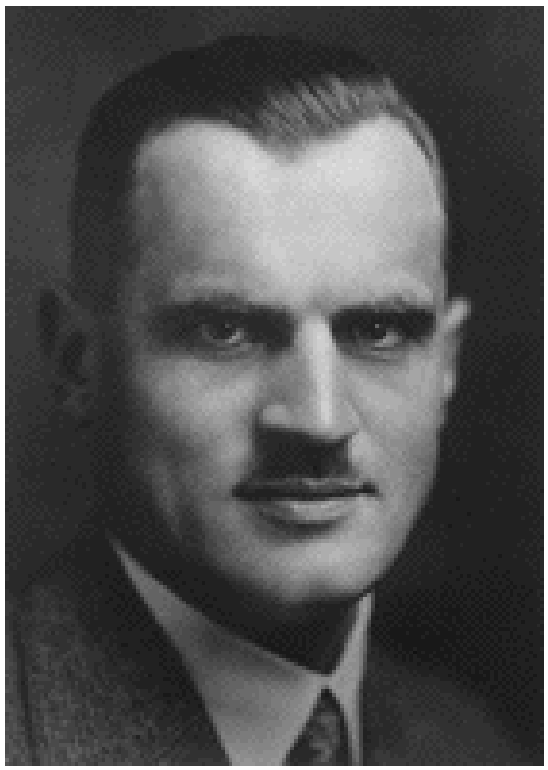
Chapter 3

Experiment # 1

Study of the Compton Scattering



Arthur H. Compton

3.1 Introduction

The theory of classical electromagnetism cannot explain the scattering of electromagnetic radiation by charged particles. Compton and Debye obtained independently in 1923 the relationship between wavelength (or energy) and scattering angle for the electromagnetic radiation diffused by free and at rest electrons.

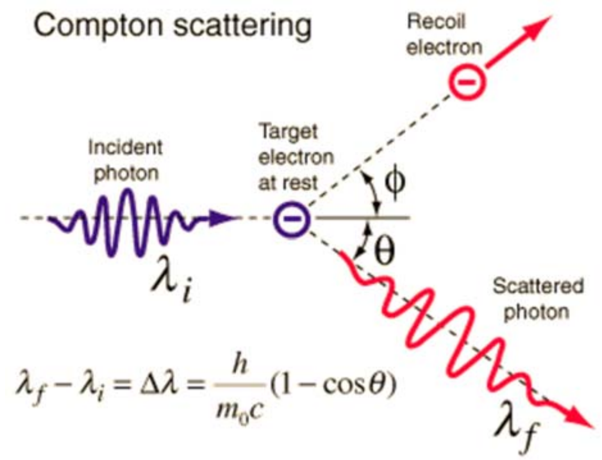


Fig.3.1: Schematic representation of the Compton scattering.

The energy of the diffused photon (f) can be expressed as:

$$h\nu_f = \frac{h\nu_i}{1 + \frac{h\nu_i}{m_e c^2}(1-\cos\theta)} \qquad (1)$$

as a function of the scattering angle θ and of the energy of the incoming photon. As a consequence, for a given wavelength of the incoming radiation, there is a univocal relationship between the wavelength and the angle of the diffused radiation.
Compton used eq. (1) to analyze the experimental data about the diffusion of photons by solid samples. The diffused wavelength at a given angle resulted having a distribution characterized by a finite width. Such observation could be understood as the evidence that the electrons in the solids cannot be considered at rest.

In 1929 Klein and Nishina could derive the expression for the differential cross section of the Compton scattering:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{h\nu_f}{h\nu_i}\right)^2\left(\frac{h\nu_f}{h\nu_i} + \frac{h\nu_i}{h\nu_f} - sen^2\theta\right) \qquad (2)$$

where $r_e = e^2/m_e c^2$ is the classical radius of the electron.
In the elastic limit $(h\nu_f)^{free} \sim h\nu_i$ that is valid if $h\nu_i << m_e c^2$, eq. (2) reduced to the classical (Thomson) expression for the elastic scattering on free electrons:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(1+\cos^2\theta\right) \qquad (3)$$

The dependence of the cross section on the scattering angle is depicted in Fig.3.2 for some of the energies of the incoming photon.

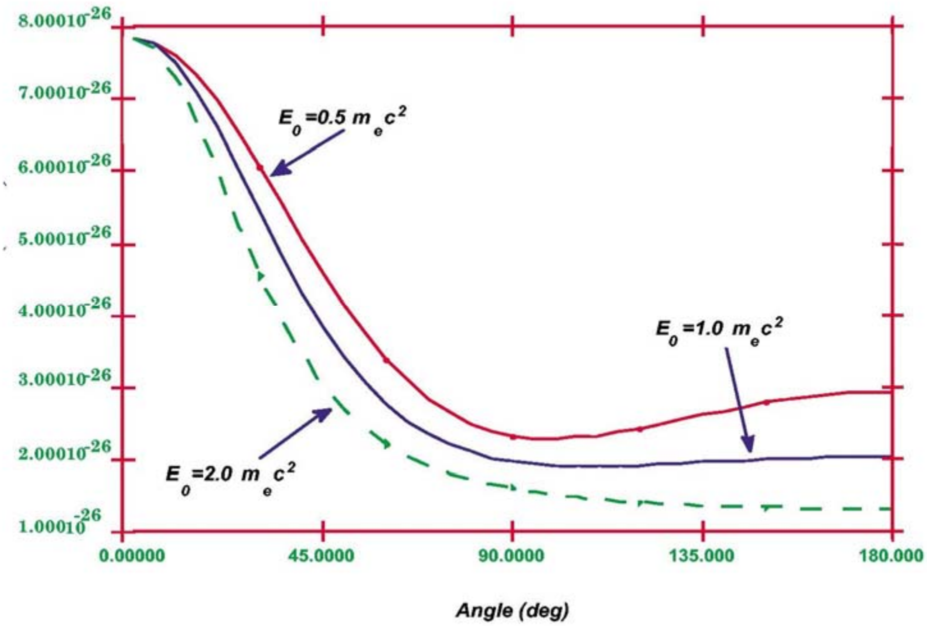


Fig.3.2 : Differential cross section for the Compton scattering as a function of the outgoing angle and for three different incoming energies: 256, 511 and 1022 keV (given in units of $m_e c^2$).

Compton scattering plays an extremely important role in modern Physics because it is the predominant way of interaction with matter of electromagnetic radiation in the MeV energy region, as shown in fig. 3.3. Moreover the Comton scattering can be used to study the properties of matter.

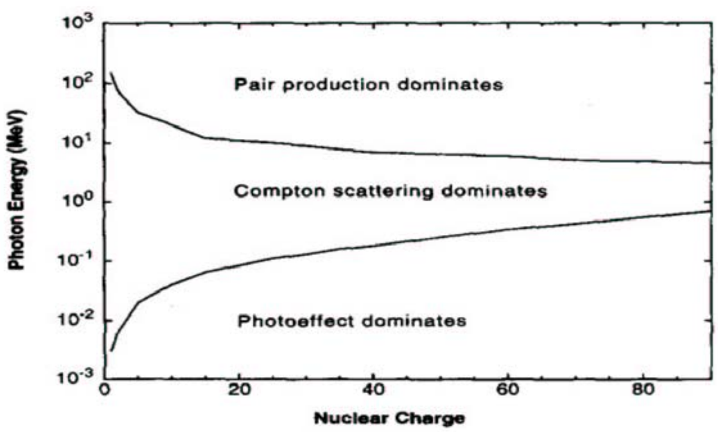


Fig.3.3: Relative importance of photoelectric effect, Compton scattering and electron-positron pair creation as a function of the energy of the incoming photon and the atomic number Z of the scatterer material.

3.2 Experimental setup

The aim of this experiment is:

1) **To verify the relationship between energy and angle of the diffused photon.**
2) **To measure the differential cross section of Compton scattering**

A ^{22}Na source is collimated using a properly shaped lead brick in order to obtain a photon beam with a properly defined geometry. The beam hits a the SCATTERER which, for the first part of the experience, consists of a NaI(Tl) scintillator detector mounted vertically. The NaI(Tl) scintillator used as scatterer is a cylinder with diameter 7.5 cm and height 7.5 cm.

As the ^{22}Na source yields gamma of 511 and 1275 keV, the photons that hit the Scatterer have to be selected. To this purpose the incoming beam can be "tagged" using the coincidence with a second 511 keV photon that is emitted by the source. In order to detect the "tagging" photon a second NaI(Tl) scintillator similar to the first is used. Such detector is named TAGGER.
The coincidence between the TAGGER and the SCATTERER provide the trigger for the scattered event and can be used to normalize the measurements. We observe that, while the coincidence efficiency for two photons of 511 keV is unitary because the emission of such photons is back-to-back correlated in direction, for the case of 511-1275 keV coincidences there is not an angular correlation. This means that for each of the 511 keV identified by the TAGGER, the 1275 keV photon in coincidence can be emitted isotropically. The coincidence efficiency for the 511-1275 keV can be estimated evaluating the fraction of solid angle ($\Delta\wedge/4\pi$) covered by the SCATTERER and defined by the lead collimator.
The collimated source, the TAGGER and the SCATTERER are placed on independent supports. The alignment of the system is verified by the laboratory personnel.
The scattered photons are detected at the angle θ_{lab} by a third NaI(Tl) scintillator, similar to the first two, named DETECTOR. Such scintillator is placed on a rotating arm that allow the variation of the angle θ_{lab} in step of 10 degrees between tra 0 and 110 degrees. Moreover the distance between the SCATTERER and the DETECTOR and be varied continuously. The setup is reported in fig. 3.4.

Fig.3.4: Experimental setup for the study of Compton scattering.

3.3 Electronics for the Compton scattering experiment

The block diagram of the electronics that will be used for the experiment on Compton scattering is reported in Fig. 3.5.
The only output used on the basis of the photomultiplier is the one coming from the last dinode.
The detectors are operated at HV = +600 Volt values via the CAEN N1470 module. Normally you will already find the detectors in operation with set appropriate HV values.

To form the trigger for the data acquisition, you will use Nuclear Instrument Modules (NIMs). The NIM is one of the available standards for electronics that can be used for physical experiments.
The standard is defined by the geometric characteristics of each module allowing its insertion into a NIM-BIN containing the stabilized power supply that provides the necessary power differences ($\pm$6,$\pm$12,$\pm$24 Volt) via a multipin connector. NIM modules are controlled by helipot or normally accessible switches on the front panel.
For each detector, the output of the anode is connected to a Quad Linear Gate FAN-IN / OUT mod. Philips 744 for signal doubling. A signal will be inserted directly into the capture system: a CAEN digitizer mod. DT5720, see Chap 12.4 for details on the Digital Electronics and Appendix V for the daq system.

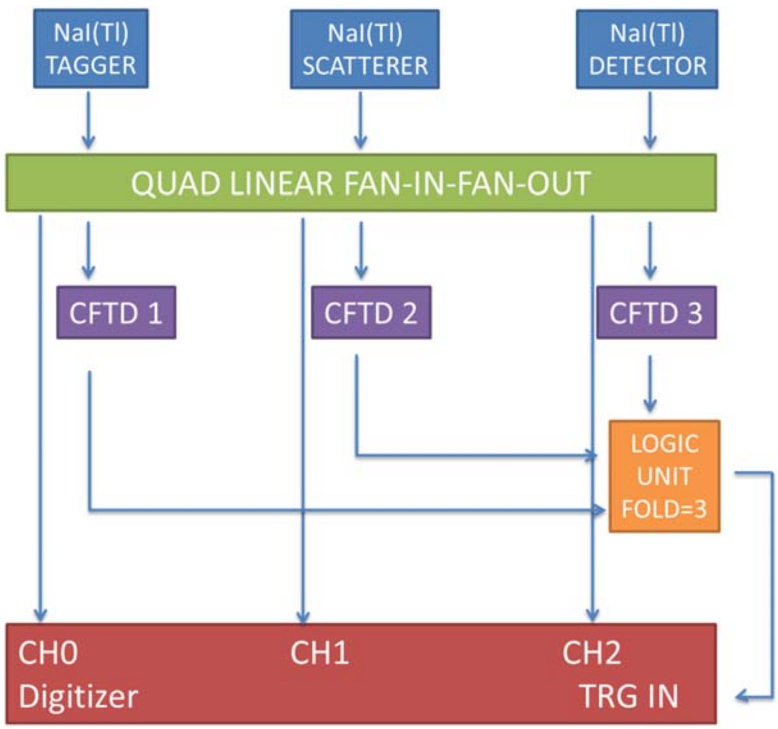


Fig. 3.5: Electronics Diagram for the Compton Experiment.

The second signal is connected to the input of one of the Constant Fractional Discriminator channels (CFTD mod INFN Pd). The CFTD provides two types of output signals, a prompt signal, and a delayed signal, of which it is possible to vary both the duration and the delay by microswitches. The possibility of adjusting the logic signal duration and delay is extremely useful for making a coincidence overlap between the various detectors using the 32 Inputs Logic Unit (SEN mod LU 278). This module allows to obtain coincidences between N detectors (with N <32) providing output signals (standard NIM, -800 mV) depending on the signal fold. "Fold" refers to the number of detectors that coincide with each event, irrespective of the input order number. For example, if we connect the three NaI(Tl) to the inputs 1,2 and 3, an output signal from the connector of fold = 1 will be obtained when at least one of the three signals is present; a fold = 2 signal will mean that at least two (between the three connected) are present and fold = 3 in our case will only be obtained when all the signals are present.
The overlap coincidence is verified when two signals V1 (t) and V2 (t) give a non-zero time intersection, as shown in Fig 3.6.

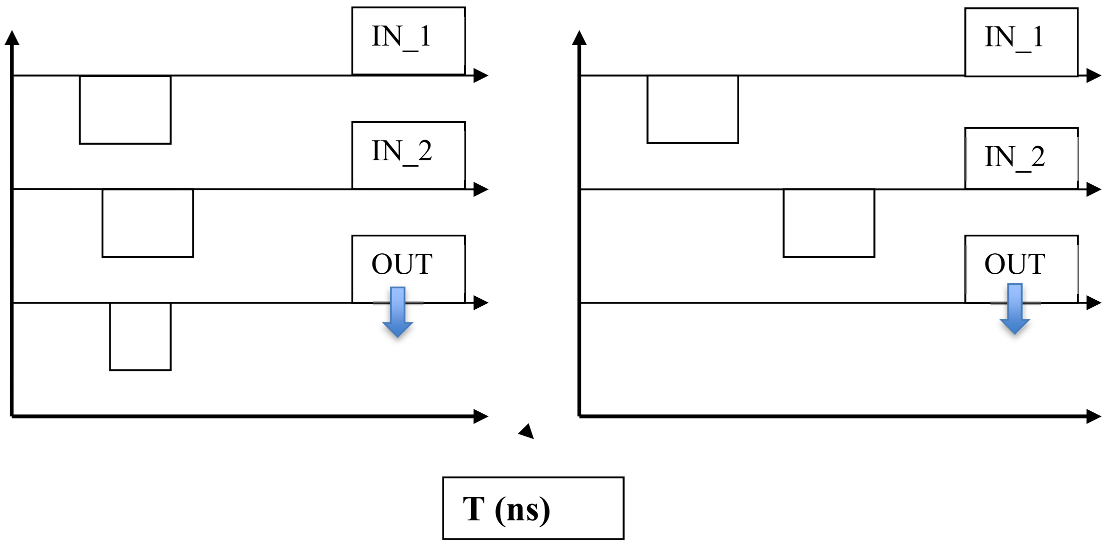


Fig.3.6: Examples of overlap coincidences.

The output of the Logic Unit module is NIM standard (-800 mV) and can be used as a MASTER GATE by the digitizer for capture, i.e. as a signal enabling the reading of the channels # 1, # 2, # 3.

3.4 Experimental protocol

As already mentioned, the purpose of the experiment on Compton scattering is:

1. To verify the diffused photon energy and electron energy dependence on the diffusion angle.
2. To determine the value of the differential cross-sectional area for Compton diffusion from an aluminum sample.

For point a), the three detectors will be used (TAGGER, SCATTERER, DETECTOR), and for point b) the SCATTERER detector will be replaced by an aluminum sample.

The experimental protocol is subdivided into the three sessions available for the experiment. The timing chart below is just a guide to the activity and can be varied by students also in relation to issues or further investigations stimulated in the lab.

3.5 First session: preparation and calibration of the scintillators

1) You will find the ^{22}Na source already inserted in the collimator. Connect the TAGGER detector signal directly from the FAN-IN-FAN-OUT to the oscilloscope: write down the polarity, amplitude and signal rising time. Identify on the oscilloscope the amplitude corresponding to the full-energy peaks of the 511 keV and 1275 keV transitions.
2) Connect the second output of the FAN-IN / OUT to the CFTD input and send the CFTD output prompt signal to the oscilloscope and observe it. By triggering the output signal prompt, connect the delayed output signal to the second oscilloscope channel and observe it. Understand the effect of the operation of the microswitches for different *width* and *delay* values.

3) Setting of the CFTD threshold. The CFTD provides an output signal only if the input signal amplitude is greater than a V_{th} threshold value. The discrimination threshold is used to prevent the CFTD from operating on the white noise of the electronics. In this experiment relatively low energies will be measured in the case of retro-diffused photons. It is therefore of utmost importance to verify the values of the threshold of discrimination. To do this, proceed as follows: connect the anode signal to the oscilloscope from the FAN-IN-FAN-OUT and one of the outputs of the CFTD, triggering on the latter signal. Depending on the threshold value (set via the special trimmer that can be adjusted using the screwdriver) it is possible to check how the anode signal distribution changes, with the disappearance of the corresponding noise signals and low energy signals. Fix the threshold to the minimum value that is needed to cut the noise of the electronics.

4) Connect the anode signal from the FAN-IN-FAN-OUT of the detector to input #1 of the data acquisition. Connect the delayed output (with minimum delay) to the input of the Logic Unit and select FOLD 1 for the output. The Logic Unit output will be our trigger and should be already connected to the digitizer TRG-IN. Connect the CFTD prompt output to the CAEN scaler to verify the counting speed.
You are now ready to record the source spectrum of ^{22}Na. Verify that in the spectrum the peak at 511 keV lies around the channel number 10000. Acquire the spectrum and record it as a file. Since in the spectrum of ^{22}Na there are two peaks, you can determine the centroids by a Gaussian fit and then obtain the spectrum calibration:

$$E_{\gamma} = a + b \cdot N_{canale}$$

To improve the accuracy of the calibration, especially for the energies $E_{\gamma} < 511$ keV, you should also use a ^{241}Am source (see Chapter 2) that emits photons with $E_{\gamma}=59$ keV. Acquire the Americium spectrum. Typical examples of spectra obtained in the laboratory are shown in Figure 3.7.

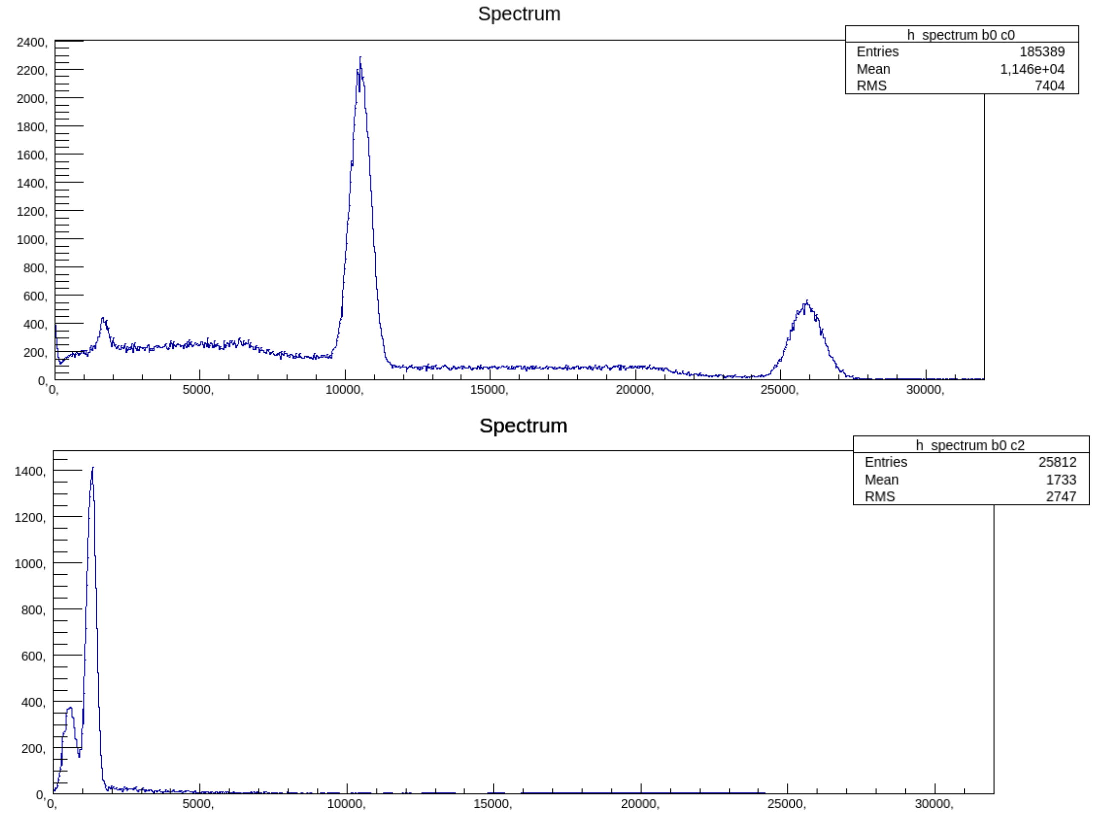
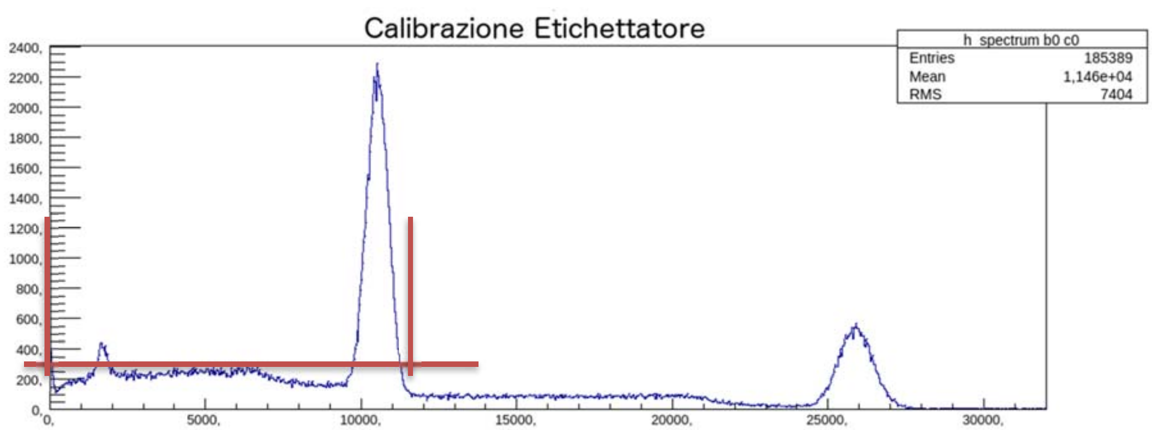


Fig. 3.7: Typical energy spectra with the source of Sodium (top) and Americium (bottom).

5) Repeat steps 1-4 for the SCATTERER and the DETECTOR. To calibrate the DETECTOR, ask for the use of a second ^{22}Na source to be placed near the detector.
In the case of sodium spectrum of the TAGGER detector, determine the fraction of events due to 511 keV photons in the detector, subtracting from the total number of events in the range of interest (red markers in Figure 3.8), the background due to the Compton shoulder due to the 1275 keV photon.



If A(511) is the result of this operation, that is, the area of the peak at 511 keV, and A_{tot} is the total number of events in the spectrum, we can define F(511) as follow:

$$\mathbf{F(511)= A(511)/(A_{tot})}$$

F(511) represents how many events are in the full-energy peak of the 511 keV photon with respect to the total number of events in the detector. This size will be used to determine the cross section.

It is interesting to evaluate the relationship between the statistics in the gamma spectrum and the precision with which you will be able to determine the photopeak centroid, used to measure the photon energy. This point is essential since the purpose of the first part of the experiment is indeed the measurement of the correlation between diffusion angle and diffused photon energy.

Please note that the peak centroid error is provided by ROOT when performing peak fit with a Gaussian function. To verify the relationship between statistics in gamma spectrum and measurement accuracy, it is suggested to take a series of sodium source spectra with the DETECTOR corresponding to different statistics (e.g. 500, 1000, 2000, 5000, 10000 acquired events) and fit the peak at 511 keV in such spectra with a Gaussian to determine the centroid value and its error. Report these values based on the acquired statistic and use this information for subsequent measurements.

COMPTON EXPERIMENT
SETUP OF THE DETECTORS#1

Group........... Padova..........................

TAGGER HV=.......................Volt

Characteristics of the signals terminated at 50 Ohms

	Fall time (ns)	Vmax @511 keV (mV)	Rise time (ns)	Noise level (mV)
Anode PMT				

CFTD threshold (measured by the oscilloscope):.............................mV
RATE:..c/s

SCATTERER HV=.......................Volt

Characteristics of the signals terminated at 50 Ohms

	Fall time (ns)	Vmax @511 keV (mV)	Rise time (ns)	Noise level (mV)
Anode PMT				

CFTD threshold (measured by the oscilloscope):.............................mV
RATE:..c/s

DETECTOR HV=.......................Volt

Characteristics of the signals terminated at 50 Ohms

	Fall time (ns)	Vmax @511 keV (mV)	Rise time (ns)	Noise level (mV)
Anode PMT				

CFTD threshold (measured by the oscilloscope):.............................mV
RATE:..c/s

COMPTON EXPERIMENT
SETUP OF THE DETECTORS#2

Group........... Padova..........................

Energy calibration

TAGGER

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
59 keV			
511 keV			
1275 keV			

Calibration (E= α x channel + β)
α=................................ β=..................................

SCATTERER

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
59 keV			
511 keV			
1275 keV			

Calibration (E= α x channel + β)
α=................................ β=..................................

DETECTOR

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
59 keV			
511 keV			
1275 keV			

Calibration (E= α x channel + β)
α=................................ β=..................................

3.6 Second session: search for the coincidences, and definition of the measurement geometry.

Search for the coincidences. In order to check that the CFDs' "delayed output" signals of the three detectors have an overlapping region, use the following procedure:

1) Adjust the width of the three CFTDs delayed signals to the value W = 100 ns using the oscilloscope.

2) Connect the delayed output of the SCATTERER CFTD to the channel 1 of the oscilloscope and trigger it on this signal.

3) Connect the delayed output of the CFTD of the TAGGER to the channel 2 of the oscilloscope. Check that the two signals have some timing overlap. To obtain the overlap, if needed, modify the two CFTD delays.

4) Ask for a second ^{22}Na source and place it between the DETECTOR and TAGGER. Connect the delayed output of the DETECTOR CFTD to the channel 2 of the oscilloscope. Check that the two signals have some timing overlap. To obtain the overlap, if needed, modify the delay of the CFTD of the DETECTOR.

5) Connect CFTD delayed outputs to Logic Unit inputs 1,2,3 and select FOLD = 3.

You are now ready to take data for the first part of the experiment.

Definition of measurement geometry.

6) Note the activity of the ^{22}Na source, gamma geometry and available collimators, define the measuring geometry: D1 source-tagger distance, D2 source-scatterer distance and D3 scatterer-detector distance. Collimators allow you to have a collimated beam with diameter $\Phi < 3.5$ cm in the position corresponding to the axis of the diffuser where, in the second part of the experiment, an aluminum sample will be mounted for the measurement of the cross section. Estimate the expected counting rate.

7) Using the CAEN scalers, measure the counting rate for the TARGET - DIFFUSER coincidences by disconnecting the DETECTOR from the Logic Unit and selecting FOLD = 2. Record a spectrum corresponding to this type of coincidence and interpret the results obtained by comparing them with what is expected from geometric considerations.

8) Insert the DETECTOR in the Logic Unit and select FOLD = 3. Using the CAEN scalers measure the triple coincidence counting rates for the different angular positions of the detector. Based on the counting rates, choose the angles to measure and the measurement time for each position, taking into account that you also have one night available to acquire a high-statistics spectrum.

COMPTON EXPERIMENT
SETUP OF THE DETECTORS#3

Group........... **Padova..........................**

TAGGER

CFTD Delayed signal Width:..........................ns

Rate.................................c/s

SCATTERER

CFTD Delayed signal Width:..........................ns

Rate.................................c/s

DETECTOR

CFTD Delayed signal Width:..........................ns

Rate.................................c/s

D1: distance source - TAGGER...............cm

D2 distance source - SCATTERER...........................cm

D3 distance SCATTERER - DETECTOR................cm

Detection angle...

Coincidence Rate 2-fold:…………………c/s

Coincidence Rate 3-fold:…………………c/s

3.7 Second-third session: first part of data taking.

For each angular position you have decided to measure, use the attached log file. Arrange the measurements so that you measure immediately at angles around 90 degrees in order to check if the device is working properly. The measurement of the backward angles can be left to be taken during the night between the second and the third day.

3.8 Third session: measurement of the Compton cross section.

Ask that the SCATTERER detector is dismounted. The absolute measure of the Compton scattering shock section is obtained from the relationship:

$$\left[\frac{d\sigma(\Theta_f)}{d\Omega}\right]_{\exp} = \frac{\Sigma_\gamma}{(\varepsilon \cdot N \cdot \Delta\Omega_f \cdot I/S)}$$

where:

Σ_γ is the number of events in the full energy peak in the spectrum of scattered photons
ε is photopic efficiency for the energy of scattered photons
N is the number of electrons in the sample of Al (N = volume x density x N Avogadro x Z / atomic weight)
$\Delta\Omega_f$ is the solid angle underlined by the DETECTOR
I/S is the number of photons accidental on the sample per unit of surface.

The measurement of the efficiency for the 511 keV energy can be obtained easily. Place the DETECTOR at 0 degrees in contact with the source lead collimator in such a way as to ensure that all the tagged beam is within its angular acceptance. Use as the Master Gate of the acquisition the coincidence between the TAGGER and the DETECTOR. Record the spectrum of the TAGGER and DETECTOR under these conditions. From the recorded gamma spectra, you get the total number of events in the spectrum of the TAGGER (N_{tot}) and that of the events in the 511 keV peak of the DETECTOR (N_1) with a subtracted backgroud, as in Fig. 3.8. If you now assume that, as a consequence of the spatial correlation of the two photons, for each photon recorded in the TAGGER there has been one in the DETECTOR, the full-energy efficiency at 511 keV of the DETECTOR will be:

$$\varepsilon(511 keV) = \frac{N_1}{N_{tot}}$$

Typical full-energy efficiency values of a NaI (Tl) scintillator such as the one used are in the range of 50-60%.

Now mount the aluminum sample. Place the detector at a backward angle and measure on the CAEN scalers the coincidence rate TAGGER-DETECTOR, selecting fold = 2. On the basis of the counting rate choose the duration of the measurement. It is suggested that a backward angular position is chosen (about 100-110 degrees) and for the same angular position a background run is acquired as well. Such run can be obtained by measuring without scatterer for a significant amount of time.

During these measurements you must record the total number of events in the CAEN scaler on the TAGGER by sending the Constant Fraction prompt output to the scaler. Such number will be called N_{scaler}.

In order to derive the cross section, it is necessary to estimate how many 511 keV photons hit the sample. In the case of a photon beam "tagged", as in this experiment, that number can be obtained directly. Indeed, if N_{scaler} indicates the total number of events in the TAGGER, Nscaler x F(511) represents the number of 511 keV photons that hit the TAGGER and were processed by the electronics. As a consequence the number of photons that hit the Aluminum sample and deposited 511 keV in the TAGGER will be:

$$I = N_{scaler} \cdot F(511)$$

Since we are considering only the photons that produced a photopeak in the TAGGER, during the analysis of the data, this condition should also be imposed in determining the number of events in the DETECTOR.

Record for each measurement the data on the appropriate log-file.

COMPTON EXPERIMENT
LOG FILE PART I

Group........... **Padova..........................**

TAGGER

HV=..............Volt RATE:..................c/s

SCATTERER

HV=..............Volt RATE:..................c/s

DETECTOR

HV=..............Volt RATE:..................c/s

MASTER TRIGGER DATA ACQUISITION:……………………………..RATE……………c/s

DETECTOR ANGLE:………………..

DISTANCES D1=…………….. D2=…………….. D3=……………..

ACQUISITION TIME:

Start……………. Stop…………………

Notes

Spectra to be attached

EXPERIMENT #1
COMPTON SCATTERING
LOG FILE PARTE II: MEASUREMENT OF THE CROSS SECTION

GROUP .... Padova,............................

TAGGER

HV=..............Volt RATE:..................c/s

DETECTOR

HV=..............Volt RATE:..................c/s

MASTER TRIGGER DATA ACQUISITION:……………………………..RATE……………c/s

SCATTERER: Al Cylinder with dimensions……………………

DETECTOR ANGLE:………………..

DISTANCES D1=…………….. D2=…………….. D3=……………..

ACQUISITION TIME:

Start……………. Stop…………………
Scaler CAEN……………………………………………

Notes

Spectra to be attached

3.9 Suggestions for the data analysis.

Measurement of the energy of the scattered photon

1) Calibrate the gamma spectra.
2) Define the conditions for accepting a photon energy event detected in the TAGGER by placing a window close to the full energy peak of the 511 keV photon.
3) Define the conditions for accepting an event related to the electron energy revealed in the scatterer.
4) The events that satisfy the AND of conditions 2) and 3) define the number of diffused photons for each file.
5) Using conditions 2) and 3) for each angular position you get the diffused photon energy spectrum.
6) Build a table showing: DETECTOR angle, total number of diffused events, average photon energy revealed in the full-energy peak, the average electron energy revealed by the SCATTERER.

UNDERSTAND THE DATA OBTAINED COMPARING TO THE THEORETICAL PREDICTION BOTH FOR THE SCATTERED PHOTON (DETECTOR) AS WELL AS FOR THE ELECTRON (SCATTERER). CHECK THE ENERGY CONSERVATION.
Check the possibility of obtaining the sum of energy (SCATTERER + DETECTOR) event-by-event and verify the energy conservation directly from the constructed spectrum.
The cross section for Compton scattering (Fig. 3.2) has a strong dependence on the angle, especially for small angles. Check if the angle given by the goniometer provides a good estimate of the average angle: the angular acceptance of your setup is finite and this has to be taken into account by a weighted average on the differential cross section.
Build the two-dimensional energy spectrum SCATTERER - DETECTOR. What can you learn from this distribution?

Measurement of the Compton cross section

1) Calibrate the gamma spectra.
2) Define the proper conditions to accept an event. Specifically require the proper energy for the photon detected in the TAGGER using a wide window in the energy region associated with the 511 keV photon.
3) The events that satisfy the condition 2) can be used to determine the number of scattered photons. Build the energy spectrum of the scattered photon and determine the number of events in the full-energy peak.
4) Analyze the background spectrum.

Measure the value of the cross section comparing the data obtained to the theoretical predictions and to the reference values.