Compton Scattering Investigated With Vireo Digitizer and NaI(Tl) Detectors

Ujval Madhu, Wojtek Skulski

Skutek Instrumentation, www.skutek.com

Abstract:

This report presents an experimental investigation of Compton scattering using a ^{137}Cs gamma-ray source and two sodium iodide (NaI) scintillation detectors coupled to a table top digital data acquisition system. The experiment was designed to verify the angular dependence of Compton scattered photon energies and demonstrate the Compton scattering formula. We are also showcasing a novel data acquisition system where the coincidence between two detectors is established within the data acquisition unit, without reliance on any external coincidence electronics such as NIM modules or crates. Setting up the experiments took less than two hours, including trouble shooting a faulty cable connector, adjusting the HV for the detectors, and recording sample data files. The events were saved to disk in the event-by-event format (Appendix A) over approximately one week and processed offline.

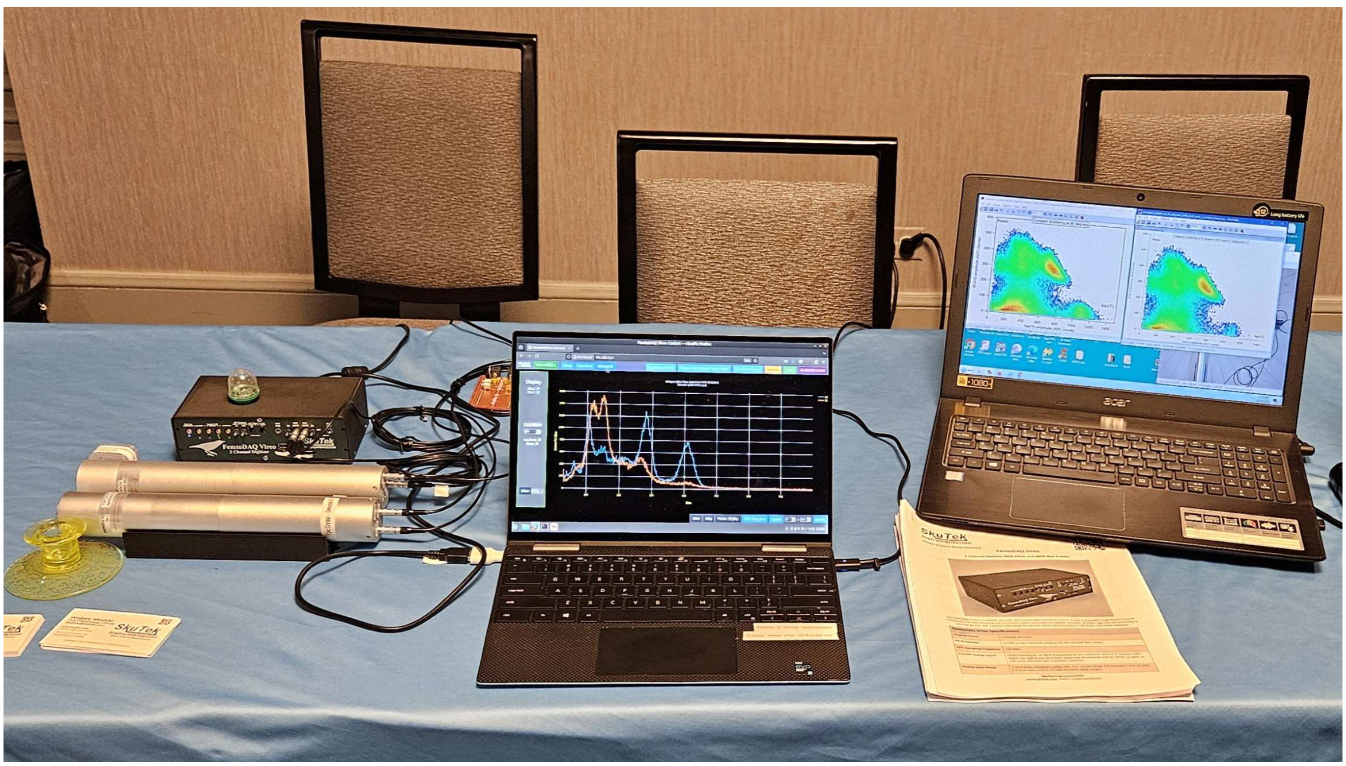

Figure 1: Vireo digitizer (dark box on the left) next to two NaI(Tl) detectors (aluminum cylinders next to Vireo) collecting data during the recent APS Division of Nuclear Physics 2025 conference in Chicago. One detector is collecting radiation from the antique uranium glass candle holder (yellow), while the other is collecting events from half a dozen LYSO crystals, which are slightly radioactive. The laptop in front is showing the pulse height histograms growing in real time. The color maps on the right show a record of a previous Compton scattering investigation with a BC412 detector, completed prior to the conference.

Theory:

Compton scattering is one of the most important ways in which γ-rays interact with matter. In Compton scattering, the incoming gamma-ray photon is deflected at an angle θ with respect to its original direction. The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as a recoil electron.

Because all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma-ray energy. The most energetic recoil electrons are produced in head-on scattering, where the γ-ray bounces backwards at 180º relative to its initial direction, while the recoiling electron moves forward. The division of energies between the two particles depends on the "apparent mass" of the impinging γ-ray.

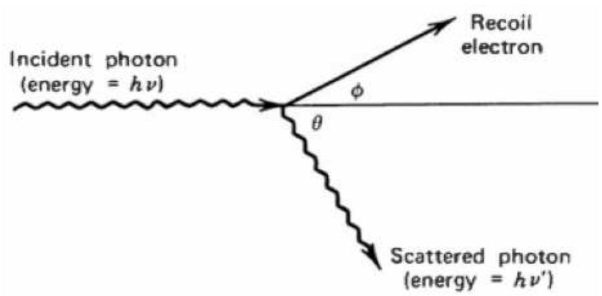

Figure 2: Compton Scattering, Ref: Radiation Detection and Measurement, Glenn F Knoll

The energy *hν*' of the scattered gamma-ray can be calculated using the conservation of energy and momentums. We note that this formula, though relativistic, is in fact entirely classical, if we visualize both particles in analogy to classical billiard balls.

$$h\nu' = \frac{h\nu}{1+\frac{h\nu}{m_0 c^2}(1-\cos\theta)}$$

Here, *hν* is the energy of the incident photon, which is the 662 keV characteristic γ-ray from the decay of ^{137}Cs. The energy of the scattered photon is denoted as *hν*'. We note that we do not need to enter the values of the electron mass in kilograms, the speed of light in meters per second, the Planck constant in joule-seconds, or the frequency of the photon in hertz, if we consistently express all the masses in the energy units. The only important values are the mass (or energy) ratios.

h = Planck's constant = 6.626×10^{-34} joule-seconds (J-s)
v = The frequency of the photon
m_0c^2 = the rest mass energy of the electron = 511 keV
m_0 = 9.109×10^{-31} kilograms (kg).
c = Speed of light in vacuum = 3×10^8 m/s

Objective:

The primary objective of this experiment is to experimentally demonstrate the Compton scattering phenomenon and validate the theoretical relationship between scattering angle and scattered photon energy. Specifically, this experiment aims to demonstrate the following:

1. The existence and nature of Compton scattering.
2. Investigate the Compton formula and characterize the angular dependence of Compton scattering.
3. Coincidence detection and handling by the Vireo digitizer by SkuTek.
4. Offline processing of the collected event files.

The γ-Ray Source

Cesium-137 (^{137}Cs) in the form of 5 micro Curie sealed exempt calibration source

- Half-life: 30.17 years
- Primary gamma energies:
    - 662 keV (85% emission probability per decay)
    - Barium X-ray K lines, about 32 keV
    - Barium X-ray L lines, about 5 keV
- Decay mode: β^- decay to ^{137m}Ba, followed by gamma emission with 2.5 min half life
- Reference: Idaho National Lab gamma-ray catalog

Data Acquisition System: FemtoDAQ Vireo by SkuTek Instrumentation:

2 channels, 14 bit ADC, 100 MHz sampling frequency, +/- 1 volt input range.

In this set of measurements we used its built in multichannel analyzer MCA histogramming mode. We also used the built-in coincidence detection and handling which we recently added to the Vireo firmware. This recent addition enabled us to avoid the classic NIM coincidence electronics.

Detection System:

- 2 x Scionix NaI(Tl) detectors from Ebay with combined signal and HV.
- 2 x High Voltage power supplies for both detectors.
- 2 x iRad Labs high voltage splitter box, from their online store on Ebay.

All experiments used the following settings on the Vireo (unit ID = 20). Prior to the measurements we adjusted the following parameters for the best results.

Coincidence Window	: 10 (=100ns)
Pulse Height Window	: 100 (=1μs)
Trigger Mode	: Multiplicity
Multiplicity Required	: 2
Pulse Height Averaging Window	: 8 (= 80ns)

Digital Offset Channel 0	: 620
Digital Offset Channel 1	: 630
Analog Offset (Both Channels)	: 0
Trigger Sensitivity (both channels)	: 16 samples. Note: trigger is differential.
Trigger Averaging (both Channels)	: 8 samples.
Trigger Edge (both channels)	: Rising
Histogram Scaling (both channels)	: 2
Histogram Quantities (both channels)	: Pulse height
Invert ADC Signal	: ☑
Require Coincidence Between Channels	: ☑
Termination Setting on Input (Both Channels)	: 1 kΩ
Total events recorded per experiment	: 100,000

Voltage to Detector #0 Channel 0: 883 V. The voltages were chosen to match the PMT gains.
Voltage to Detector #1 Channel 1: 872 V

As explained in the book by Glenn Knoll, the 1 kΩ input termination serves to increase the duration of the PMT pulses, and to boost their amplitudes without using an active amplifier. This classic trick works by storing the charge on internal capacitances, and slowly discharging them via the 1 kΩ resistor. One has to use a short coax cable (about 1 meter) to avoid ringing and pulse reflections.

Setting up the experiment

The setup sequence was executed using the web GUI presented by the instrument, shown in the next page. The entire process of setting up and tuning the experiment took us about two hours. This included trouble shooting the apparent lack of one of the signals, caused by a faulty cable connector.

The following parameters were adjusted with the GUI before running the experiment. The values below correspond to the screen shot shown in Figure **4** on page 5.

1. Multiplicity = 2, meaning "coincidence between both channels within the Coincidence Window".
2. Coincidence Window = 10 samples, meaning 100 ns.
3. Pulse Height Window = 50 samples, meaning 500 ns from the trigger. (One can also choose 1 μs.)
4. Pulse Height Averaging = 8 samples. Valid values range from 4 to 16.
5. Invert ADC Signal in order to deal with positive pulses for histogramming.
6. Trigger Averaging = 8 samples, meaning 80 ns.
7. Trigger Enable in both channels, with rising edge in both (a valid setting after inverting the ADC).
8. Trigger Sensitivity: between 6 to 16 (i.e., 0.7 to 2 mV). Note: trigger is differential.
9. Histogrammed Quantities = Pulse Height in both channels, with binning = 2 to increase the range.
10. Digital Offsets = 620 (channel 0) or 630 (channel 1) to move the baselines slightly above zero.

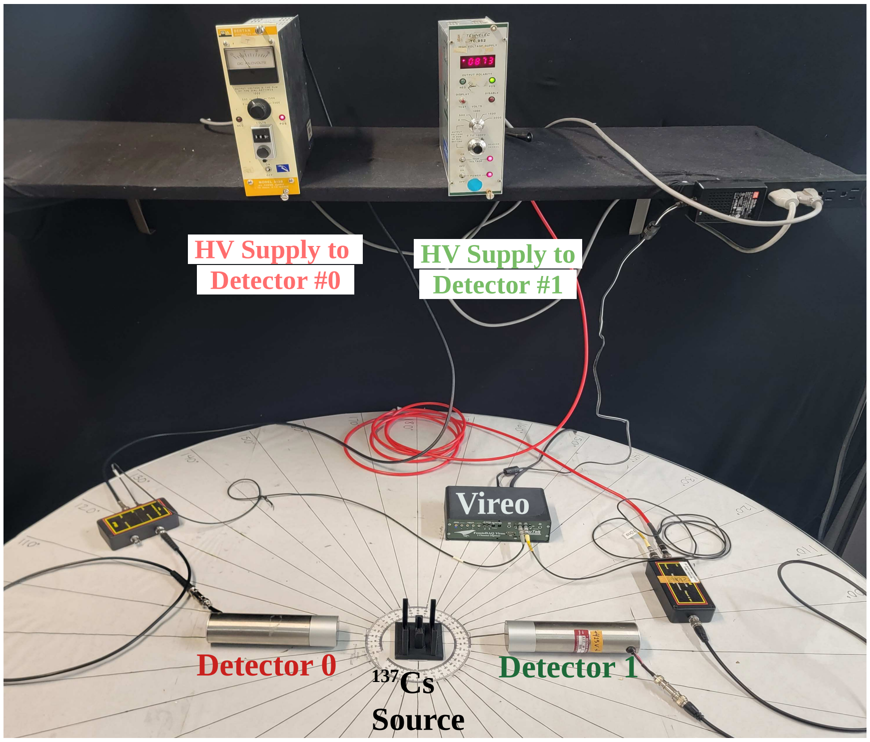

Figure 3: The complete experimental setup configured for the Compton back scattering at 180 degree, from detector #0 to detector #1 at 180 degrees. NIM electronics was not used. All triggering and pulse processing were performed using Vireo. The same experimental setup was used for the other configurations, except the relative position of detector #1 was later changed relative to detector #0 serving as an active target.

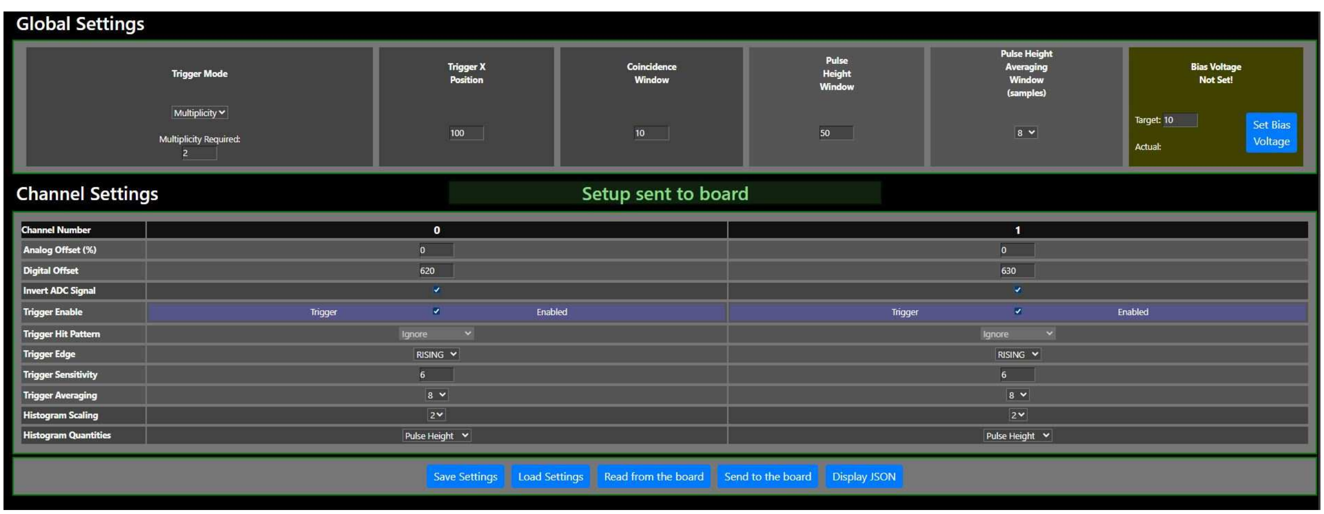

Figure 4: Web GUI of the Vireo digitizer served with "Ethernet over USB".

Pulse shapes and the online "singles" histograms.

Since the coincidence mode acquisition takes a long time (small solid angles!), we first tested the operation of our setup.We collected waveforms in both the singles and the coincidence modes. Then we collected the real-time histograms in singles mode. Thanks to a very convenient GUI, we could optimize the settings and quickly adjust the detector's HV to match their PMT gains. NB, after a few days of running the detectors drifted out of alignment, probably due to the self-heating of the HV dividers.

We verified in the left panel of this figure that Peak Height Window of 500 ns was adequate for NaI(Tl) pulses, but then we switched to 1 µs to measure the maxima with a sufficient timing margin.

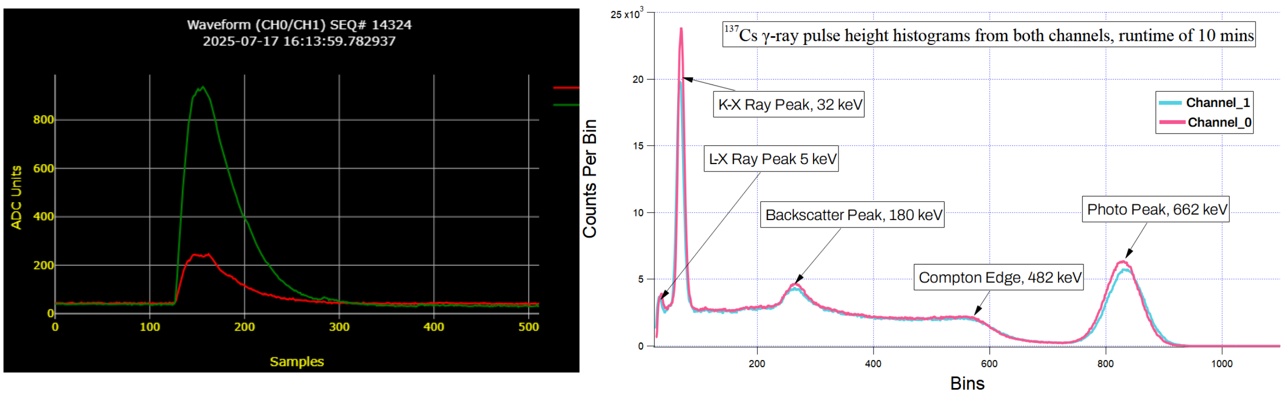

Figure 5. Left: typical NaI(Tl) waveforms collected in the coincidence mode. Right: Real-time ^{137}Cs gamma spectrum gathered in one of the previous experiments using Vireo's built-in MCA firmware - no external electronics required. The detector bias was adjusted in order to match the pulse heights in both channels shown as blue and pink histograms

Experimental Results

1) Compton back scattering in colinear geometry (back-to-back detectors, Fig. 3)

When detector #1 is placed at 180° from detector #0, the back scattered photon transfers the maximum energy to the electron. The energy of the back scattered photon can be calculated as:

$$hv' = \frac{662}{1+\frac{662}{511}(1-\cos 180°)} = 184.35\,keV$$ Photon back scattered from detector #0 to detector #1.

$$662\,keV - 184.35\,keV = 477.65\,keV$$ The coincident electron scattered into the detector #0.

The backscatter peak should appear at 184.3 keV in detector #1 and the corresponding Compton edge would appear at 477.6 keV in detector #0. Since the same process can happen in reverse, we expect that two peaks, the Compton edge and the backscattered photon peak, will appear in both detectors. This is demonstrated in Figure 7 on the next page.

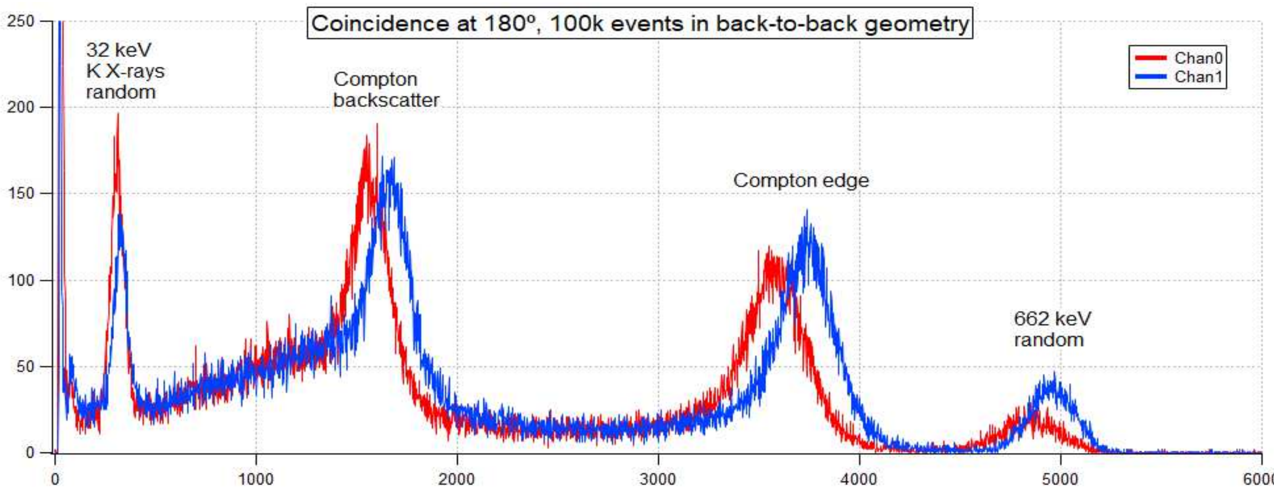

Figure 7: Histograms obtained from Vireo's MCA coincidence mode for the back-to-back geometry. The Compton edge peaks are around X=3500. The Compton back scatter peaks are close to X=1500. The HV's in both detectors were adjusted to match their responses to γ radiation. The gains went out of alignment after a few days of running, probably because of the self-heating of the HV voltage dividers.

1.1) Detector Calibration

We performed detector calibration using a linear equation *energy = a*bin + b*, using the centroids of the 662 keV photo peak and the 32 keV X-ray peak. We used the coincidence histograms for that, because the 32 keV and 662 keV peaks were present due to the random coincidences leaking into the spectra.

Detector	Peak centroid	Energy keV
0	309.41	32
1	326.15	32
0	4842.0	662
1	4955.6	662

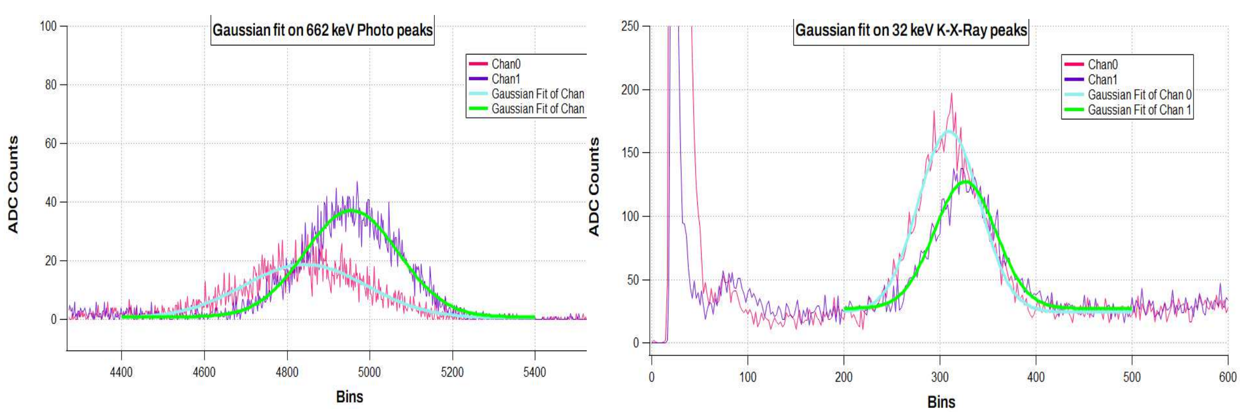

Figure 8: Gaussian fits of the 662 keV photo peaks (left) and 32 keV X-rays (right).

We can calculate the linear equation using the formula: *energy = a*ADC + b.*

Detector 0

$a_0 \times 309.407 + b_0 = 32$ keV $a_0 \times 4842.96 + b_0 = 662$ keV

Solving we get $a_0 = 0.1389$ and $b_0 = -11.0$

Channel 0 linear response function : energy (keV) = 0.1389 × (histogram position) – 11.0

Detector 1

$a_1 \times 326.153 + b_2 = 32$ keV $a_1 \times 4955.63 + b_2 = 662$ keV

Solving we get $a_1 = 0.1360$ and $b_1 = -12.38$

Channel 1 linear response function: energy (keV) = 0.1360 × (histogram position) -12.38

1.2 2D Correlation Plot with the Colinear 0 / 180^{o} Geometry

We generated the 2D correlation plots from the event files recorded with Vireo and then processed using Igor, available from www.wavemetrics.com. Our Igor data analysis scripts are available on request. We observed the following 2D coincidence plot.

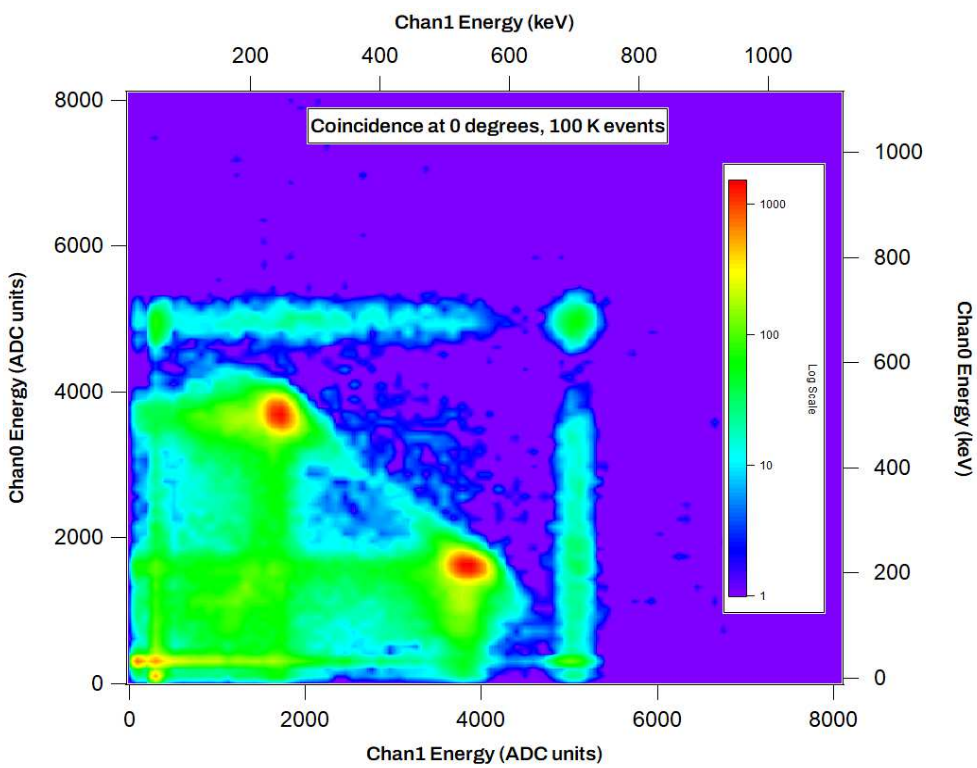

Figure 9: The Compton edge and back scatter peaks can be seen as the red clusters of high intensity, positioned on the anti-diagonal due to energy sharing. The vertical (or horizontal) event bands at X or Y around 5000 are due to random coincidences. We used them for detector calibration.

We observe the back-scatter peak at 1657 in channel 1 and the Compton edge at around 3573 for channel 0. Energy calibration used the values from section 1.1.

Back scatter peak in channel 1		Compton edge peak in Channel 0	
Predicted (keV)	Measured (bin value)	Predicted (keV)	Measured (bin value)
184.35 keV	212.96 keV (bin 1657)	477.65 keV	485.29 keV (bin 3573)

The measured energies of the backscatter peak and the Compton edge add up, as follows.

Back scatter in detector 0 + Compton edge in detector 1: 212.96 + 485.29 = 698.25 keV.

This value does not let us claim that we have quantitatively proven the energy conservation in Compton scattering. The resolution of our detectors does not permit such a quantitative claim. All that we can say is that we have shown the energy conservation "at the qualitative level".

The anti-diagonal pattern in Figure 9 and subsequent figures provides additional insights into how the energy is partitioned in Compton scattering. When a gamma ray Compton scatters at 180° (well defined backscatter), the Compton formula predicts a specific energy split:

- The scattered photon carries a fraction of the original energy (the smaller portion)
- The recoil electron absorbs the remaining energy (the larger portion)
- These two energies should add up to the original gamma ray energy (662 keV)
- Since either detector can play either role, symmetric spots are seen on the plot

The anti-diagonal line represents this energy-sharing relationship: when one detector measures more energy, the other must measure correspondingly less, keeping their sum constant.

2) Compton scattering at 135^{o} detector angle (photo next page)

The energy of the photons scattered at 135^{o} can be calculated as:

#0 → #1 at 135 degrees *Remaining in #0*

$$hv' = \frac{662}{1+\frac{662}{511}(1-\cos 135°)} = 206.13\,keV \qquad 662\,keV - 184.35\,keV = 455.87\,keV$$

In the 135^{o} results we observe the back-scatter peak at 1837 in channel 1 and the Compton edge at around 3429 for channel 0, adding up to 703 keV, due to a poor resolution of our detectors.

Back scatter in channel 1		Compton Peak in Channel 0	
Predicted (keV)	Measured (bin value)	Predicted (keV)	Measured (bin value)
206.13 keV	237.45 keV (bin 1837)	455.87 keV	465.29 keV (bin 3429)

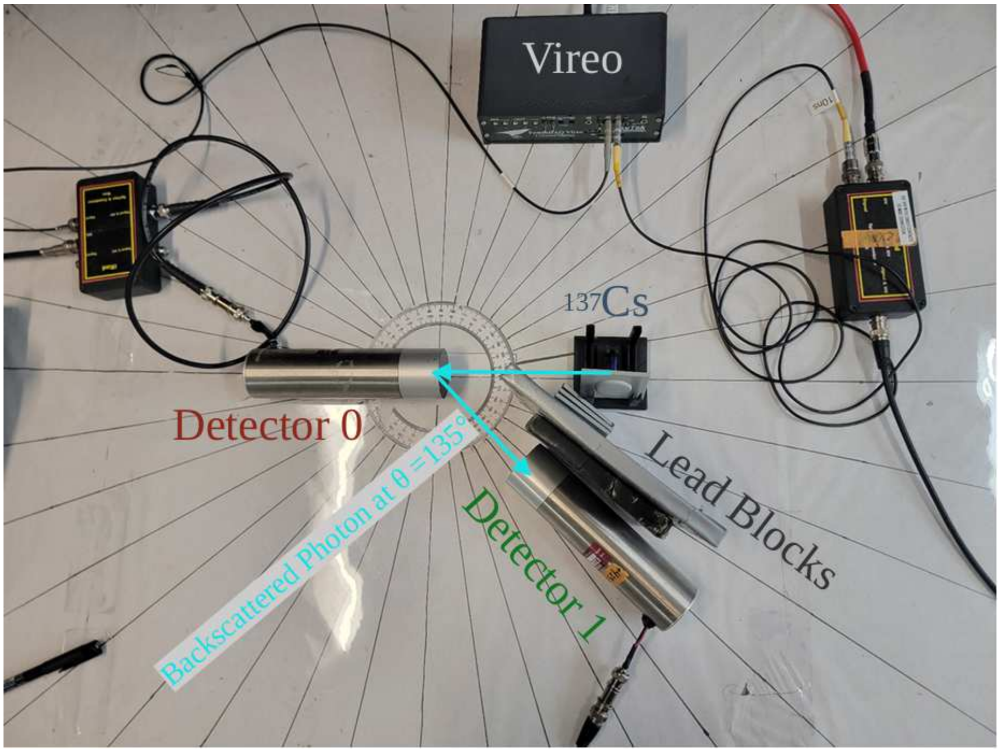

Figure 10: The experimental setup shows Compton scattering at 135 degree when the detector 1 is placed at 45 degrees from detector 0. Lead sheets were used to attenuate the gamma-rays from the source directly hitting detector 1.

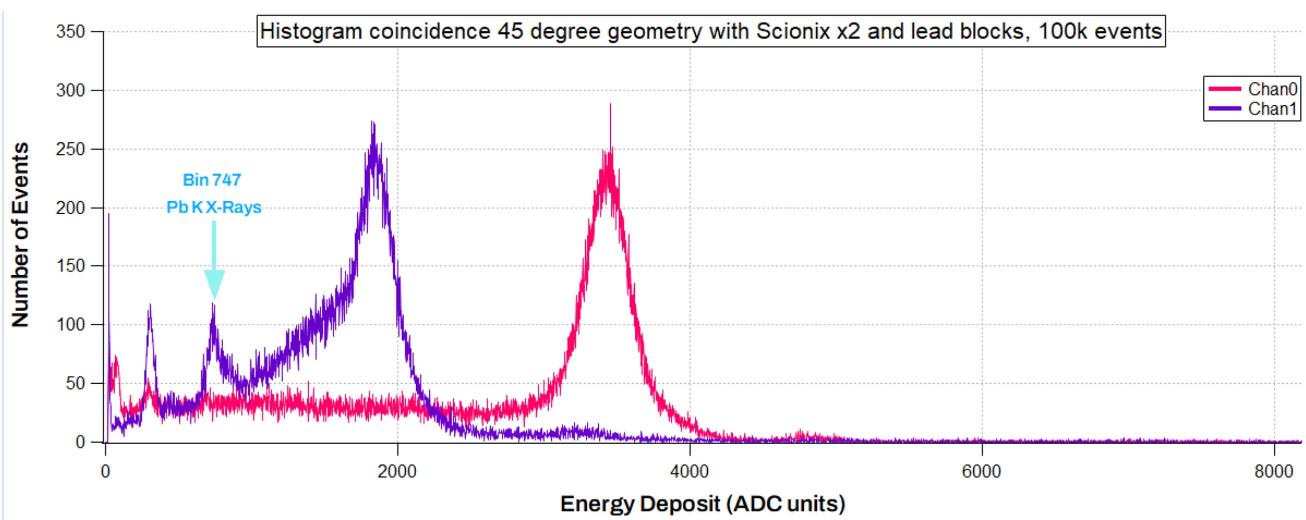

Figure 11: Histograms obtained from Vireo's MCA coincidence mode for the 135 degree geometry. An unexpected peak at X=747 most likely originates from characteristic K X-rays from the Pb shielding.

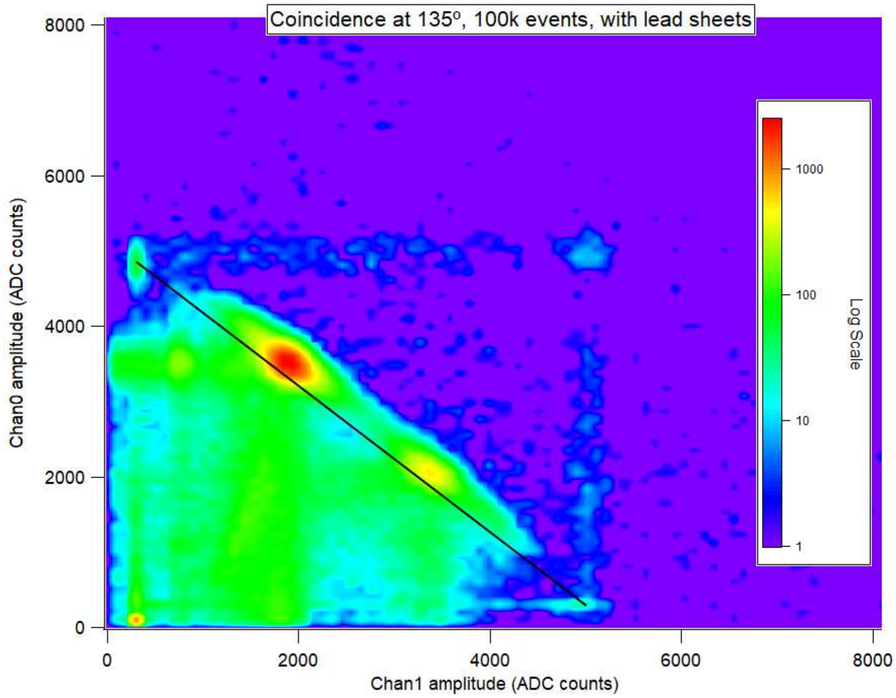

Figure 12: At 135^o the Compton edge and backscatter can be seen as the cluster of high intensity at (1837, 3429). The complementary anti-diagonal cluster was attenuated by the lead shielding. Its remnants are visible in the map at X ~= 3750. The antidiagonal line of 662 keV constant sum energy is shown in black.

It is interesting to note an unidentified peak in Channel 1 histogram at bin 747. We calculate the energy of the peak at bin 747 as follows:

0.136 × (747) -12.384 = 89.208 keV

This value is indicative of characteristic X-ray emissions of lead when excited by gamma rays:

- Pb $K_{\alpha1}$: ~75 keV
- Pb $K_{\alpha2}$: ~72 keV
- Pb $K_{\beta1}$: ~85 keV
- Pb $K_{\beta2}$: ~87 keV

Ref: X-Ray Fluorescence (XRF): Understanding Characteristic X-Rays, Amptek,

The 89 keV could be Pb K_β X-rays produced when 662 keV gammas from ^{137}Cs interact with the lead shielding. A K X-ray arises from a transition to the K shell from an outer shell. The K_β lines correspond to transitions from the M and N shells, with energies of 85 and 87 keV. The K_α lines arise from transitions from the L shells, with energies of 72 and 75 keV. This peak may be due to random events.

We added an antidiagonal line of constant energy *(chan0 + chan1) = 662 keV* in order to illustrate that the true coincidences between the detectors add to the original energy of the 662 keV γ-ray.

2.2 2D Correlation Plot at 135 Degree Backscatter

At 135 degrees we see a reduction of the energy of the Compton peak in Channel 0 and an increase of the energy of the back scatter peak in channel 1. The complementary peak, which was well visible in Figures **7** and **9**, here is strongly attenuated by the lead shielding. We conclude that the peaks have shifted in accordance with the Compton formula.

3) Compton scattering at 90° detector angle

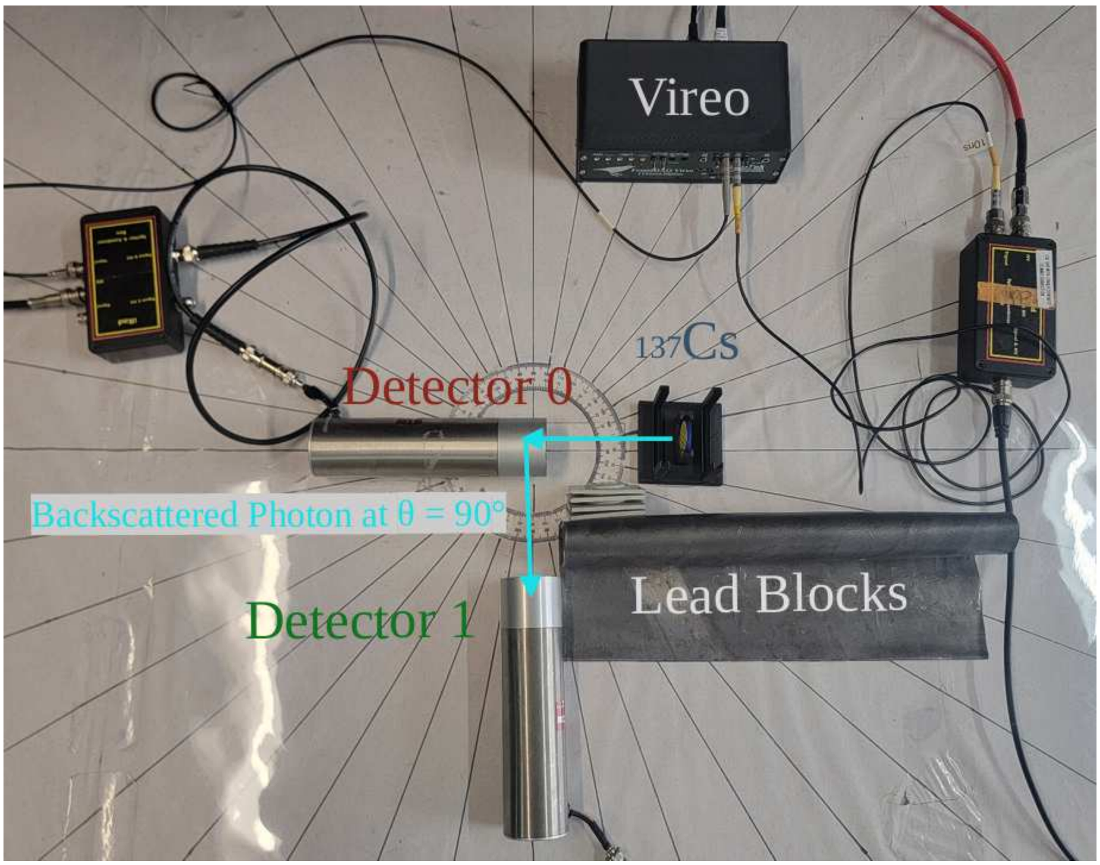

Figure 13: The experimental setup shows Compton scattering at 90 degrees when the detector 1 is placed at 90 degrees from detector 0. Lead sheets were used to prevent the γ-rays from the source from directly hitting detector 1.

The energy of the photon scattered from detector 0 to the detector 1 at 90 degrees can be calculated as:

#0 → #1 at 90 degrees　　　　Remaining in detector #0

$$hv' = \frac{662}{1+\frac{662}{511}(1-\cos 90°)} = 288.39\,keV \qquad 662\,keV - 288.39\,keV = 373.61\,keV$$

At 90 degrees we observe the back-scatter peak at 2392 in channel 1 and the Compton edge at around 2822 in channel 0. The energy calibration from section 1.1 yields the following table. The sum of the measured energies equals 312.9 + 381.0 = 693.9 keV, agreeing qualitatively with the expected 662 keV.

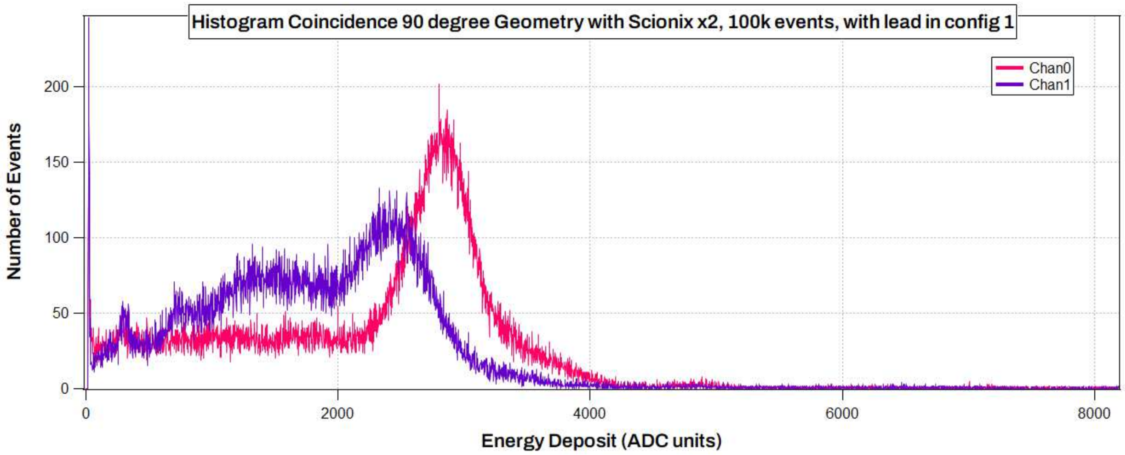

Figure 15: Histograms obtained from Vireo's MCA coincidence mode for the 90 degree scattering.

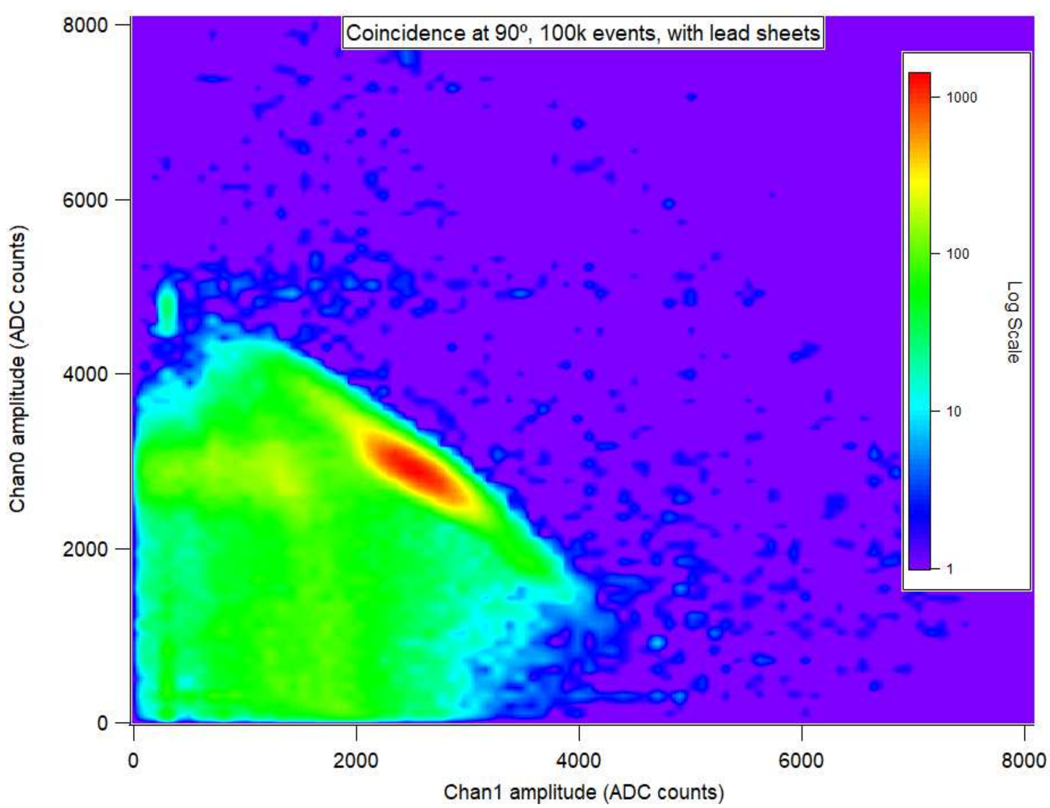

Figure 14: At 90 degrees, the Compton edge and backscatter components are so wide and close to each other that they merge to a single anti-diagonal band of high intensity. See the 1D histograms in the previous Figure to appreciate the degree of overlap between these two components.

3.2 1D and 2D Plots at 90 Degree Scattering (previous page)

In 1D plots we see a reduction in the energy of Compton edge peak in Channel 0 and an increase in the energy of the back scatter peak in channel 1 as predicted by the Compton formula. However, in the 2D plots these components are hard to tell apart because they are very wide.

4) Forward scattering at 45 degree detector angle

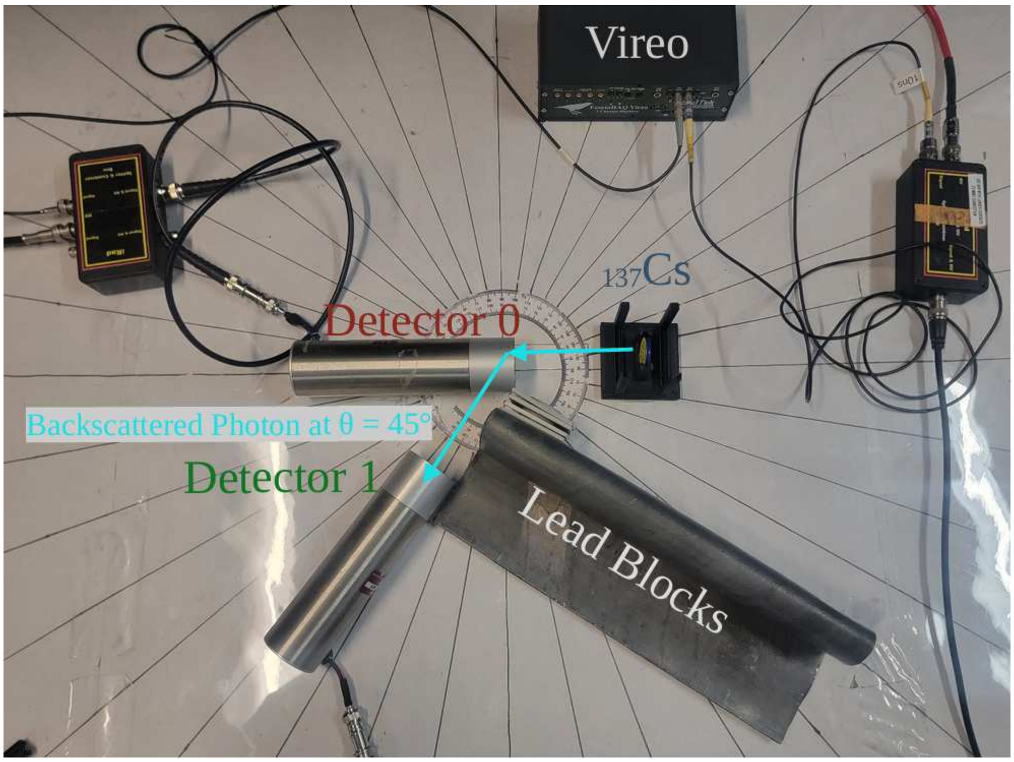

Figure 16: The experimental setup shows Compton scattering at 45 degrees when the detector 1 is placed at 45 degrees from detector 0. Lead sheets were used to attenuate the gamma-rays from the source directly hitting detector 1.

Forward scattered photon from the detector #0 to #1 at 45 degrees and can be calculated as:

#0 → #1 at 45 degrees | Remaining in detector #0

$$hv' = \frac{662}{1 + \frac{662}{511}(1 - \cos 45°)} = 479.90\, keV \qquad 662\, keV - 479.90\, keV = 182.1\, keV$$

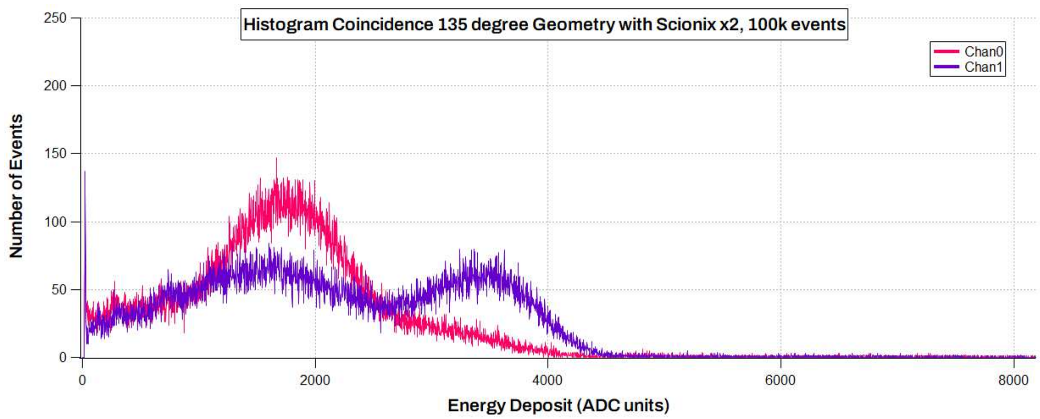

Figure 17: Histograms obtained from Vireo's MCA coincidence mode for the 45^o geometry. The broad peak in channel 1 at X = ~1500 may be due to insufficient shielding with lead sheets.

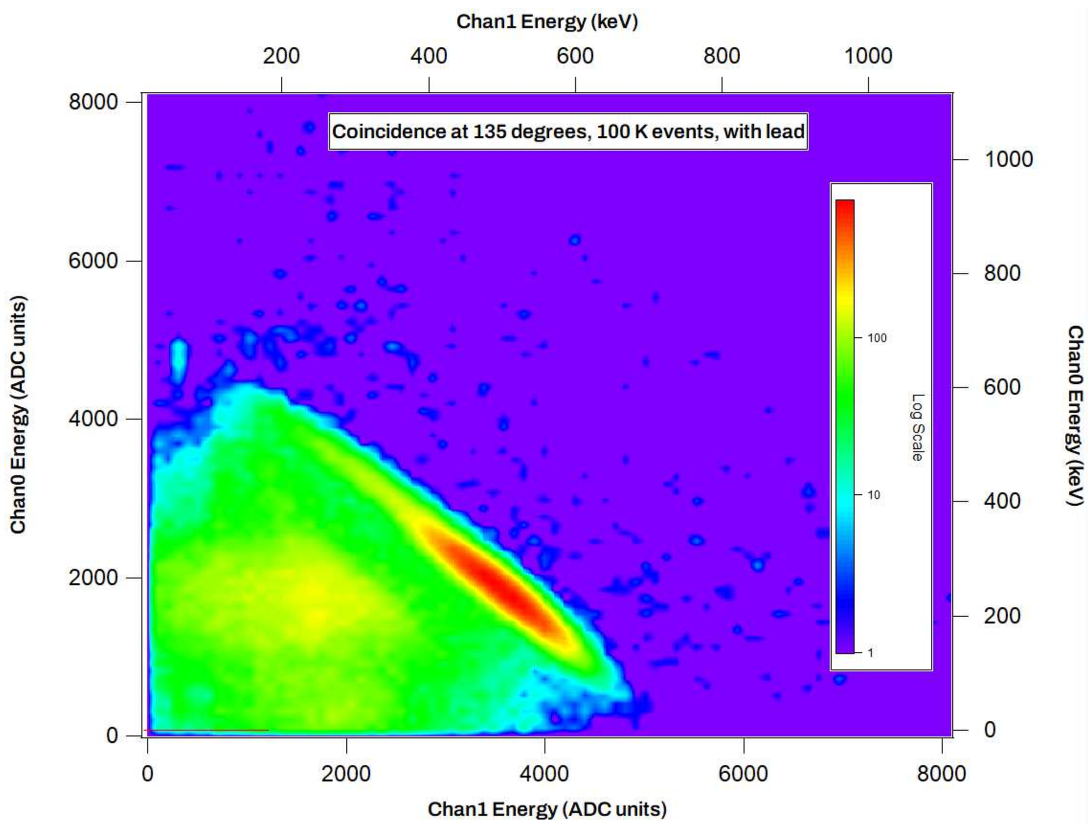

Figure 18: At 45 degree forward scattering, the Compton edge and side scatter peaks merged into a wide antidiagonal band due to a poor definition of the scattering angles.

At 45 degrees forward, we observe the forward scatter peak at 3402 in channel 1 and the Compton edge at around 1719 for channel 0. The energy calibration yields 450.3 + 227.8 = 678.1 keV.

Back scatter in channel #1 at 45° forward		Compton edge in Channel #0	
Predicted (keV)	Measured (bin value)	Predicted (keV)	Measured (bin value)
479.9 keV	450.3 keV (bin 3402)	182.1 keV	227.8 keV (bin 1719)

We conclude that despite the poor resolution and large widths of the NaI(Tl) peaks, the agreement with the predicted energy split is quite remarkable.

Comparing the observation with the theory in a single plot

Angle of Detector 1 w.r.t detector 0	Back scatter peak in detector 1		Compton peak in detector 0	
	Predicted (keV)	Measured	Predicted (keV)	Measured
0° (θ =180°)	184.4	1657 (= 213.0 keV)	477.65	3573 (= 485.3 keV)
45° (θ =135°)	206.1	1837 (=237.4 keV)	455.87	3429 (=465.3 keV)
90° (θ =90°)	288.4	2392 (=312.9 keV)	373.61	2822 (=381.0 keV)
135° (θ =45°)	479.9	3402 (=450.3 keV)	182.1	1719 (=227.8 keV)

Figure **19** (next page) is showing that the energies of the predicted and observed scattering peaks agree remarkably well. The discrepancies can be attributed to the large width of the peaks, caused by the wide ranges of scattering angles (due to substantial solid angles subtended by both detectors).

In most cases, the energy of the observed back scatter peak is higher than the prediction. It is lower than the predicted value only at the 135° geometry. Discrepancies between the measured and predicted values indicate that the effective scattering angle could be weighted towards other-than-center angles due to the size of the detectors. A full analysis would call for Monte Carlo simulations.

Conclusion:

This experiment successfully demonstrated the phenomenon of Compton scattering and validated the fundamental relationship between scattering angle and scattered photon energy as predicted by energy and momentum conservation. Using a ^{137}Cs gamma-ray source (662 keV) and two NaI(Tl) scintillation detectors with coincidence detection, we measured scattered photon energies at four different angles: 0°, 45°, 90°, and 135°.

Observed agreement with the Compton Formula: The results showed substantial qualitative, though not quantitative agreement with theoretical predictions. The observed energy distributions demonstrated the expected inverse relationship between scattering angle (θ) and scattered photon energy.

•

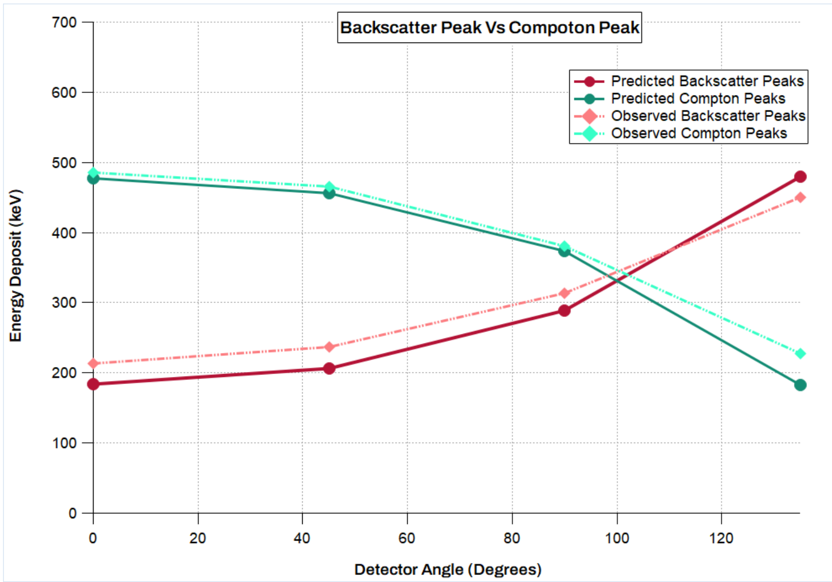

Figure 19: Backscatter and Compton edge peak positions predicted by the Compton formula and the ones observed with Vireo and calibrated NaI(Tl) detectors

Coincidence Detection Effectiveness: The 100 ns coincidence window combined with the use of lead sheets successfully isolated true Compton scattering events from random background radiation. The systematic variation of peak positions with angle, along with the clear identification of both backscatter and Compton edge peaks, demonstrates that the coincidence technique effectively filtered out uncorrelated events.

Event file analysis: We demonstrated that Igor from www.wavemetrics.com is a very efficient event processing tool for a table top experiment of moderate complexity. Igor produced all plots shown herein.

Angular Dependence: The experiment clearly showed that as the detector angle increased from 0° to 135° (scattering angle decreases from 180° to 45°), the energy of the scattered photon increased progressively. This monotonic relationship confirms the energy-momentum conservation principles underlying Compton scattering. The complementary increase in the backscatter peak energy in detector 1 further validates that the energy lost by the photon is transferred to the recoil electron.

Calibration of Detectors: The observed bin positions when calibrated with a linear response function derived using the photopeak and K-X-ray peaks of ^{137}Cs produced the correct directional trends when compared to predictions made by the Compton formula.

X-Ray Fluorescence of Lead Shielding: Pb K_β X-rays were detected when the lead shielding was placed very close to the ^{137}Cs source and the detectors. Random coincidences were the most likely mechanism of why the lead X-rays leaked into the histograms.

Overall, we demonstrated how Vireo can be used as a complete experimental system without using any additional electronics other than the HV supplies for the NaI(Tl) phototubes. Thanks to a high integration of this system, setting up the experiment took less than two hours.

Appendix A. The format of the event file.

We adopted the simplest possible concept and developed a very simple event file format. The events are processed in firmware. The Pulse Height Window is started by the trigger. The peaks of the pulses are found during the Pulse Height Window, effectively turning the device into a 2-channel Multi Channel Analyzer (MCA). The events are written to a file when both channels triggered (coincidence level = 2). Each event consists of three numbers: the time stamp in clock ticks, and two values of the pulse heights. Since the event rates are low due to small solid angles, we could afford to write the events in ASCII. Such a file can easily be processed with any software. We chose Igor for this purpose because of its high quality graphics. The “analysis” is a big word for plotting the X-Y matrix (the scatter plot). Such plots were sufficient to show the present results. We are currently developing a very simple Python utility for generating the same kind of plots using Python.

In addition to just the numbers, the event file recorded some control information shown below. All these extra items are treated as comments under Igor.

```
IGOR
X // Datetime        = "UTC Time: 2025-10-23 16:16:34"
X // GlobalID        = 0
X // Product         = "VIREO100_REV_B"
X // SerialNumber    = "000020"
X // SoftwareVersion = "5.5.6"
X // FirmwareVersion = "5.5.4"
WAVES/o/D timestamp, chan0, chan1
BEGIN
67268478325959 29 2848
67268533920930 3422 1829
67268563270330 2939 3577
67268745792282 23 3211
67268766348986 3627 749
67268791689175 367 658

.. continues for 100k lines

END
```

In addition to the ASCII format, the instrument can also write the same information in binary. We would have used binary if we planned to record millions rather than thousands of events. Another option, not used in these experiments, is to write the waveforms. We provide both the ASCII format for a small number of waveforms, or binary format if the number of waveforms is large.

Finally, the instrument can save the on-board histograms shown in Figure 1. We saved them and then reploted under Igor. Any other graphics software can be used for this purpose, for example gnuplot.