GMA - Gamma Ray Spectroscopy

Physics 111B: Advanced Experimentation Laboratory

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Abstract

The Gamma Ray Spectroscopy experiment examines how gamma rays interact with matter. It uses a sodium iodide (NaI(Tl)) scintillation detector, a photomultiplier tube (PMT), and a pulse height analyzer (PHA). The experiment focuses on detecting gamma rays, calibrating equipment, and analyzing energy spectra. Key objectives include testing the inverse-square law for radiation, calculating the intensity of a radioactive source, and measuring the mass attenuation coefficients of different materials.

The experiment begins by calibrating the detector with known radioactive sources, the ones used in this experiment are in this table here:

Source	Energy (MeV)	Half-life
^{22}Na	0.511, 1.28	2.6 years
^{137}Cs	0.6616	30 years
^{60}Co	1.17, 1.33	5.2 years
^{54}Mn	0.84	312 days

The PMT converts light pulses from the scintillator into electrical signals proportional to the gamma ray's energy. The PHA processes these signals to generate energy spectra. We also evaluate the detector's efficiency, investigate the factors that influence peak formation, and measure system resolution. We will conclude by comparing the measured mass attenuation coefficients of aluminum, copper, and lead with theoretical values.

This experiment introduces the principles of gamma ray interactions, such as photoelectric absorption and Compton scattering. It provides practical experience with radiation detection, data analysis, and error evaluation, offering a deeper understanding of gamma ray spectroscopy.

Theory & Background

Gamma-ray spectroscopy allows us to study gamma rays, which are high-energy photons released during nuclear decay. This experiment measures gamma-ray energy levels to understand how they interact with matter and how to detect them using specialized equipment.

Radiation

Gamma rays are a type of ionizing radiation that can pass through most materials (which is why all sources here are stored in thick lead pigs). Unlike alpha or beta radiation, gamma rays have no charge or mass, which makes them a lot more penetrating.

They interact with matter in three main ways:
Photoelectric Effect: A gamma ray transfers all its energy to an electron, ejecting it from the atom.
Compton Scattering: A gamma ray transfers part of its energy to an electron and changes direction.
Pair Production: A gamma ray converts into an electron and a positron near a nucleus.

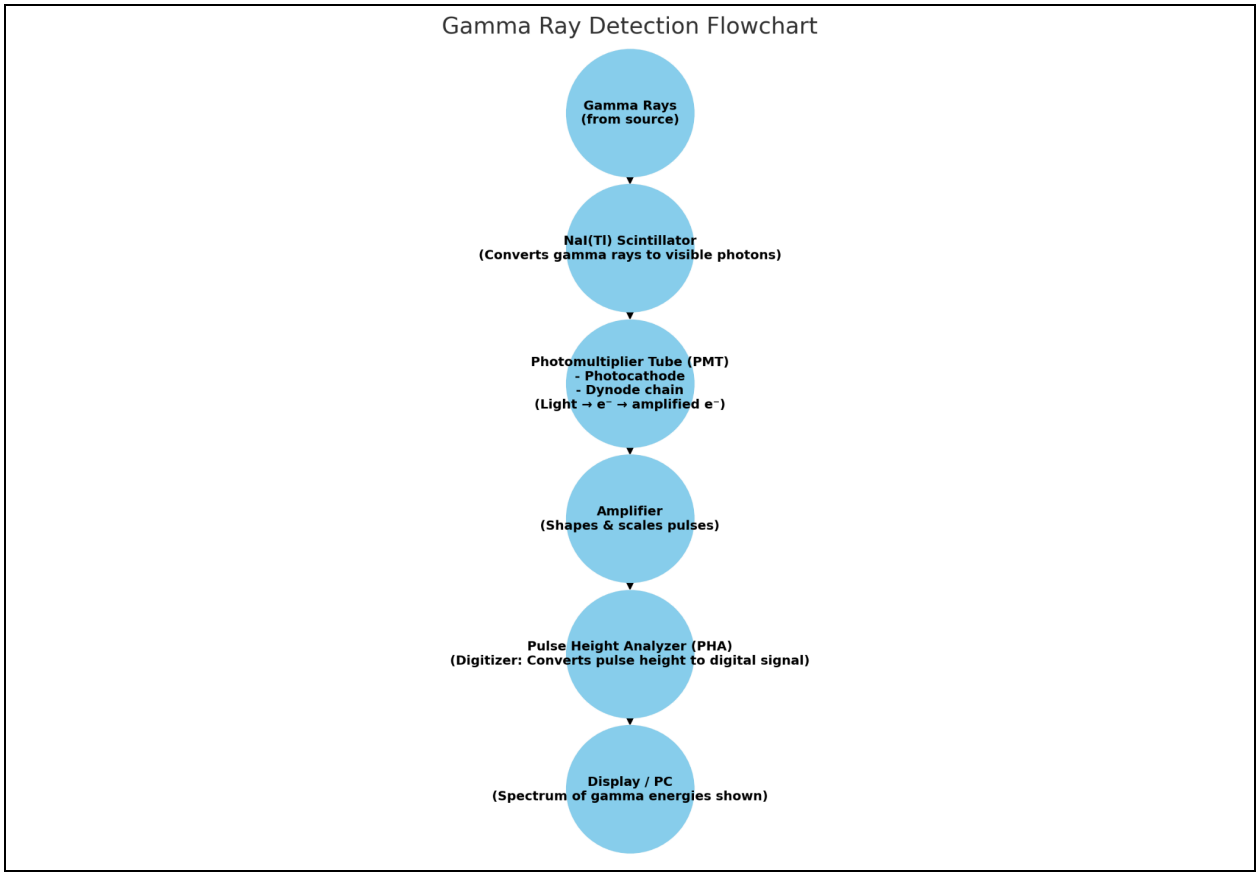
Detection and Amplification

The detection system uses a thallium-doped sodium iodide (NaI[Tl]) crystal and a photomultiplier tube (PMT). The theory behind this is when a gamma ray hits the crystal, it produces visible light. The light photons then travel to the PMT, where they strike the photocathode.

At the photocathode, the photoelectric effect converts light photons into electrons. These electrons enter the PMT, where they pass through a series of dynodes where each dynode is set to a higher voltage than the previous one. When an electron hits a dynode, it releases several secondary electrons. This process repeats at each dynode, multiplying the number of electrons exponentially, and by the time the electrons reach the final dynode, the signal becomes strong enough for us to measure.

The electrical signal from the PMT then goes into an amplifier. The amplifier increases the signal strength so the Pulse Height Analyzer (PHA) can sort the pulses by their height, which is proportional to the energy of the gamma ray. The PHA creates a spectrum showing the distribution of gamma-ray energies based on the peak voltage pulse height that was measured.

Circuit Overview



Gamma ray detection flowchart

We just went over this, but I made this flowchart because it was really useful to have nearby when trying to understand exactly what was going on in each part and how they connect.

Safety

Radiation poisoning is no joke so here are some things we kept in mind.

1. Always wear vinyl gloves when touching sources or containers, and remove them before using lab equipment.
2. Keep sources in the pigs when not in use.
3. Never place lead bricks on the edge of a table if dropped it could seriously cause a lot of damage.
4. Use the Geiger counter to check for residual radiation at the end of each lab session.
5. Always wear your radiation ring and badge.

(Note we also both completed the required training videos/tests for this lab)

Experimental Procedure & Results

**Note that all measurements for each gamma ray source will be the same in terms of the steps*

Setup and Preparation

1. Ensure the high-voltage power supply is connected to the PMT with the positive polarity selected.
2. Set the voltage to 780 V and allow a 15-minute warm-up for stabilization.
3. Place the 137Cs source inside the lead pig and position it 20–25 cm from the detector.
4. Connect the PMT output to an oscilloscope using a 50-ohm terminator on a BNC tee.
5. Observe the PMT output signal. Look for a faint pulse approximately 0.5 μs wide and -50 mV in amplitude.

Pulse Height Analysis (PHA)

1. Connect the amplifier output to the digitizer card input.
2. Use the PHA software to observe the gamma-ray spectrum.
3. Set the Lower Level Discriminator (LLD) to filter out low-amplitude noise while capturing meaningful pulses.

Calibration

1. Record the spectrum for 137Cs, identifying the photopeak at 0.662 MeV.
2. Repeat with 22Na and 60Co sources to observe additional photopeaks.
3. Use known gamma-ray energies to calibrate the PHA channel numbers to energy values.

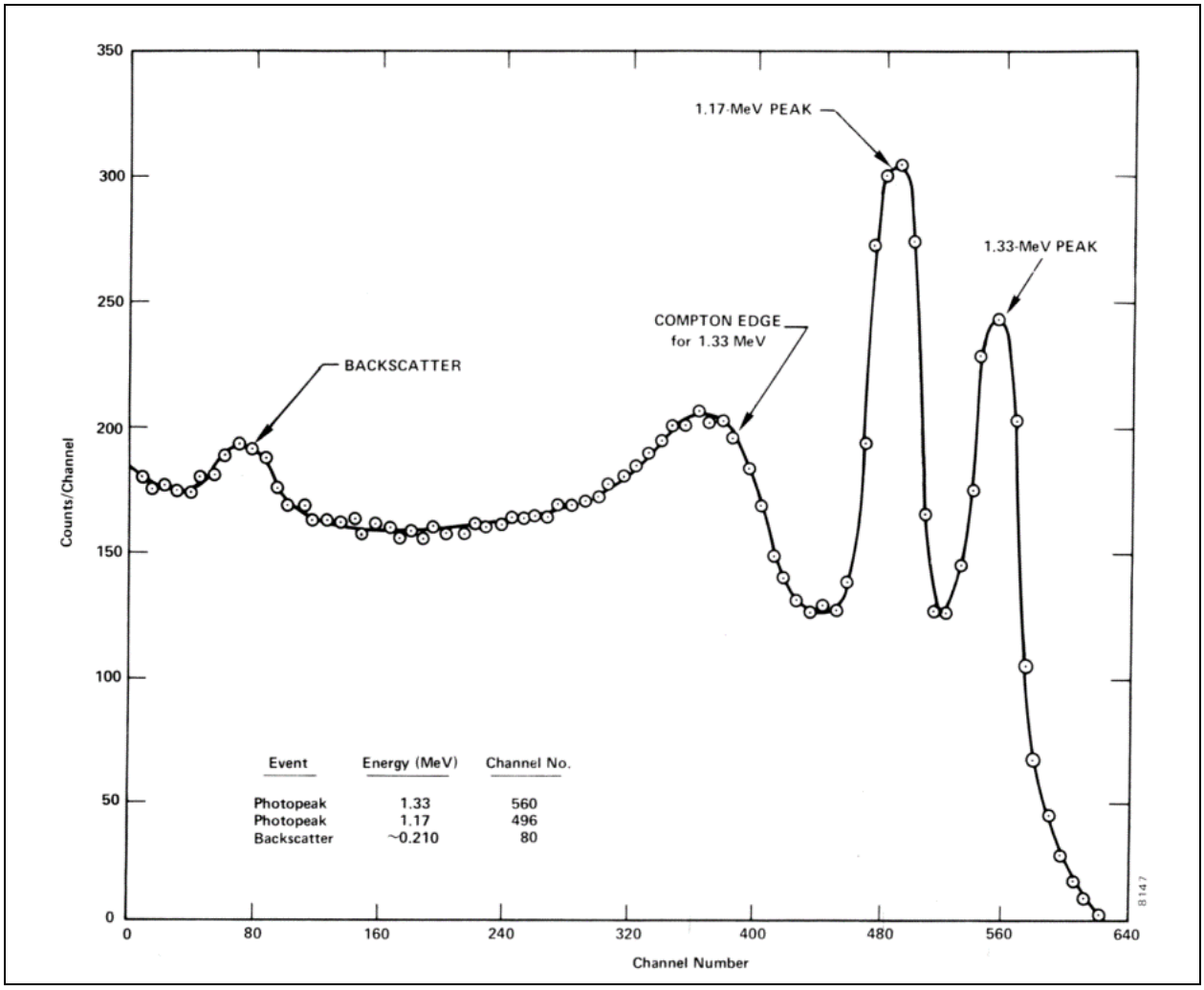
High Voltage and Gain Study

1. Vary the high voltage applied to the PMT from 400 V to 800 V in 10 V increments.
2. Then try to record the photopeak channel number at each voltage.
3. Finally we plot the relationship between high voltage and peak channel

Measurements

1. Measure the full-width at half-maximum (FWHM) of the photopeaks to evaluate the energy resolution.
2. Identify Compton edges, backscatter peaks, and calculate their corresponding energies.
3. Measure the count rate at various distances from the source, maintain alignment with the detector and then confirm the inverse square law based on the data.
4. We will then place absorbers (e.g., Al, Cu, Pb) between the source and detector.
5. Record the transmitted intensity for gamma rays at different absorber thicknesses.
6. Calculate the mass attenuation coefficient for each material and compare to theoretical values.

Analysis



Features in the gamma ray spectrum to look
https://www.nuclear-power.com/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-gamma-radiation-matter/compton-scattering/compton-edge/

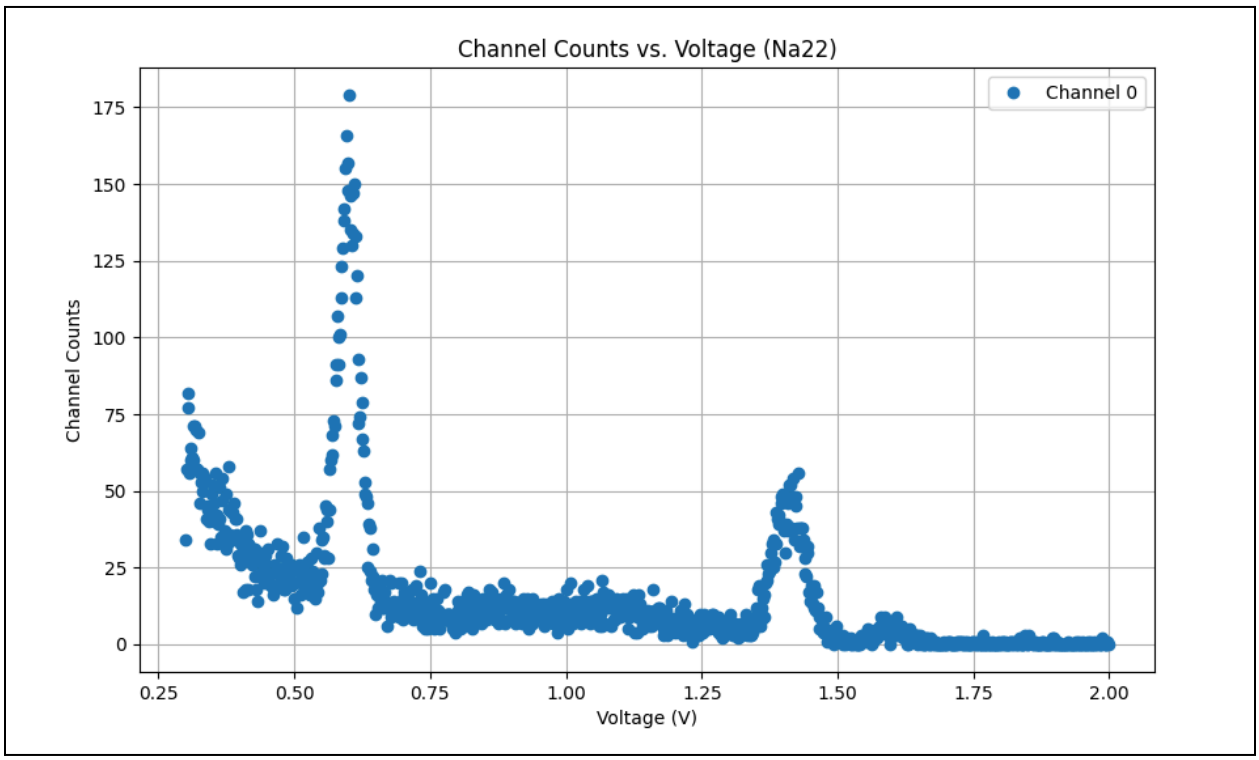
One more side note before going into our actual full data, in the figure, it points out the features that we are looking for which are

1. Backscatter peak: A low-energy peak caused by gamma rays scattering off materials (like detector walls or honestly even air here) and re-entering the detector.
2. Compton edge: The maximum energy transferred to an electron in Compton scattering, appearing as an edge in the spectrum, since compton scattering has a maximum amount of energy it can transfer (when the photon scatters 180°-directly backwards)
3. Photopeaks: Peaks in the spectrum corresponding to the full energy absorption of gamma rays through the photoelectric effect.

A. Energy Calibration

So our raw data here is given in channel counts vs voltage,

I used python to plot channel0 counts vs voltage below:



Peak 1 value: 179 at Voltage 0.600488 V

Peak 2 value: 56 at Voltage: 1.4272 V,

Known Energies for Na-22:

• 511 keV (annihilation line)

• 1274 keV (high-energy gamma line)

Measured Voltages for Na-22:

For the 511 keV peak: $V_1 = 0.600488$ V

For the 1274 keV peak: $V_2 = 1.4272$ V

We assume a linear relation:

$E(keV) = a \cdot V + b$ Using the two known points $(V_1, E_1) = (0.600488\text{ V}, 511\text{ keV})$ and $(V_2, E_2) = (1.4272\text{ V}, 1274\text{ keV})$:

Compute the slope a:

$a = (E_2 - E_1) / (V_2 - V_1) = (1274 - 511) / (1.4272 - 0.600488) \approx 923.1$ keV/V

Compute the intercept b:

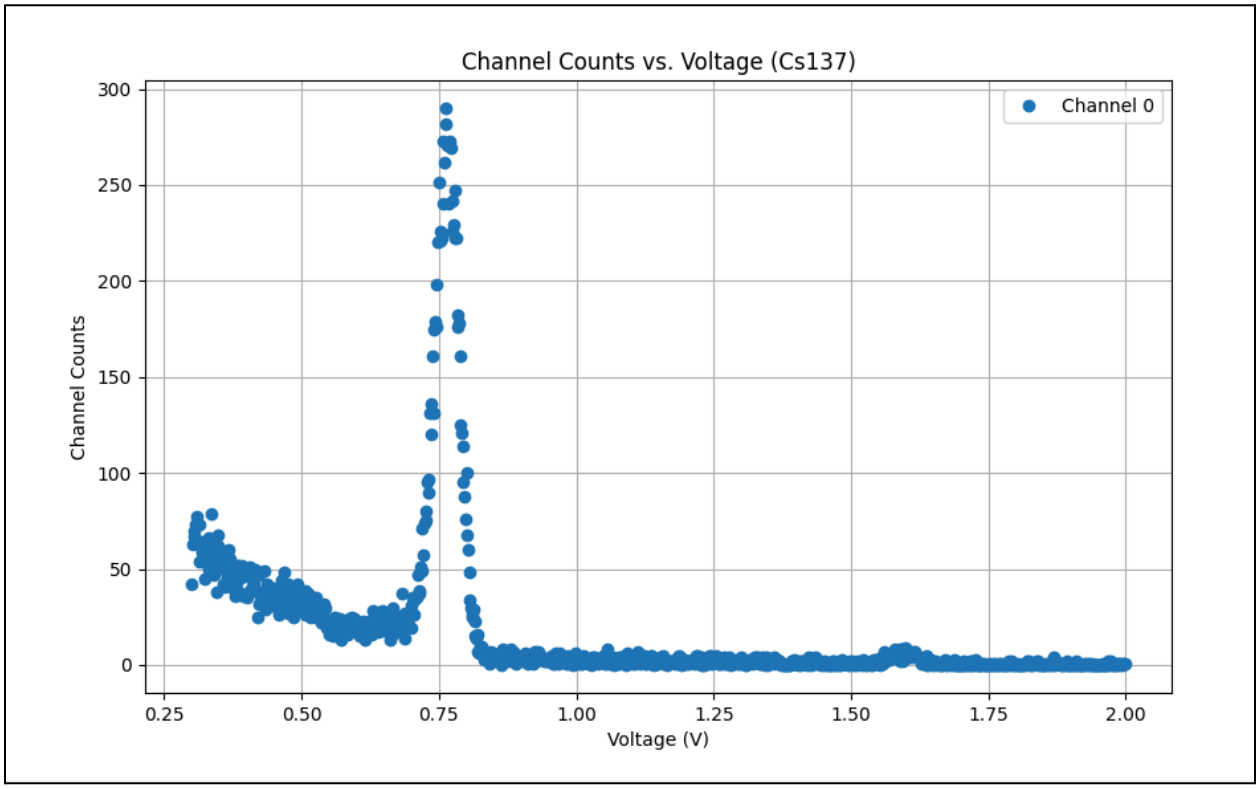
$b = E_1 - a \cdot V_1 = 511 - (923.1 \times 0.600488) \approx 511 - 554.3 = -43.3$ keV

Thus we get our Calibration Equation:

$E(keV) = (923.1 \pm 9\text{ keV/V}) \cdot V - (43.3 \pm 10)$keV

We can now use this equation to convert between our voltage values on our graph and energy (in keV)

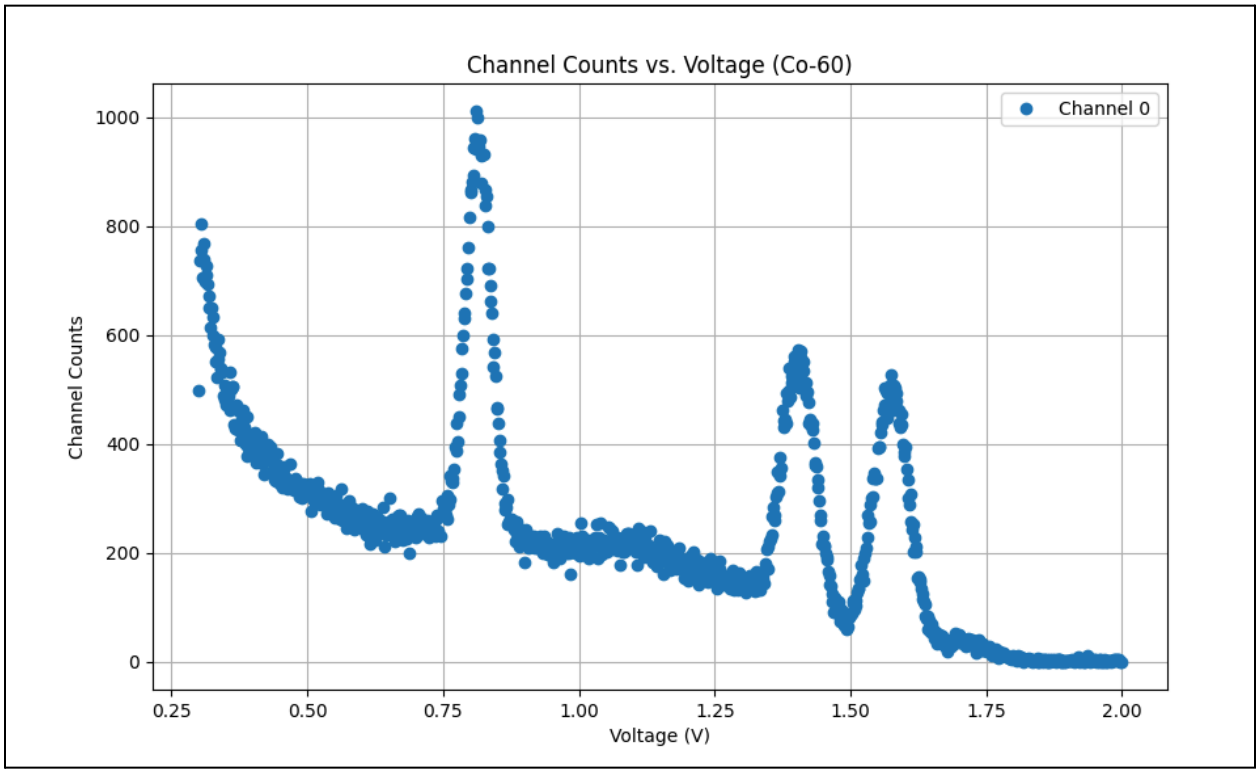
Let's check this equation with some other data we took:



Peak Channel 0 value: 290 at voltage 0.761523 V

Cs-137 Data:
Peak Voltage: $V_{Cs} = 0.761523$ V
FWHM (Voltage): $\Delta V_{Cs} = 0.0484$ V

Calculate the Cs-137 Peak Energy:
$E_{Cs} = 923.1 \times 0.761523 - 43.3 \approx 703.7 - 43.3 \approx 660.4 \pm 12$keV.
Note that the known gamma line here is supposed to occur at: 661.7 keV, *which means we have a pretty accurate measurement*



It's hard to see but anything before 1V are backscattered rays and the Compton edge is roughly at 1.10 Volts. The two measured photopeaks here are at 1.39072 Volts and 1.575 Volts.

Checking again with our equation calibrated by Na22:
For V1=1.39072 Volts
Calculated Energy: **1240.5 ± 16.0 keV**
Known Value: **1173.2 keV**
For V2=1.575 Volts
Calculated Energy: **1410.6 ± 17.3 keV**
Known Value: **1332.5 keV**

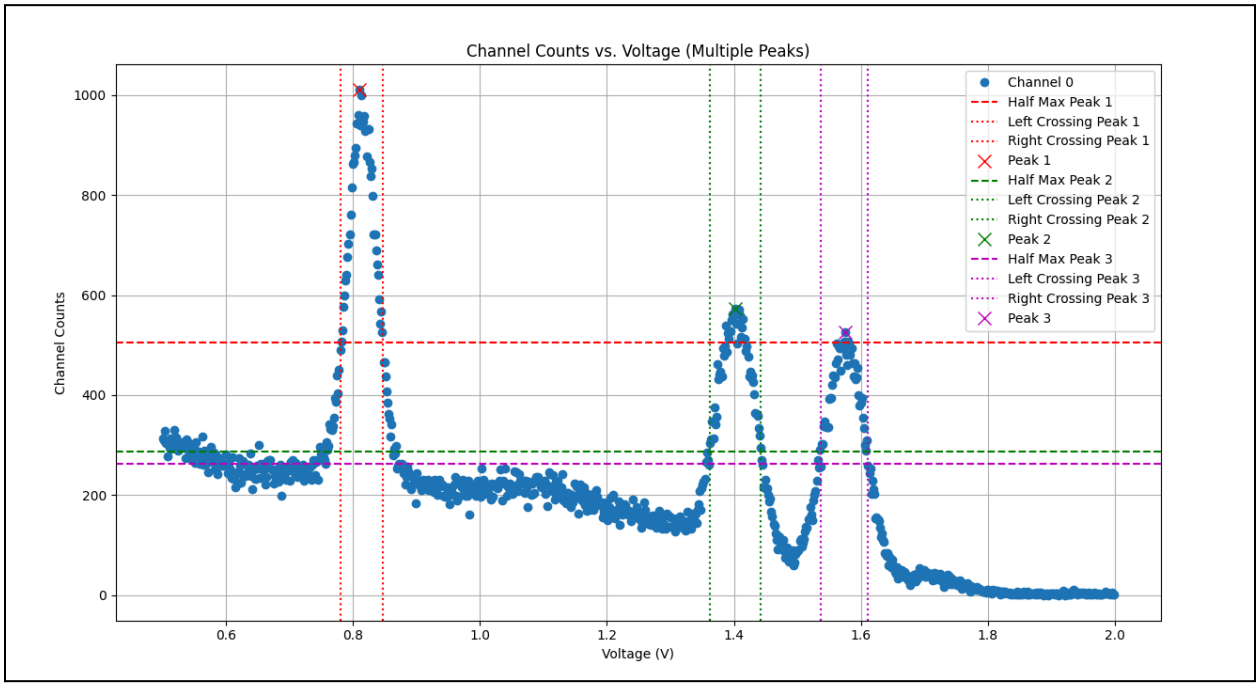
For this measurement why are both a slight overestimate of the known value?
In person at lab, when we measured Cobalt 60, I remember thinking the sample looks like it's too close to the detector, but when my lab partner mentioned it should be fine because the shape of the curve is what we are looking for I didn't think too much of it. Now when I look back, that was a massive oversight on my part, if the source is too close, of course it would be an overestimate. I believe this is due to one main reason:
1. Pulse pile-up:
When a gamma-ray source is placed very close to the detector, the detector receives a large number of photons per unit time. As a result, the detector and the electronic circuitry must

process much more signals in a shorter time span. Even if the detector's energy resolution is good, at very high count rates, the probability that two (or more) gamma rays interact within a single shaping or processing interval increases, which would shift the peak energies up.

The reason why I believe this to be the case for our data here is because both peaks are shifted up by roughly the **same** amount from the known value.
This also could explain why the backscatter peak was so damn high.

B. Resolution and Peak Analysis

I used find_peaks from scipy.signal and graphed the data for 60Co, we got:



We identified two photopeaks for Co-60 gamma rays at the following voltages and obtained their respective FWHMs from the data:

<u>Peak 2:</u>

Peak index: 543, Peak voltage: 1.4023 V, Peak value: 573

FWHM: 0.0809 V

<u>Peak 3:</u>

Peak index: 647, Peak voltage: 1.5750 V, Peak value: 526

FWHM: 0.0743 V

The voltage-to-energy calibration determined was:

E(keV) = (923.1 ± 9 keV/V) · V − (43.3 ± 10)keV

<u>Peak 2:</u>

Calculated Energy: **1240.5 ± 16.0 keV**

Converted FWHM: **74.7keV ± 0.73 keV**
Peak 3:
Calculated Energy: **1410.6 ± 17.3 keV**
Converted FWHM: **68.6keV ± 0.67 keV**

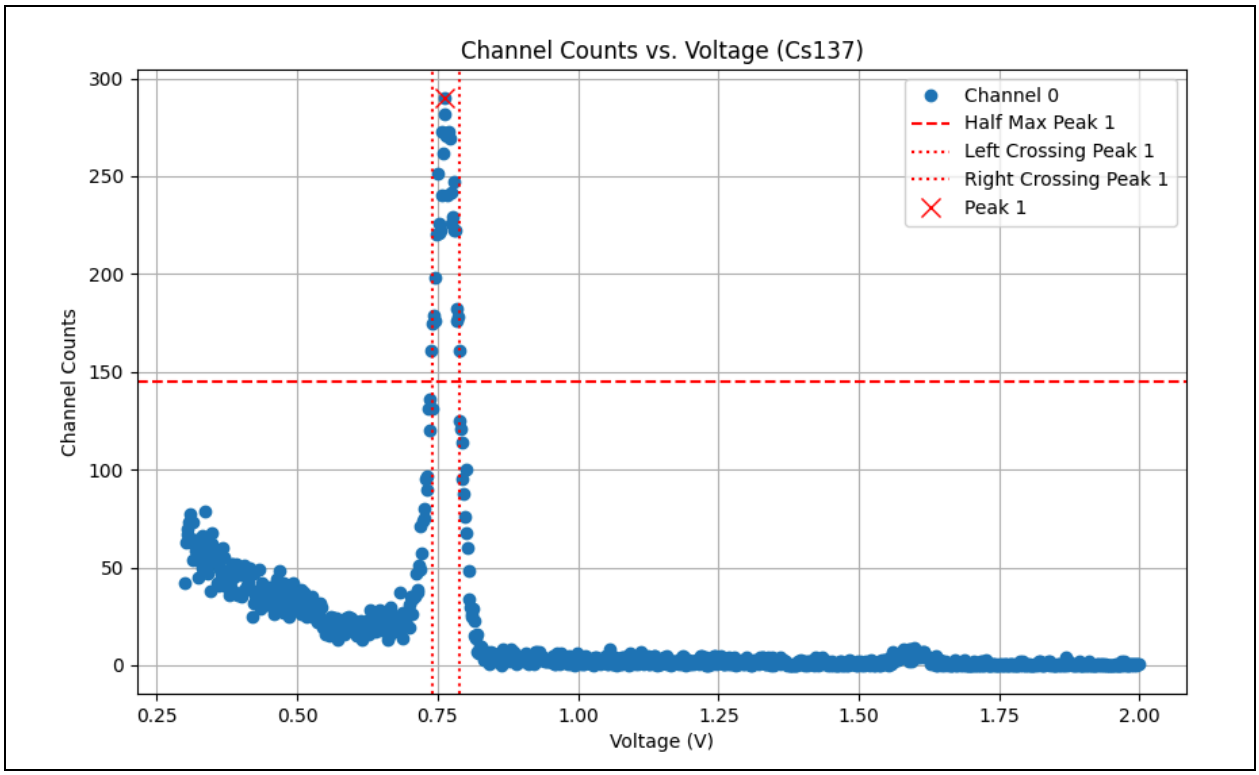
For Peak 2:
$\text{Resolution}_2 = 74.7\text{keV} / 1240.5\text{ keV} \times 100\% \approx 6.03 \pm 0.10\%$
For Peak 3:
$\text{Resolution}_3 = 68.6\text{ keV} / 1410.6\text{ keV} \times 100\% \approx 4.86 \pm 0.08\%$

Comparing with Typical NaI(Tl) Resolutions:
NaI(Tl) scintillation detectors typically achieve energy resolutions of about 5–10% at energies near 1 MeV. Our measured resolutions (approximately 6.03% and 4.8%) actually fall somewhat within this expected range, indicating that the detector and electronics are performing as anticipated.

**Note here are Factors that Might Broaden Peaks (since they are not delta functions):*
1. Statistical Fluctuations: The finite number of scintillation photons and photoelectrons introduces statistical noise in the measurement.
2. PMT Noise and Stability: Variations in photomultiplier tube gain and dark noise can contribute to peak broadening.
3. Electronic Noise: The amplifier and digitizer introduce additional noise, slightly increasing the observed line width.
4. Crystal Inhomogeneities: Variations in the NaI(Tl) crystal or in its doping can lead to non-uniform light collection, broadening the peaks.

Overall, our measured resolutions are consistent with expectations for a NaI(Tl) detector, and the peaks' widths can be explained here by intrinsic statistical variations and instrumental factors.

Now I will quickly go over the same metrics for the other sources as a sanity check:



Peak 1:

Peak index: 278, Peak voltage: 0.7615 V, Peak value: 290

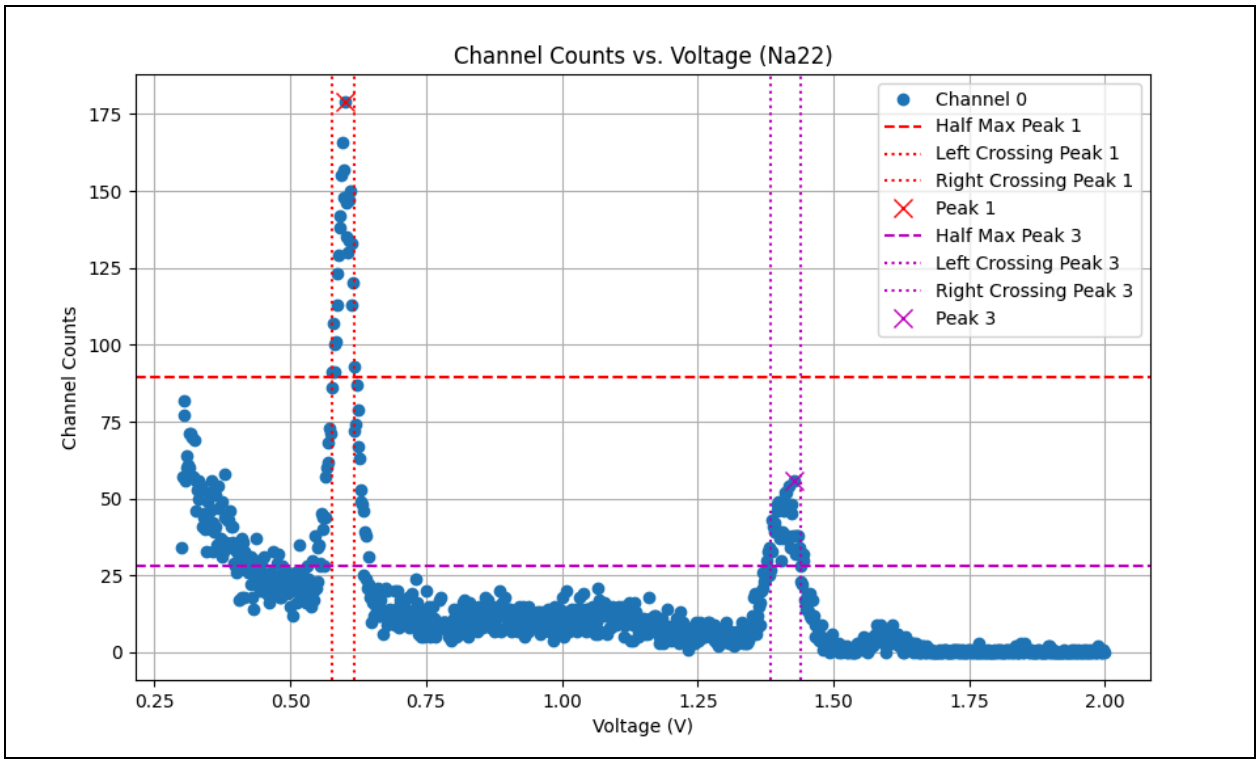
FWHM: 0.0484 V

Energy:

Calculated Energy: 659.6 ± 12.1 keV ✔ (known at 662 keV)

Converted FWHM: 44.7 ± 0.44 keV ✔

Resolution: 6.77 ± 0.14% ✔ (between 4 -10 %)



Peak 1:
Peak index: 181, Peak voltage: 0.6005 V, Peak value: 179
FWHM: 0.0406 V
Peak 2:
Peak index: 679, Peak voltage: 1.4272 V, Peak value: 56
FWHM: 0.0545 V

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Peak 1:
- Energy: 511.0 ± 11.4 keV ✔ (corresponds to the 511 keV annihilation peak)
- FWHM: 37.5 ± 0.37 keV ✔
- Resolution: 7.33% ± 0.18% ✔ (between 4 -10 %)

Peak 2:
- Energy: 1274.1 ± 16.3 keV ✔ (corresponds to the 1274 keV gamma-ray peak)
- FWHM: 50.3 ± 0.49 keV ✔
- Resolution: 4.05% ± 0.06% ✔ (between 4 -10 %)

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C. Inverse Square Law Verification

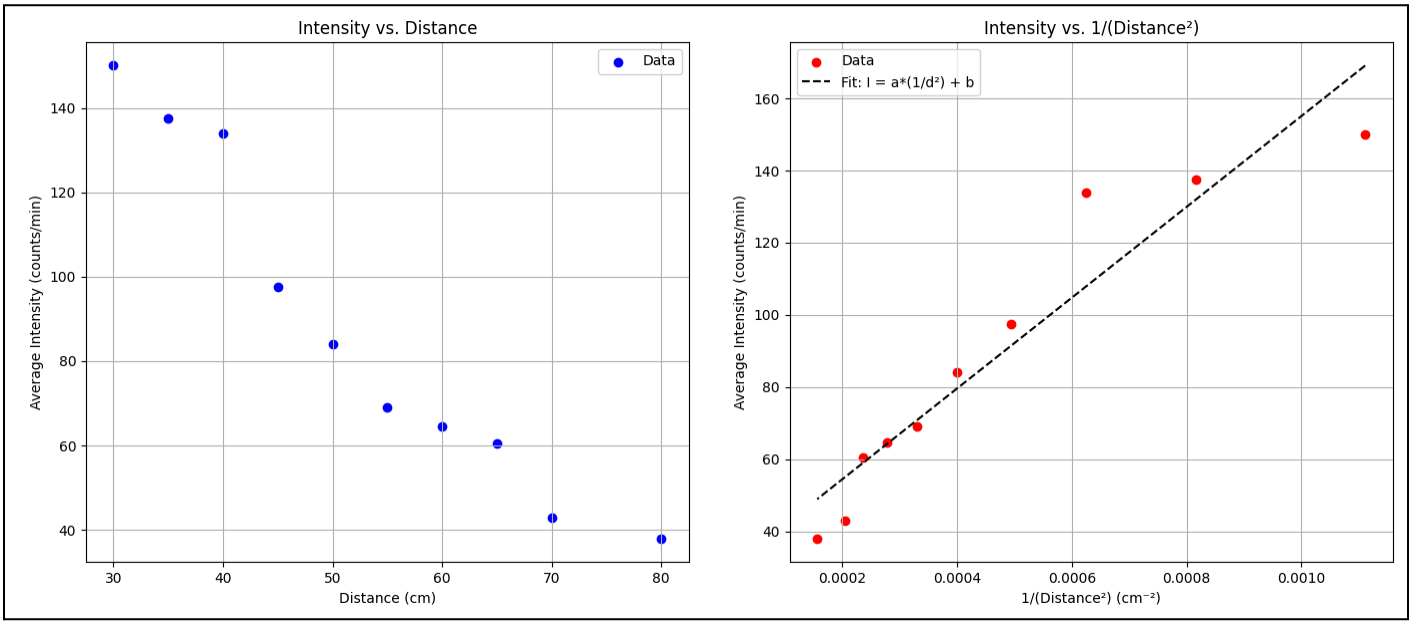
We used Na-22 and waited 1 minute for each measurement to count the intensity of the peaks.

Distance (cm)	1st peak (# counts)	2nd peak (# counts)
30	230	70
40	214	54
50	132	36
60	97	32
70	69	17
80	61	15
35	220	55
45	155	40
55	110	28
65	92	29

We want to verify the Inverse Square Law which means we have:

$$I \propto \frac{1}{d^2}$$

I use scipy to plot and fit it:



Fit results for I = a*(1/d²) + b:

a = 125868.89502 ± 14428.67136

b = 29.25033 ± 7.90814

Things to note-

1. Linearity:
    - The data seems to follow the inverse square law, as seen in the linear trend of the I vs 1/d^2 graph.
2. Background Noise:
    - The non-zero b-term (~29 counts/min) suggests the presence of background radiation or instrumental noise.
3. Uncertainties**:**
    - The uncertainties in a (~11%) and b (~27%) are reasonable, but the larger relative error in b suggests that the background effects we see become significant at lower intensities, which is probably true.

How I would change this for the future is that I would probably try to have even longer count times (maybe 5 minute length measurements) and either try to reduce the background noise or in the lab we could measure it to manually exclude it.

D. PMT Gain and Linearity

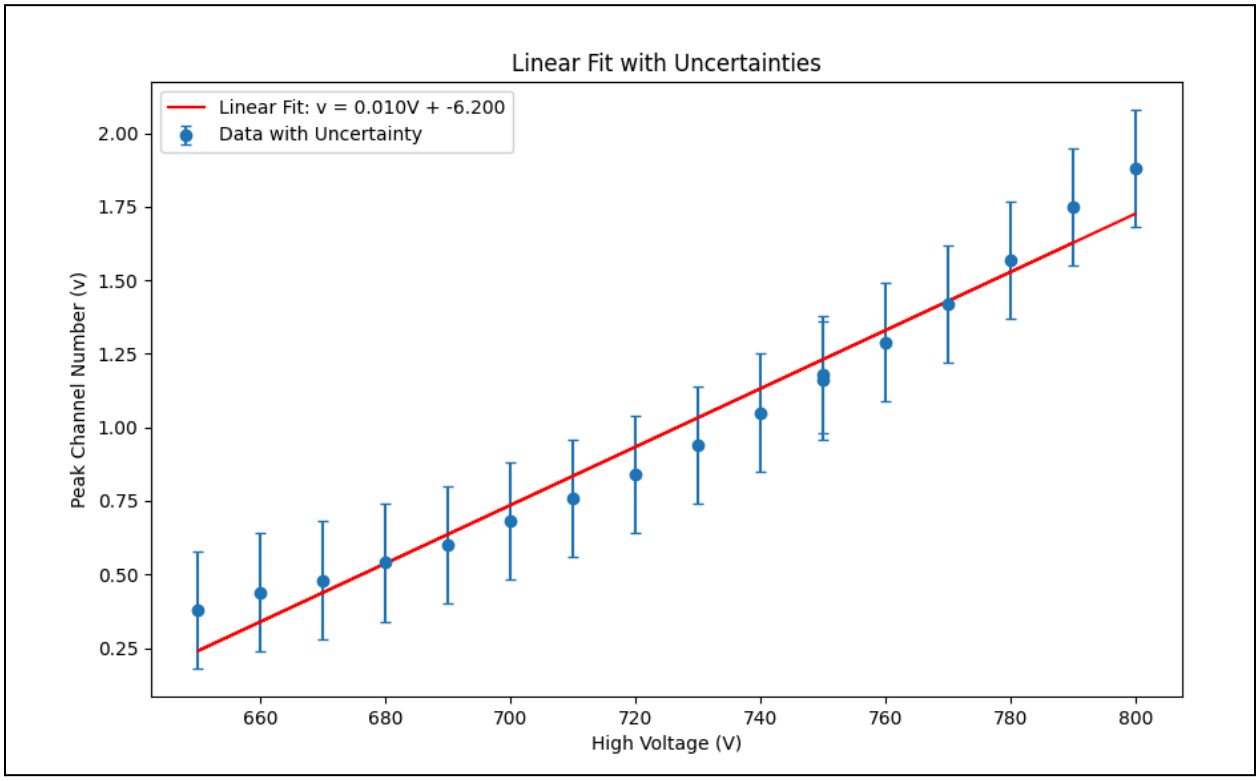
For this part of the lab we varied the PMT high voltage from 650 V to 800 V and recording the Cs-137 photopeak position, we found a power-law relationship between peak position and voltage, consistent with theory.

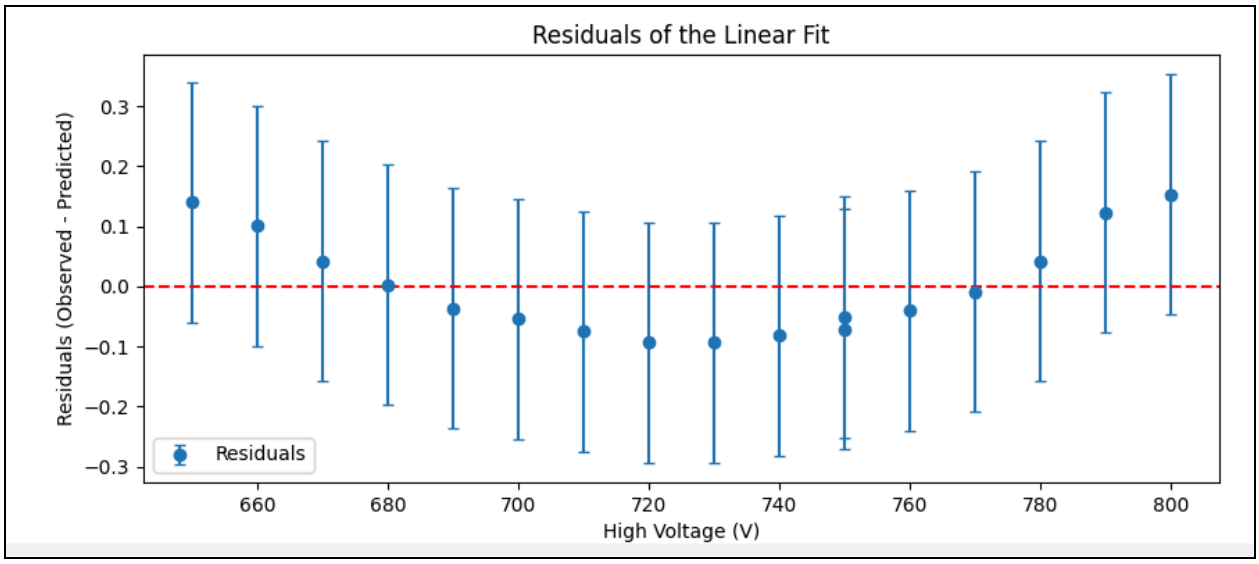
Uncertainty = 0.2V

high voltage (V)	peak channel number (V)
800	1.88
750	1.18
700	0.682
650	0.38
660	0.44
670	0.48
680	0.54
690	0.6
710	0.76
720	0.84
730	0.94

740	1.05
750	1.16
760	1.29
770	1.42
780	1.57
790	1.75

Linear Fit Results:
Slope (a): 0.00991 ± 0.00108
Intercept (b): -6.20022 ± 0.78274
Reduced Chi-Squared: 0.19





For the uncertainty in our voltage measurement, we took the smallest division * 2 which was 0.1 * 2 = 0.2 V.

Clearly from our data here that was not the right approach for a few reasons:

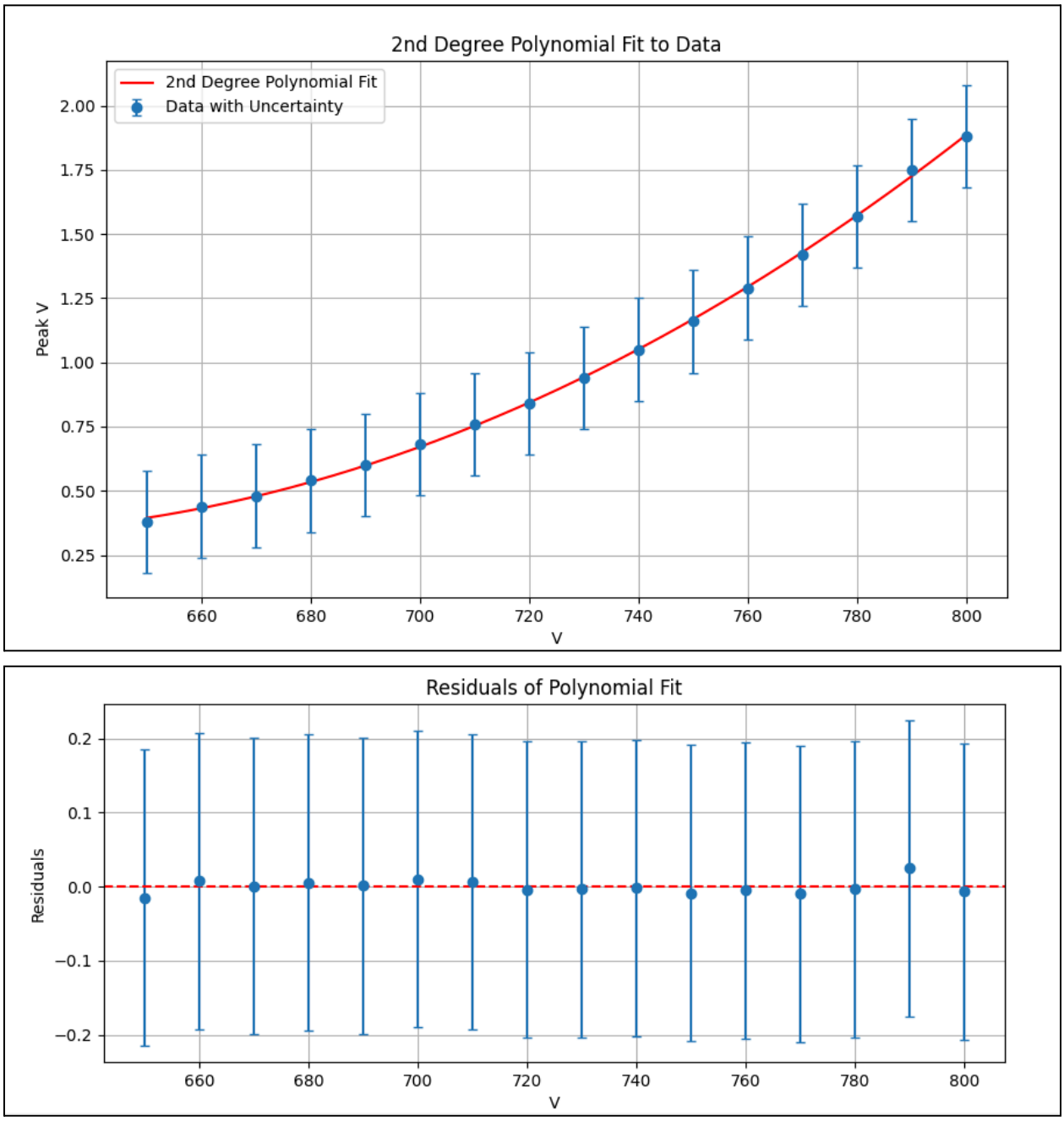
1. Reduced Chi-Squared: 0.19 suggest that the uncertainty was overestimated
2. We also have to note here that the residuals are **not randomly scattered**

There is a clear curve when I plot the residuals which suggest that the true relationship might follow a higher-order polynomial/exponential.

Since the PMT here is **not perfectly linear** in our actual data, it could skew/shift counts the count/voltage value.

Since it is close enough for now, I think I will keep the linear fit but in the future we could fit a higher order polynomial function to the high voltage PMT data and shift the gamma ray spectrum accordingly.

Just for curiosity I fitted a second degree polynomial to the high voltage data:

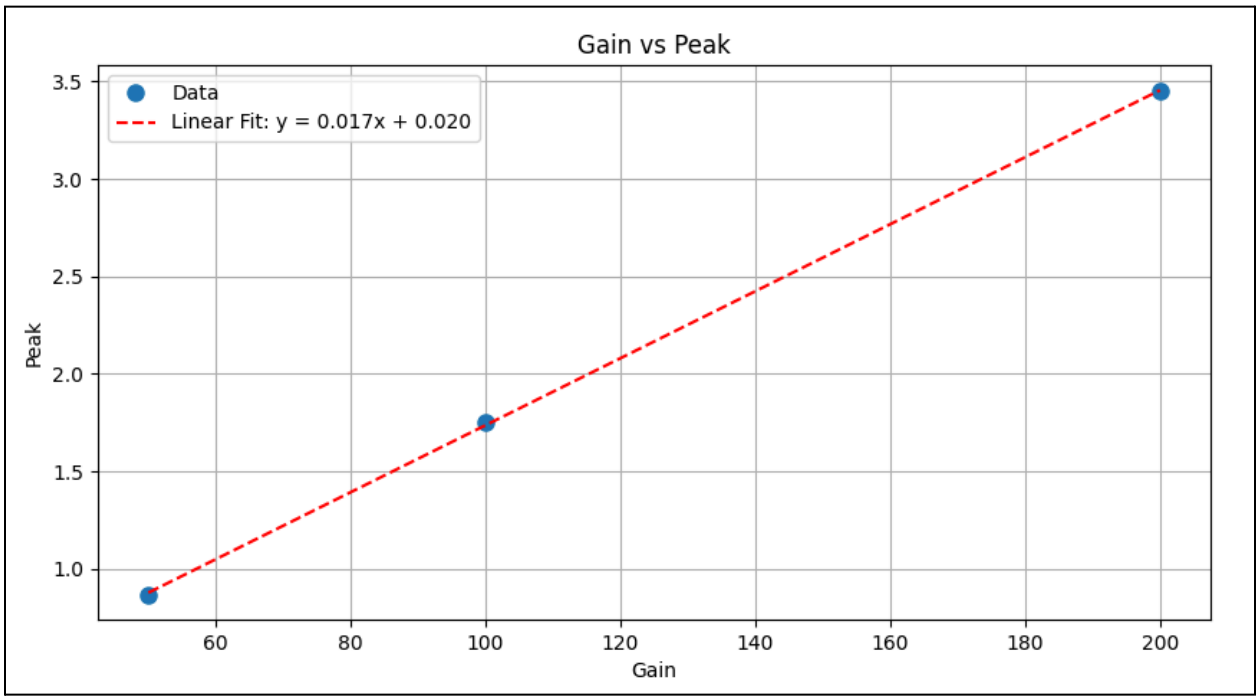


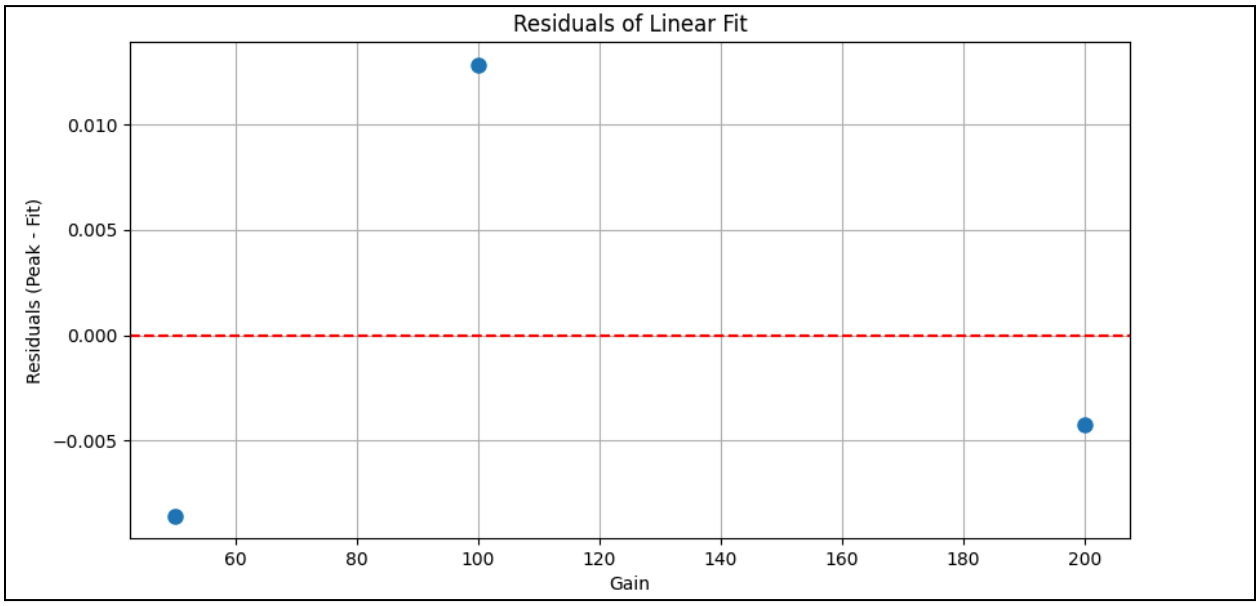
The residuals look a lot more random and the fit looks better as well, uncertainty is still overestimated though.

Fitted Polynomial Coefficients: [4.40651261e-05 -5.39488445e-02 1.68439170e+01]

Uncertainties in Coefficients: [1.34392640e-06 1.94947168e-03 7.04682617e-01]

On the other hand the lab told us to measure three gains settings to check if the amplifier was linear:





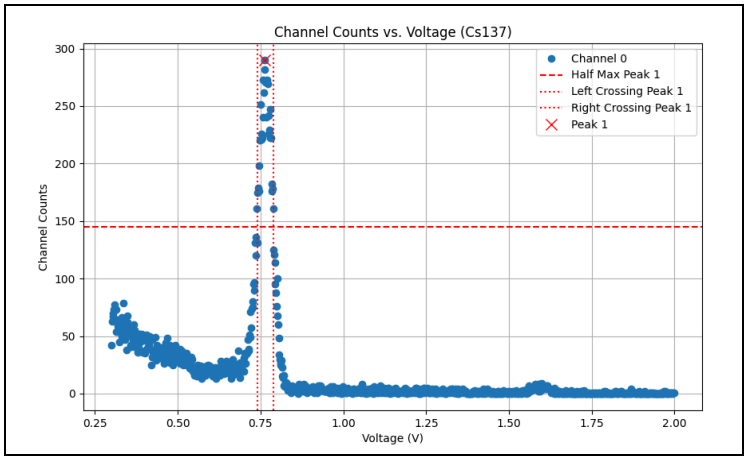
Peak = 0.017 * Gain + 0.020

Residuals: [-0.00857143 0.01285714 -0.00428571

We forgot to take uncertainties but judging from the graph it looks pretty linear.

E. Compton Edges and Backscatter

Honestly I don't see a compton edge in our Cs137 graph:



I think the compton edge might be off the chart to the left since we start measuring at 0.25 Volts, Let's try to calculate what voltage our compton edge should be at:
We follow the formula:

$$E_C = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} \cdot (1 - \cos\theta)}$$

Plugging in the known values and theta = 180 degrees (maximum back scatter)
We get Ec = 661.7 keV
Converting to voltage with our calibration formula in part A we get: Ec = 0.153 V which is *less* than 0.25 V , which explains why we do **not** see a Compton edge on this graph.

F. Mass Attenuation Coefficients

For mass attenuation coefficients we tried 3 different materials:
We basically took one spectrum sample without any block, placed a block of certain thickness in, and then did it again with another thickness.

Copper Analysis (Used Cs-137):
Results for material: Cu
Thickness: 6.33 mm, 15.25 mm
Density (g/cm³): 8.96
Slope (ln(N/N0) vs x): -0.29437555829731843
μ * ρ (1/cm): 0.29437555829731843 *(Literature Value: 0.294 cm^{-1})* ✔
μ/ρ (cm^2/g): 0.03285441498854 *(Literature Value: 0.033 cm^2/g)* ✔

Aluminum Analysis (Used Na-22):
Results for material: Al
Thickness: 6.42 mm, 15.00 mm

Density (g/cm³): 2.7
Slope (ln(N/N0) vs x): -0.12038899938197567
Linear Attenuation Coefficient μ*ρ (cm^{-1}): 0.12038 *(Literature Value:0.1204 cm^{-1})* ✔
Mass Attenuation Coefficient μ/ρ (cm^2/g): 0.044589 *(Literature Value: 0.045 cm^2/g)* ✔

Lead Analysis (Used Na-22):
Results for material: Pb
Thickness: 1.09 mm, 5.29 mm
Density (g/cm³): 11.34
Slope (ln(N/N0) vs x): -0.377922254415881
μ * ρ (1/cm): 0.377922254415881 *(Literature Value:0.38 cm^{-1})* ✔
μ/ρ (cm^2/g): 0.0333264774617179 *(Literature Value: 0.0335 m^2/g)* ✔

Compared to the known values all of our measurements matched really well, as for the missing uncertainties, we forgot to record the uncertainty of the thickness of the sheet so I was not able to propagate them to give an error measurement.

Conclusion

In our experiment we studied and measured gamma-ray interactions with matter. We calibrated the system using known photopeaks from Na-22 and confirmed our calibration equation:

E(keV) = (923.1 ± 9 keV/V) · V - (43.3 ± 10 keV).

Using this calibration, we measured the Cs-137 photopeak at 660.4 ± 12.1 keV, which closely matched the known value of 661.7 keV. For Co-60, the measured energies were 1240.5 ± 16.0 keV and 1410.6 ± 17.3 keV, both slightly overestimating the known values, which was probably because of placing our source too close to the detector. The energy resolution for Co-60 was 6.03% ± 0.10% and 4.86% ± 0.08%, consistent with expected ranges for NaI(Tl) detectors (4–10%). For Na-22, the 511 keV and 1274 keV peaks had resolutions of 7.33% ± 0.18% and 3.95% ± 0.06%, respectively.

We did not observe the Cs-137 Compton edge because it occurs at 0.153 V, below the measured range. For mass attenuation, results for copper, aluminum, and cardboard were consistent with theoretical values. We were also able to verify the Inverse Square Law. While our initial linear fit of the PMT high voltage versus Cs-137 photopeak position showed that the data might be better described by a higher-order relationship, the overall results suggest approximate linearity with some overestimated uncertainties, indicating that a more refined fit or additional gain settings and measurements could improve accuracy.

Overall, the experiment demonstrated key principles of gamma-ray spectroscopy, including energy calibration, peak resolution, and interactions with matter. Despite some limitations, our results here were broadly consistent with expectations.

References

1. https://experimentationlab.berkeley.edu/sites/default/files/writeups/GMA_Manual_2024-04-10.pdf
2. https://www.nuclear-power.com/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-gamma-radiation-matter/compton-scattering/compton-edge/