Physics 307 Experiment 1:
Elements of γ-ray Counting and γ-ray Spectroscopy

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1 Purpose

To determine the Compton edge and photoionization effects of a Sodium Iodide (NaI) crystal due to incident gamma-ray radiation from Cs-137 and Co-60 sources, using three different methods of measurement (oscilloscope, SCA and MCA).

2 Theory

Cesium-137 and Cobalt-60 emit gamma-ray radiation during their radioactive decay. When gamma-rays are incident on a material (in this case a Sodium Iodide NaI crystal), three types of interactions can occur: Photoionization, Compton Scattering and Pair Production. The gamma-rays in this experiment are of low enough energies that only the first two interactions apply. Photoionization occurs when the incident gamma-ray excites an electron. When the electron relaxes to its ground state, a secondary photon is emitted, which we can detect as a short burst of light.

Compton Scattering occurs when a gamma-ray collides with an electron, transferring some of its energy to the electron. There is a limit to the amount of energy that can be transfered, known as the Compton edge. Since the gamma-ray can transfer any arbitrary fraction of its energy (up to the Compton edge) to the electron, the Compton scattering spectrum is continuous, whereas the Photoionization spectrum is a discrete spike. In this experiment we will be interested mostly in studying the Compton edge and Photoionization peak.

The energy of gamma-rays emitted by Cesium-137 is 662 keV. We will use this value to determine the energies of other interactions throughout the experiment. The theoretical Compton edge is:

$$\begin{aligned} E_e &= E_\gamma - E_{\gamma'} \\ &= E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)} \end{aligned}$$

Where $E_{\gamma'}$ is given by the Compton scattering equation. Maximum energy is transfered to the electron when $\theta = \pi$, so the equation becomes

$$\begin{aligned} E_e &= E_\gamma - \frac{E_\gamma}{1 + \frac{2E_\gamma}{m_e c^2}} \\ &= (662\text{keV}) - \frac{(662\text{keV})}{1 + \frac{2(662\text{keV})}{0.51\text{MeV}}} \\ E_e &= 478\text{keV} \end{aligned}$$

3 Procedure

The experimental setup consisted of a NaI crystal with a Photomultiplier Tube (PMT). The PMT was being fed high voltage, and its data signal was being directed into either an oscilloscope, single-channel analyzer (SCA), or multi-channel analyzer (MCA). The specific setup for each section is highlighted in the below sections.

3.1 Part 1: Response of NaI crystal to γ-rays

Max	Min	Amplitude	Error
24mV	-638mV	662mV	30mV
Left	Right	FWHM	Error
-2.40us	4.60us	7.00us	0.16us

Table 1: Characteristics of our PMT counts without the preamp

In the first part of the experiment, we placed the Cs^{137} sample below the NaI crystal, and used the oscilloscope to determine the Compton edge and photoionization peak. For our first measurements, we did not use the ST 450 preamp.

Our oscilloscope settings were:
Sweep 10 μs/div
Sensitivity: 500 mV/div

From the gap in the oscilloscope image, it is also easy to find the Compton edge using the cursors. We determined it to be 400 $\pm$ 80 keV. The error has been estimated using the resolution of the oscilloscope.

Left	Right	FWHM	Error
320ns	1.84us	1.84us	0.03us

Table 2: Characteristics of our PMT counts with the preamp

Next we connected the ST 450 preamp and set the gain to 7.04 so that our signal has both a positive and negative voltage region (see the yellow signal in figure 2). Using the preamp, the signal becomes shorter to reduce pile up. We remeasured the FWHM, and our new result is shown in table 2.

Figure 1: One gamma-ray spike as shown on the oscilloscope

3.2 Part 2: Elements of Pulse Counting

In the next section of the experiment, we used the Transistor to Transisor Logic (TTL) pulse counting feature of the ST 450 to count the number of particles at different energy levels. By adjusting the baseline from 5% to 100%, we can isolate just a small band of electron energies, and then plot each energy to measure the Compton edge and photoionization peak. Figure 2 shows both the direct amp out (in yellow) and the standard pulse (in blue) that is used to count the number of particles.

Our oscilloscope settings were:
Sweep: 2 μs/div;
Sensitivity (Ch 1 & 2): 2 V/div

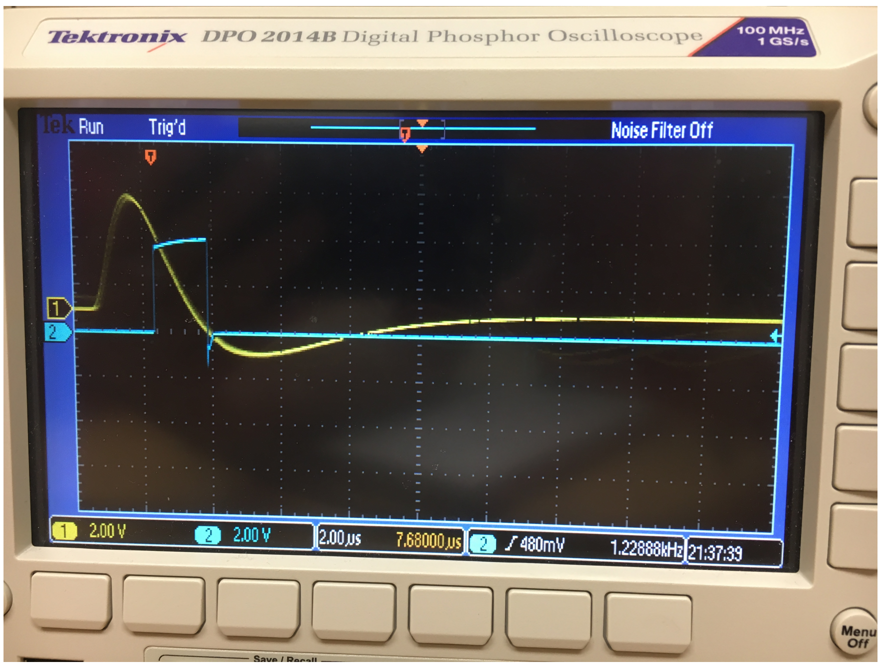

Figure 2: A gamma-ray spike and the TTL pulse

We averaged each count cycle over 10 seconds. Our raw data is shown in the appendix table 8, and a plot of our data is shown in figure 3. As the energy values (baseline) increases, the count value decreases, corresponding to fewer Compton scattering electrons of those energies. The count values drops nearly to zero at the Compton edge, before the large spike that corresponds to photoionization electrons.

Using the known Photoionization energy of 662 keV, we an use the ratio of baseline values to calculate the energy value of the compton edge from our data.

$$E_{\text{Compton}} = (662 \text{ keV}) \frac{\text{B.L.}_{\text{Compton}}}{\text{B.L.}_{\text{PI}}}$$

Where B.L. stands for the baseline values of the photoionization peak and Compton edge. The values we calculated are given in table 3. Our error values for the baseline are estimated based off our 2.5% steps, and the error for the calculated energy value is given by simple error propagation:

$$\Delta E_{Compton} = E_{Compton} \sqrt{\left(\frac{\Delta(\text{B.L.}_{\text{Compton}})}{\text{B.L.}_{\text{Compton}}} \right)^2 + \frac{\Delta(\text{B.L.}_{\text{PI}})}{\text{B.L.}_{\text{PI}}} \Bigg)^2}$$

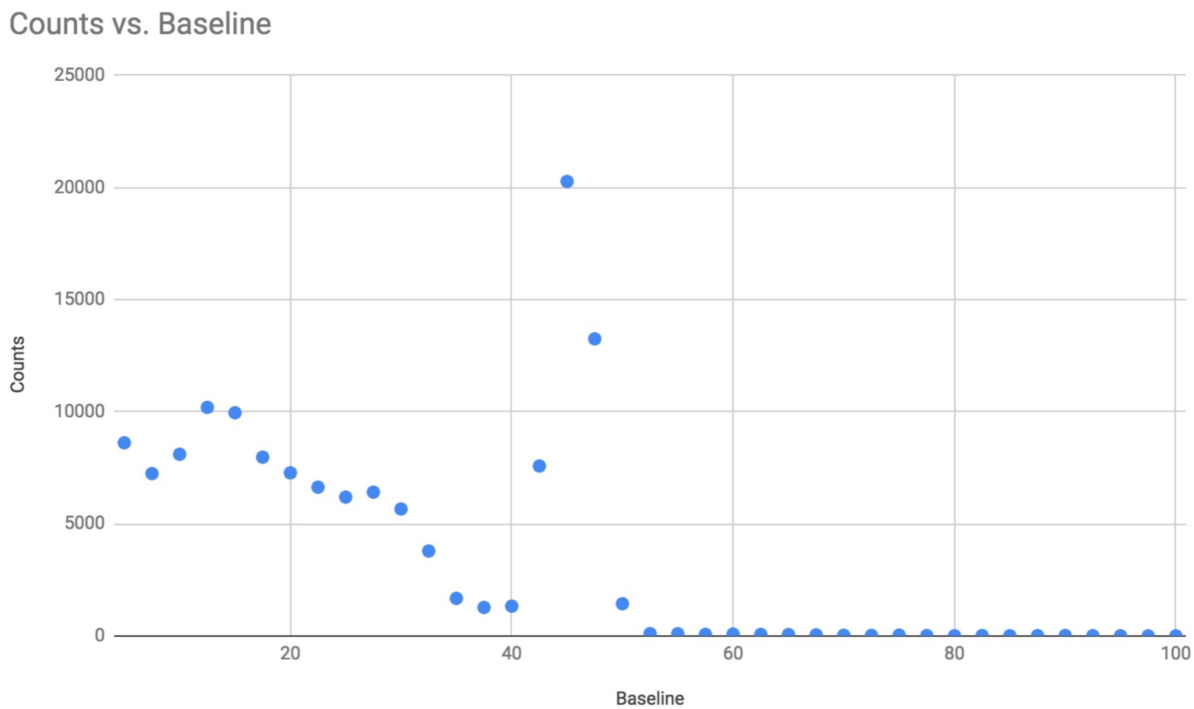

Figure 3: Particle counts (1/s) versus baseline (percent). Different baseline values correspond to different electron energies.

		Error
PI (baseline)	45	2.5
Compton edge (baseline)	31.125	2.5
Compton edge (keV)	457.9	45

Table 3: Measured baseline values for the PI peak and Compton edge and the calculated energy value of the Compton edge.

3.3 Part 3: γ-ray Spectroscopy

In the third part of the experiemnt, we used a Multichannel Analyzer (MCA). The MCA has the benefit of essentially using 1024 single-channel analyzers taking data in unison. This way, we can determine the radiation characteristics much more efficiently and accurately than before.

		Error
PI Centroid	756	7
Compton edge	554	7
Compton edge (keV)	485	7.6

Table 4: Measured channel values for the PI peak and Compton edge and the calculated energy value of the Compton edge.

Just like with the SCA baseline values, we can use the peak and edge channel ratios to calculate the energy of the Compton edge. Our data is show in the plot in figure 4, and our calculated Compton edge is given in table 4.

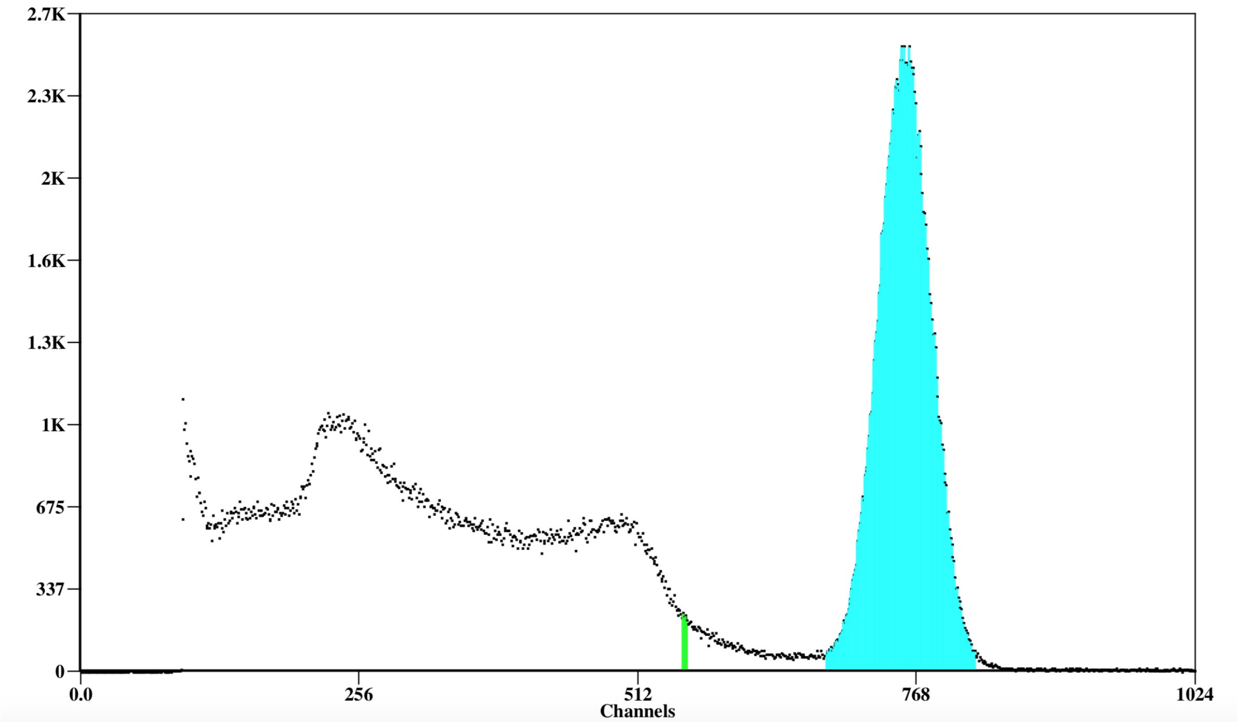

Figure 4: MCA data for Cs-137

		Error
Cs-137 PI Centroid	372	7
Co-60 peak	640	7
Co-60 peak (energy)	1139	24.8

Table 5: Calculating the (keV) PI energy for Co-60

		Error
Cs-137 PI Centroid	372	7
Co-60 peak	733	7
Co-60 peak (keV)	1304	27.5

Table 6: Calculating the (higher) PI energy for Co-60

We also ran an MCA experiment using a Co-60 source instead of the Cs-137. These data are shown in figure 5. We wanted to calculate the energies of the two (red and green) photoionizaiton peaks, so we superimposed the Cs-137 spectrum (in orange) in order to calculate these values as before. The calculated values are given in tables 5 and 6.

Our results of 1.14 and 1.30 MeV agree quite well with the actual values of 1.17 and 1.33 MeV respectively.

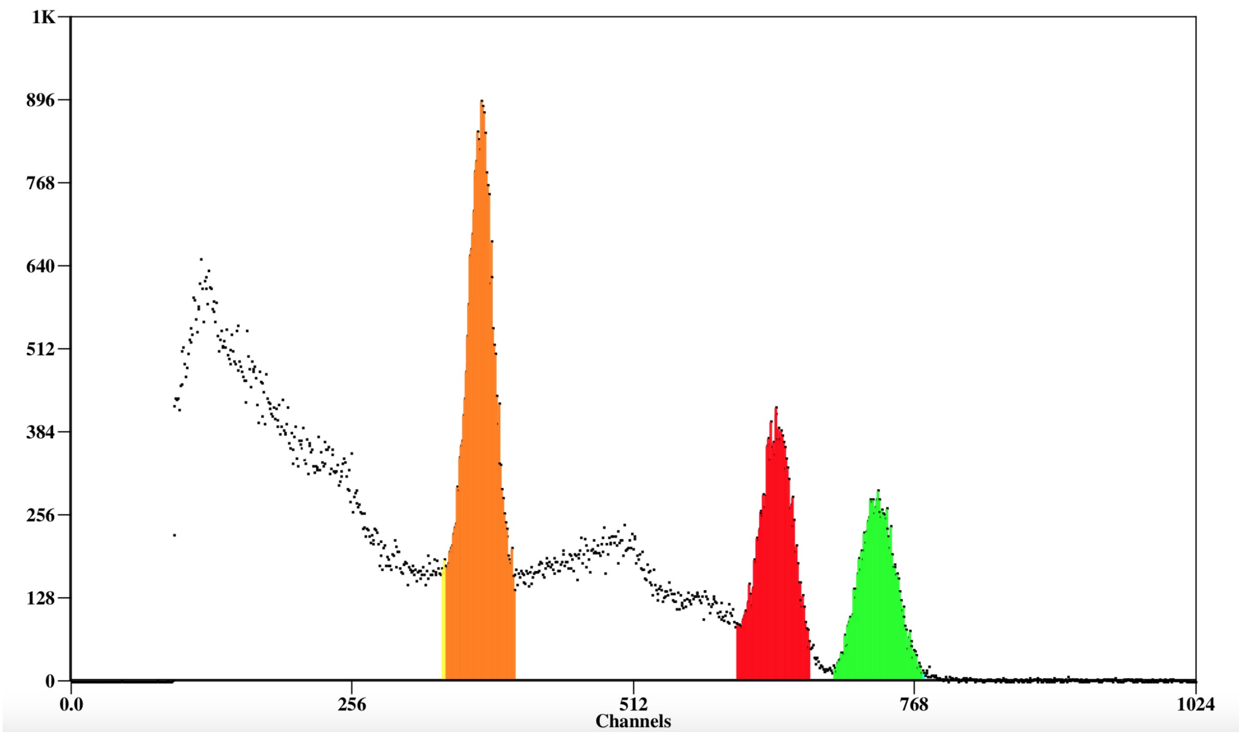

Figure 5: MCA data for Co-60

4 Results

		Error
Theoretical (keV)	478	N/A
Part 1: Oscilloscope (keV)	400	80
Part 2: SCA (keV)	457.9	45
Part 3: MCA (keV)	485	7.6

Table 7: Results

Our results are summarized in table 7. The theoretical value agrees with our experimental value for each method within our error bounds. Also, each measurement method's effectiveness is clear to see from this table with the oscilloscope, SCA, and MCA having errors of 80, 45, and 7.6 keV respectively. The MCA is clearly the most precise technique we used in this lab.

4.1 Post-Questions

1. The NaI scintillation crystal is 1.5" thick and 1.5" in diameter. On the basis of the total attenuation coefficient for NaI, what is the probability that an axially directed 0.662 MeV γ-ray will be absorbed or scattered within the crystal?

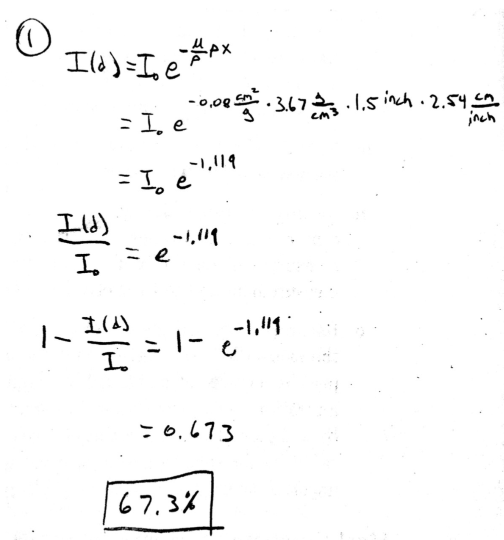

Figure 6: Question 1

2. Of all the 0.662 MeV photons that are scattered or absorbed within the crystal approximately what fraction undergo Compton Scattering (by necessity a Compton absorption requires a Compton scattering)?

   From the mass attenuation coefficient plot given in the write-up, at 662 keV, the compton coefficient is 0.07, whereas the total attenuation is 0.08. Therefore the ratio of attenuated electrons that undergo compton scattering is 0.07/0.08 = 87.5%.

3. Is the penetration depth of the released energetic electrons large or small compared with the dimensions of the crystal?

The penetration depth is very small. The electrons have a relatively high energy, so they collide and are absorbed within microns of where they are produced.

4. What physical process results in the liberation of electrons at the photocathode of the photomultiplier?

   The photoelectric effect.

5. What physical process is operative at the dynodes of the photomultiplier that results in the multiplication of the electron number?

   Secondary electron emission.

6. When voltage pulses are presented to the input of the SCA, it determines which pulses are acceptable, and then the SCA converts the acceptable pulses into standard sized TTL pulses available at its output for counting. If the SCA Baseline is 50% and the SCA WINDOW is 10%, then what range of pulse voltages are acceptable?

$$V_{\text{low}} = 10V \times 0.5 = 5V$$
$$\Delta V = 10V \times 0.01 = 1V$$
$$V_{\text{high}} = V_{\text{low}} + \Delta V = 5V + 1V = 6V$$
$$\boxed{\text{Range is 5V - 6V.}}$$

7. The MCA is equivalent to 1024 SCA's operating simultaneously. For bin number 512 of the MCA, what would be the corresponding BASELINE and WINDOW of a SCA for that bin? This is a little tricky because the UCS-30 MCA binning is between 0 and 8V (not 10V as in the ST-450)

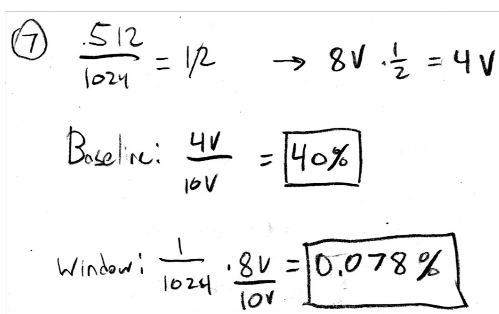

Figure 7: Question 7

5 Conclusion

We determined the Compton edge of NaI due to 662 keV incident gamma radiation using three different methods: oscilloscope, SCA and MCA. Each method agreed to the theoretical value within our error bounds. The MCA had the most accurate and precise value, followed by the SCA, and lastly the oscilloscope. We also determined the photoionization peaks of Co-60 using the MCA, and these values also agreed with the known values within our error bounds.

6 Appendix

Baseline	Counts (1/s)		Baseline	Counts (1/s)
5	861.6		52.5	10.5
7.5	724.3		55	10.1
10	810.3		57.5	7.2
12.5	1019.5		60	8.6
15	995.5		62.5	7.1
17.5	797.3		65	6.4
20	727.5		67.5	5.2
22.5	663.4		70	3.1
25	619.4		72.5	2.8
27.5	641.4		75	3.8
30	566.2		77.5	2
32.5	379		80	1.1
35	167.8		82.5	1.8
37.5	127.2		85	1
40	133		87.5	1.6
42.5	758		90	2.2
45	2026.9		92.5	1.3
47.5	1324.9		95	0.8
50	143.8		97.5	0.4
			100	0.6

Table 8: Characteristics of our PMT counts