PHGN 326 - Advanced Physics Lab II

LAB #4: Decay Chains

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PH326 Section B Lab Group R-11

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Abstract

A study was conducted on a sample of ^{60}Co in an attempt to determine how it decays. ^{60}Co can follow one of two decay paths as described in Section 4, which produce photons of differing energies. By measuring the emissions of the sample, a "gate" circuit was designed to isolate the event of a 1332 keV photo-peak being detected in one of two PMTs used in this lab. A delay was then applied to the amplified signal from the other PMT to force them into phase with one another. Then the gate function could be used to find the proportion of radiation intensity due to each process, without the interference of photons generated by intermediary processes. Values calculated for the probabilities of each decay path, as well as the corresponding accepted value, are shown in Table 1.

Beta Decay Energy (keV)	**Calculated Intensity (%)**	**Accepted Intensity (%)**
317	87.3±9.5	99.8±0.03
1490	12.7±9.6	0.12±0.03

Tab. 1: Experimental Values Compared to Accepted Values

Grade	Score	Available
Abstract and Cover Pg.		5
Fig. & Plt.		10
Data & Error Ana.		10
Writing		10
Total		35

1 Introduction

The task in this lab was to determine the primary mode of decay of ^{60}Co. This was done indirectly, by measuring the radiation of γ photons from the excited nuclear states of Ni, $^{60*}_{28}$Ni. The first step is to attenuate the circuitry to find a "gating" function (see Sec. 2.2). By multiplying this square wave by the collected signal generated by the source, we essentially limit our observations to only those photons collected at roughly the same time as a photon from the 1332 keV ^{60}Co photo-peak. Therefore, if any counts are reported for the second photo-peak, it must be the case that some decay path led directly to a low-energy excited nucleus with ability to radiate those γ-rays without first producing a higher-energy nucleus.

2 Apparatus

2.1 Layout

For the purposes of this lab, it was necessary to place the equipment into two different configurations, one to find a proper gating window, and one to apply it.

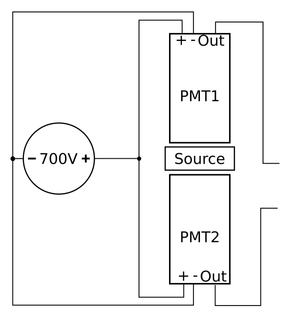

Fig. 1: Data Collection Setup

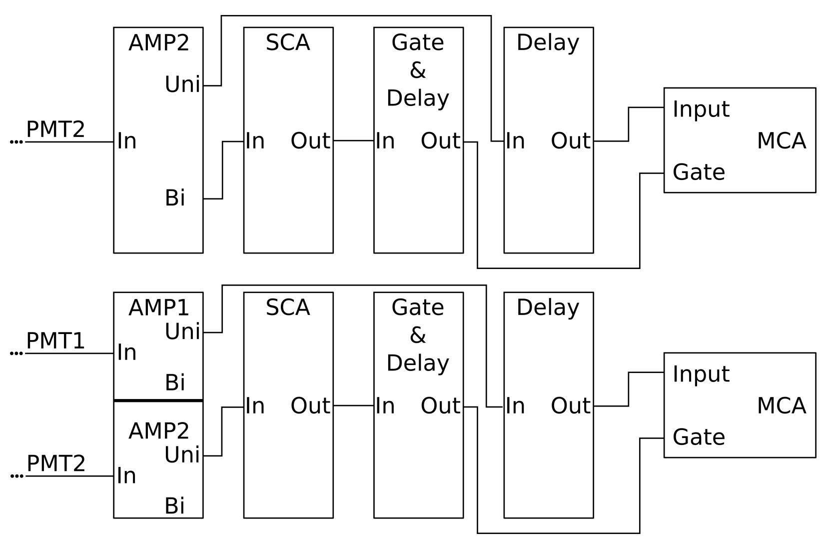

Fig. 2: Top: Layout for Finding Gating Window - Bottom: Layout for Data Collection

These two layouts are shown in Figure 2. In both cases, two Photomultiplier Tubes (PMT) were directed to the radiation source (^{60}Co) so that the output of one can be used as a gating function on the other, which is shown in Figure 1. It's important to note that those PMTs were carefully placed equidistant from the source.

2.2 Signal Modifiers

To transform the signal from one of the PMTs into a function to control the output of the other, an array of components were used in series. First, as usual, amplifiers are used immediately to produce signals strong enough to work with. The second component is a Single Channel Analyzer (SCA), which simply sets a window of currents (corresponding directly to photon energies) to transfer, blocking anything higher or lower. This output is passed to a Gate & Delay component, which turns its input into a square wave. Since the signal in question has passed through the SCA, this produces a square wave pulse corresponding to a range of detected photon energies, and now unbiased toward any particular energy inside the window itself. However, performing these operations causes an inherent delay, so the gating signal produced is necessarily misaligned with the (amplified) output of the other PMT. Therefore a Delay component is used to modify the leading signal. This component does exactly what the name implies: applies a constant time delay to a signal. Since we'd reasonably expect the raw output of each PMT to be practically identical[2], finding a gating window and setting a delay can all be done using a signal from a single PMT, as is shown in the top part of Figure 2. A visual representation of this is shown in Figure 3.

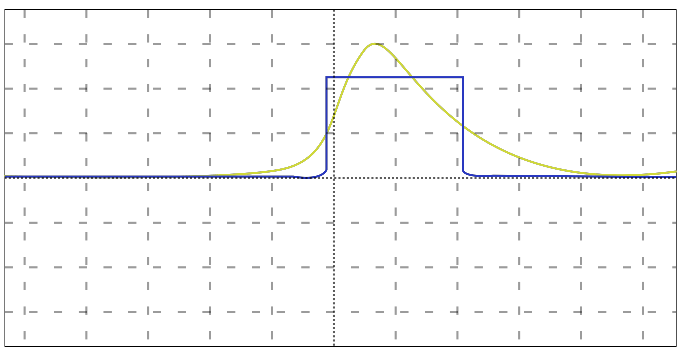

Fig. 3: Oscilloscope Output

An exported screenshot was used as a reference to produce this image, but was not included itself due to low picture quality.

3 Data Collected

3.1 Gate Construction

To find a gating window to apply later, it was first necessary to take a sample without any gating to determine the location of the 1332 keV peak. This "ungated" output is shown in Figure 4. This data was taken over a period of 115 seconds "live" time.

The two rightmost peaks correspond respectively to the 1173 keV and 1332 keV photo-peaks of ^{60}Co, from left to right. Now that the peaks had been identified, the next step was to connect the gating components as described in Section 2.2. As an intermediary step, the output of the SCA was briefly connected to the Maestro®MCA's Input (i.e. not the Gate port), and SCA settings were adjusted to isolate isolate photons belonging to the 1332 keV photo-peak. The resulting window was used as input to the Maestro®MCA's Gate port, and the output of measuring the PMT's

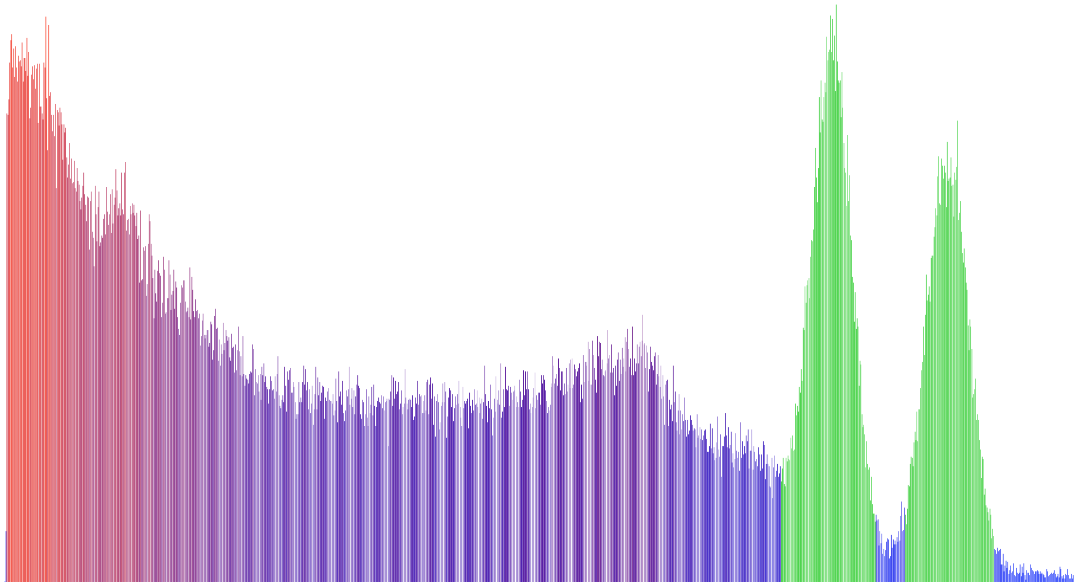

Fig. 4: Raw PMT Output

(amplified) output using the gate made from the same signal is shown in Figure 5. This data was collected over a period of 213 seconds ”live” time. Afterward, the oscilliscope was used to ensure that the gate signal overlapped the data signal, as seen in Figure 3.

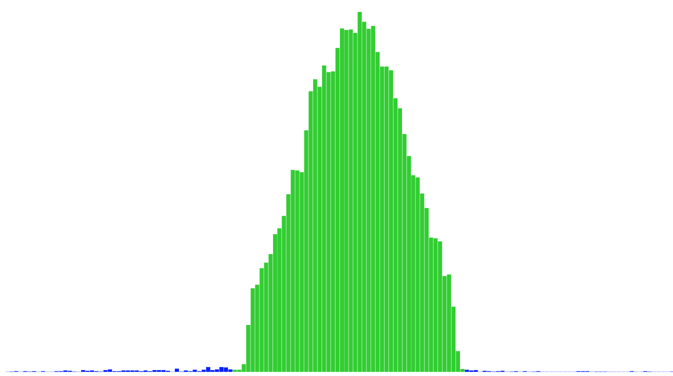

Fig. 5: 1332 keV photo-peak and Surrounding Channels (w/ Gate Applied)

3.2 Gated Data

Once the gate has been created, it is then applied to a secondary PMT’s output, which is shown in Figure 6. This data was collected over a period of 600 seconds ”live” time.

The noise shown to the left of the highlighted 1137 keV photo-peak is actually mainly consistent of Compton Scattering-generated photons. This is why there is no real peak at the low end of the spectrum.

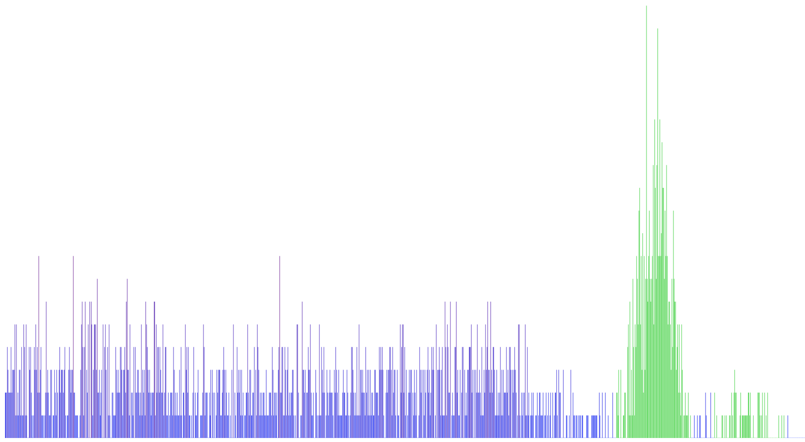

Fig. 6: PMT1 Data Using Gate Constructed from PMT2

4 Data Analysis

In Figure 6, the left-most green peak represents the 1137 keV photo-peak. The dataset shown in that figure includes all channels with non-Zero counts, apart from a few isolated channels scattered throughout the MCA's range. The decay chain for ^{60}Co is shown in Figure 7.

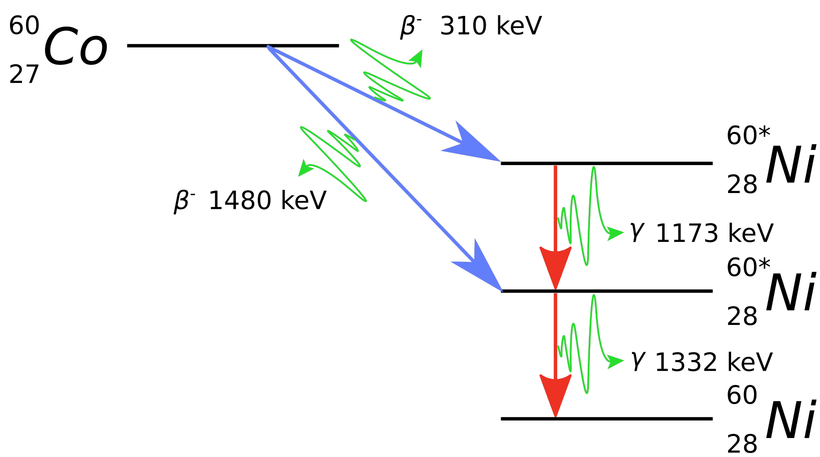

Fig. 7: Cobalt to Stable Nickel Decay Chain

PMTs cannot directly detect beta particles emitted by ^{60}Co, and so calculations of which decay path was taken must be based on the decay path of the excited Ni nucleus. Both levels of the excited nucleus shown have half-lives on the order of picoseconds[5], which is more or less instantaneous for our purposes. It's not conceivable, therefore, that a beta decay occur without subsequent gamma decay. Furthermore, for every beta decay, the appropriate gamma de-excitation chain will be followed in negligible time. Of course, it's important to note that the probability of detecting a second photon originating from the lower-energy beta decay is affected by the frequency that said beta decay occurs in the first place. The gate is used to rectify this, so that measurements of 1332 keV photons cannot be resultant from a near-simultaneous decay of the higher-energy nucleus..

Table 2 shows the data acquired for the gated signal. As shown, it is extremely difficult to separate such sparse data from noise. Even if we assume there is no noise at all, and allow the bad data's error to be 100%, the lower bound of the 1173 keV photo-peak's gross count *still* does not approach the upper bound of the 1332 keV photo-peak's gross count. This indicates that rate

Photo-Peak Energy (keV)	**Net Area**	**Gross Area**
1173	401.4±50.11	534
1332	-4.9±30.4	58

Tab. 2: Photo-Peak Data

of decay along the 1480 keV β^- path is extremely low, as compared to the other path shown in Figure 7. However, to compare this data, we need to use gross count rather than net area, because the negative net area reported means that it doesn't provide a meaningful result. The half-life of ^{60}Co is long enough that for the intervals of data collection, the source can be considered constant. Thus we can model it fairly easily with a Poisson Distribution (which is known to accurately model statistical decay in general[1]), if we take the measured value to be the mean. The variance in such a distribution is equal to the mean, so uncertainty in the gross area for the 1332 keV photo-peak is exactly $\sqrt{58}$ or approximately 7.62. Of course, this doesn't take into account any noise. Now we can calculate count rate (by simply dividing by the duration that measurements were taken) and propagate error properly. This is displayed in Table 3.

Photo-Peak Energy (keV)	**Count Rate (Counts/s)**
1173	0.669±0.0835
1332	0.097±0.013

Tab. 3: Calculated Count Rates

^{60}Co can only decay via one of these two beta decays, and so we assume that the sum of the count rates is exactly the decay rate. It's then trivial to find the proportion of each individual count rate to the total using $\beta^-_{\%}[x] = C_x/(C_a + C_b)$, where $\beta^-_{\%}$ is the probability that a given decay event uses path x, and C means count rate with a subscript telling which count rate was used (x is one of those). I'll move forward using the arbitrary convention that a indicates the higher-energy Ni nucleus was formed, and b indicates the lower-energy Ni nucleus was formed. Calculating the error is also not terribly difficult[3]:

$$\Delta\beta^-_{\%} = \sqrt{\frac{\delta\beta^-_{\%}}{\delta C_a}^2 + \frac{\delta\beta^-_{\%}}{\delta C_b}^2}$$

Obviously this changes depending on whether x is a or b, which isn't quite trivial, but can be done as below:

$$\Delta\beta^-_{\%}[x=a] = \sqrt{\left(\frac{C_b}{(C_a+C_b)^2}\right)^2 (\Delta C_b)^2 + \left(\frac{1}{C_a+C_b} - \frac{C_a}{(C_a+C_b)^2}\right)^2 (\Delta C_a)^2}$$

$$\Delta\beta^-_{\%}[x=b] = \sqrt{\left(\frac{C_a}{(C_b+C_a)^2}\right)^2 (\Delta C_a)^2 + \left(\frac{1}{C_b+C_a} - \frac{C_b}{(C_b+C_a)^2}\right)^2 (\Delta C_b)^2}$$

Now for the actual values.

The accepted values are 99.88% for 317 keV and 0.12% for 1490 keV[5]. This puts them just 3% outside both uncertainty ranges calculated for the decay. If nothing else, the calculated data reflects that path a is far more likely than path b. Each of the values was probably pushed away from what is expected due to the same underlying cause: noise. Because the probability is calculated by assuming the two count rates add to 100%, a change in the calculation of one will affect the

Beta Decay Energy (keV)	Probability (%)
317 (Path a)	87.3±9.5
1490 (Path b)	12.7±9.6

Tab. 4: Portion of Radiation Intensity According to Decay Path

other. Several channels in the 1332 keV photo-peak were most likely noise, and this would both bring the calculated proportion of those photons up as well as decrease the apparent probability of 1137 keV photons being produced. The problem is there's no real distinction. A good solution would be to simply allow the detector to run for perhaps a week (causing the count rate to possibly become non-constant, which would need to be accounted for) to obtain a high enough resolution to distinguish the peak (if any) from the noise. In fact, if for some reason all but one channel which counted exactly one photon could be disregarded, the calculated values would be 99.8%±1.2% for path a and 0.25%±13.8%, so it appears likely that much of the photo-peak was noise.

5 Conclusion

The results indicate that it is much more statistically favorable for ^{60}Co to decay along the path of a 317 keV β^- emission than the path requiring emission of 1490 keV β^-, but why is that? An obvious answer might simply be that the higher energy needed is more than is present in most nuclei. After all, the excited nuclei we observe at similar energies decay 19 orders of magnitude faster than the ^{60}Co that produced them, so such nuclei won't commonly be found in nature. On the other hand, it's also just possible that emitting photons is much easier than emitting β^- particles, because photon emission can occur at a number of different energies between 0 and 1500 keV. So perhaps it's difficult to build up enough energy in the nucleus to emit a higher-energy β^- particle. To find out which is the case would simply require measuring the spectrum of excited ^{60}Co nuclei. After excitation, the presence of photons counted in the 1332 keV photo-peak region indicates that the energies of the nuclei have been increased so that this decay path is more favorable, as opposed to rapidly decaying to ground state by emitting photons.

References

[1] Dr. Lawrence Wiencke, Professor for PHGN-326. A Brief Introduction to Nuclear Physics. Colorado School of Mines, Physics Department, 2017. http://astroserve.mines.edu/ph326/2017/lectures/1_Nuclear_326_post.pdf

[2] Dr. Ed Cecil, Professor for PHGN-326. Instructions for Experiments: Experiment 4: Decay Chains. Colorado School of Mines, Physics Department, 2017.

[3] John R. Taylor, Professor at the University of Colorado Department of Physics."An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements" Second Edition, 1982.

[4] National Nuclear Data Center at the Brookhaven National Laboratory. "NuDat 2.6", Last Modification: 2011, http://www.nndc.bnl.gov/nudat2/chartNuc.jsp

[5] E. Brown & J. K. Tuli, Nuclear Data Sheets 114, 1849 (2013)