Experiment #6: Gamma Ray Spectroscopy

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Abstract

For the final lab this semester, we will explore gamma ray spectroscopy. Using a scintillation counter, we will examine the spectra of various radioactive samples and consider the physics behind the various peaks we detect. By calibrating our spectra using known gamma ray producing energy transitions for our samples (and subtracting background radiation counts), we can use the resulting data to estimate the rest mass of the electron.

Experiment Description

To obtain gamma ray spectra from our radioactive samples, we employ a scintillation detector that uses an inorganic crystal to detect gamma ray energies. The solid state interactions that make the detection possible are beyond the scope of this report (and this course), but the detector has enough energy resolution for us to measure distinct energy differences between the gamma ray emitted from our sample and the various states we finally manage to measure it.

The principle interactions we will detect are the photopeak (around the actual energy of the known nuclear transition that initially emits the gamma ray) and the smearing of energies from Compton scattering - where the initial gamma ray loses some energy to scattering an intervening electron. The amount of energy lost depends on the angle of incidence with the scattered electron - we cannot reliably measure this angle of incidence, but we can, with reasonable precision, measure the energies of both the scattered electron and the gamma ray, and infer scattering angles from those energies due to the Compton effect.

For our Sodium-22 sample, we also hope to see evidence of antimatter in pair production - as part of its decay chain, Na-22 emits a positron, which we should be able to detect as an annihilation peak that corresponds to the rest mass of an electron. This peak energy should be comparable to the rest mass we can calculate from the Compton effect mentioned above - providing two different approaches to verify our result.

Data & Analysis

To properly analyze our spectra, we first need to calibrate the raw data from the detector using known transition energies for the samples. The plot in Figure 1 below shows this linear relation between the detector channel and the known energy levels. Only the more active samples were included in this calibration figure, as some of the older samples with shorter half-lives (less than a year in our case) did not produce very useful spectra (shown below, especially for Cobalt-57).

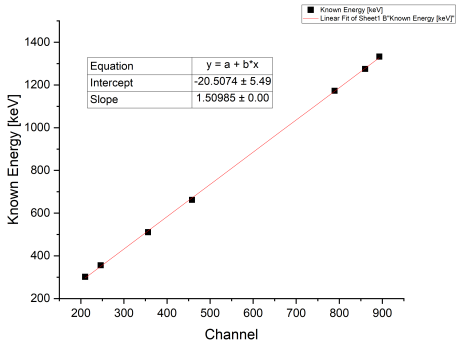

Figure 1: This calibration function allows us to transform the detector channel data to more useful energies, based on known energy values for the photopeaks of our samples (or annihilation peak in the case of Na-22).

The next series of plots shows the spectra for each sample with the energy calibration applied (after a background count subtraction). For the background counts, we ran the detector for approximately ten minutes (the exact second value was used in the subtraction), then subtracted these counts, scaled to the appropriate duration for each sample as $\frac{\text{sample duration}}{\text{background duration}}$. Since all of our spectra were taken on the same day, this seems like a reasonable assumption that the background radiation does not change significantly, especially over the timescale of our data collection (around ten minutes, or less, for each sample).

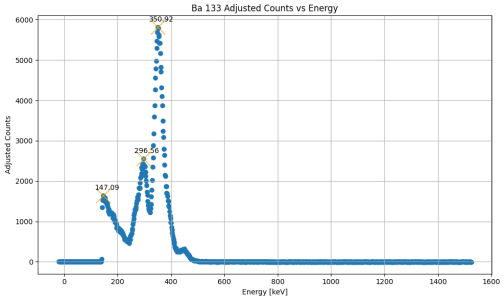

Figure 2: Barium-133, showing two peaks with similar energies, which corresponds to its more complicated decay scheme.

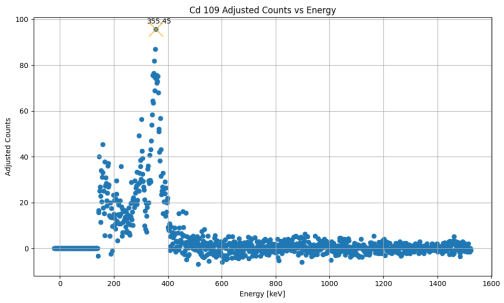

Figure 3: The Cadmium-109 sample was not especially active, a longer collection period would likely yield (slightly) better data, but as many of the samples are well over a year old (Cd-109 has a half-life of 461 days), we instead focused our efforts on analyzing the more active samples.

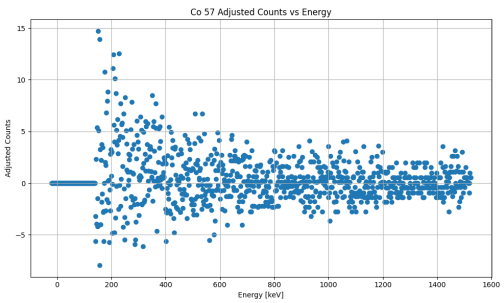

Figure 4: After subtracting the background counts, our Cobalt-57 data is effectively just noise. This sample also has a half-life less than a year, so we did not devote much time to it.

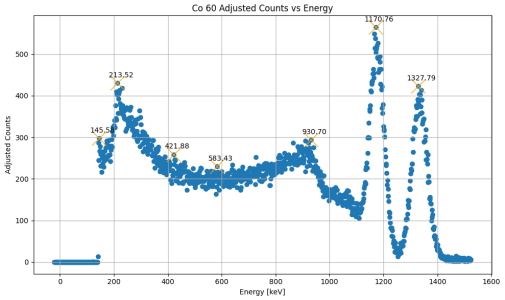

Figure 5: Cobalt-60, with a half-life over 5 years, produced a much better spectrum. Two photopeaks are evident, from its two-stage decay chain. The Compton edge is also clearly visible (around 930 keV), as well as what may be a backscatter peak near 200 keV.

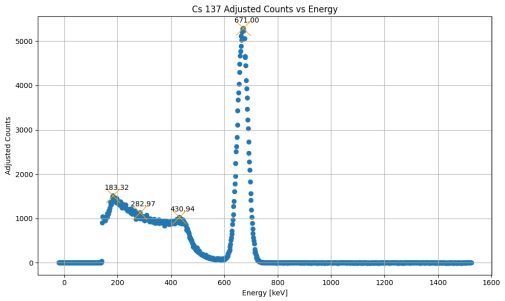

Figure 6: Cesium-137, with a half-life of 30 years, also produced a clear spectrum. The photopeak is evident at 671 keV, along with the Compton edge and backscatter peak around 430 and 183 keV, respectively.

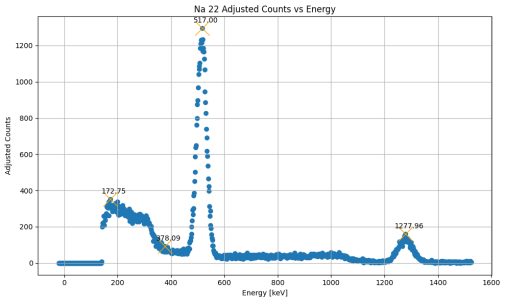

Figure 7: Sodium-22 has a half-life just over two years, but still produces a sharp annihilation peak due to pair production. The photopeak is much less pronounced, especially compared to the more active samples shown above.

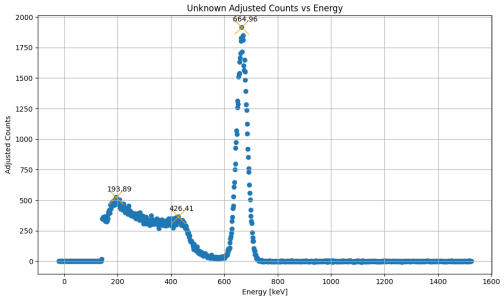

Figure 8: A sample labeled "Unknown" was included with the collection, comparing this spectrum to our other data, it seems most likely to be Cs-137.

Results & Conclusions

As noted in the captions for the plots above, we did successfully measure unique energetics involved with the detection of gamma rays. The photopeaks mentioned correspond to the principle transition, where the Compton effect is the result of the emitted gamma ray scattering off an intervening electron, where either the gamma ray quant, the electron, or both end up being detected by the scintillator, producing the broad Compton "shoulder" seen in most of the plots above. In some cases, we measured a backscatter peak, we the scattered electron is undetected but the gamma quant (which imparted most of its energy to the missing electron) travels backward through the detector. Some of the higher counts on the lower end of the energy scale could also be attributed to the detection of x-rays resulting from interactions with the lead blocks we used for shielding.

With more time, and perhaps fresher samples, we could have increased our collection duration for each sample and seen better detail in these spectra - which would also improve our electron mass calculation. However, given the nature of this course and the equipment we are using, the resolution of the detector will always be the main limiting factor - we could spend a good deal of time and energy to modestly improve our results, but these quantities have already been experimentally verified using much more precise techniques and equipment. For our purposes, we are able to very successfully explore the realm of high energy physics (safely!) while still getting acceptable estimates for electron mass, solely from our gamma ray spectra and the Compton effect.

The details of the analysis and calculations are included in this Google Colab notebook - https://tinyurl.com/qlabexp6, but by solving the Compton effect formula for the cases where the gamma ray imparts the most energy to the electron (head-on scattering, $\theta = 180°$) such that

$$E' = \frac{E}{1 + \frac{2E}{m_e c^2}}$$

where E' is the energy of the scattered gamma quant and E is the initial energy.

Solving this equation for m_e :

$$m_e = \frac{2EE'}{c^2(E - E')}$$

and we can find E' by taking the difference between the photopeak energy and the energy at the Compton edge (which represents the energy where the electron receives the maximum the scattering gamma ray and the gamma ray returns back toward the source, from $\theta = 180°$). Plugging in some of our values from our samples, we find electron mass estimates ranging from $1.05m_e - 1.2m_e$ - up to nearly twenty percent error, but again, limited by the energy resolution of the detector and the duration we collected our data.

Since the main purpose of this lab is to explore gamma ray spectroscopy and high energy physics, getting an order of magnitude result within the actual rest mass of the electron feels quite successful! More than that, we were able to witness and begin to understand some of the nuances involved with nuclear physics, from the theoretical framework and the intricacies at work in experimental detection.