Gamma-Ray Spectroscopy

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29 November 2019

Abstract

This report details a method used to calibrate an NaI(TI) gamma ray spectrometer with various samples of radioactive isotopes in an effort to analyze and further understand the nature of gamma radiation. The angular dependence of photons produced in electron-positron annihilation is observed, while the corresponding photopeak is used to calculate the mass of the electron as well as the inverse mass of the positron. Maximum photopeaks are compared to their respective Compton edges in order to estimate the energy of the gamma ray deflected during scintillation within the spectrometer. X-rays, backscatter, and background are identified along with other characteristics and limitations of the detection process.

I. Introduction and Theory

Gamma-ray spectroscopy focuses on the energy spectra of gamma-ray sources. Gamma-rays themselves are produced by most radioactive sources, and vary in intensity and energy. Through the use of a spectrometer system, these emissions can be analyzed and their energy spectrum can be evaluated. Using the methods detailed in this lab, I determine what amount of energy is released during various radioactive events, and how they are released. In doing so, I cover a breadth of territory relating to the energy spectrum of the radioactive isotopes Sodium-22 (Na-22), Cobalt-60 (Co-60), and Cesium-137 (Cs-137).

To understand the nature of radioactive decay insofar as is relevant here, I begin with beta-decay, whereby neutrons convert to protons, and protons to neutrons, through different processes of nuclear transmutation. During these processes, an excited nucleus can release its energy in one of two ways. The first of which is through Beta-minus decay, noted β-, whereby a neutron emits both an electron and an antineutrino, reconstituting itself into a proton. In the second way, both a positron and a neutrino are emitted from a proton, thereby transmuting the proton into a neutron. This is referred to as Beta-plus decay, noted β+.

The creation of Gamma-rays themselves, again as far as is relevant to the experiment, occurs either as the downstream consequence of Beta Decay, or as the immediate de-excitation of an unstable nucleus. In the first case we are reminded of the relationship between electrons and positrons. The two being anti-particles of one another, any contact between them necessitates the annihilation of the pair into an isotropic cloud of radiation. The radiation energy, in this case, is of the highest known frequency, and is referred to as gamma radiation. In the second case, where the unstable nucleus releases its energy through the emission of gamma radiation, we are reminded of excited electron states, whereby the electron returns to its ground state, or unexcited state, through the emission of moderate energy photons. The de-excitation of the nucleus itself occurs in much the same way the de-excitation of its electrons does, by releasing its energy in the form of photons. The great difference in either case is the frequency of the emitted photons.

The incidences of gamma radiation I am interested in, whether a consequence of pair annihilation through Beta Decay or through immediate de-excitation of the nucleus, all originate from within the nucleus, meaning however the gamma ray is produced, it will be emitted from

within the nucleus. One relevant consequence of this is when the gamma ray collides with one of the electrons orbiting the innermost electron shell of the atom, the K-shell, and forces the electron out of the atom. This ejection of a low order shell electron results in the downward transition of the next highest electron to take its place, and then the next highest electron to take the second one's place, and so on out to the farthest orbiting electron of the atom. This downward cascade of electrons, each falling into the place of the previous, results in the emission of numerous x-rays by the atom, which must be accounted for when evaluating the energy distributions detailed in the later sections.

Also of importance here is that certain unstable nuclei can absorb K-Shell electrons in a process known as 'K-Capture,' whereby the electron is absorbed into a proton to create another neutron. This absorption of a k-shell electron results in the same downward cascade of the upper bound electrons mentioned in the previous paragraph. Again, these processes are only mentioned because the X-rays produced are significantly detectable in our experiment, and account for about 4% of the energy distribution in the relevant analyses.

II. Apparatus

The consequences of all these activities are detected by one of either two scintillators. The scintillators themselves yield useful data through a series of interactions and processes within the scintillation chamber. In this chamber, on the side facing the sample of radioactive isotopes, there is a crystal, in this case comprised of Thallium-doped Sodium Iodide (NaI:Tl), through which the gamma-rays and x-rays emitted from the radioactive sources must pass. In this crystal, these photons (rays), transmit their energy to the electrons orbiting the NaI:Tl molecules in their path. Immediately following this interaction, the NaI:Tl ions, excited by their newly imparted energy, quickly de-excite through the emission of visible light. The photons comprising this light are directed towards the next section of the scintillation chamber, a photosensitive surface that ejects electrons upon being struck by incident photons. These electrons are then amplified by a photomultiplier in the final chamber of the tube to produce a current pulse, which is converted to a voltage pulse of proportionate height to the energy imparted by the initial gamma-ray or x-ray, and which is then registered as a 'count' by either our SCA or MCA (single-channel or multi-channel analyzer).

These analyzers collect the voltage pulses in slightly different ways. The SCA is itself a piece of hardware - mine is the Canberra 2015A SCA, which allows the user to select a window of voltage magnitudes within which the corresponding pulses will register as single counts. As a brief illustration, there will be pulses ranging from almost zero up to 10 volts, but the SCA will only count the pulses within the window preset by the user. This means that if the user sets the window to a range of 6V to 7V, the only counts that will register in a given time interval will be the ones corresponding to pulses with a magnitude between 6 and 7 volts. The MCA used, in this case a piece of computer software called the Nucleus Personal Computer Analyzer, adds another dimension. It does what the single channel analyzer does, but instead of being restricted to one window of concern, the MCA will organize thousands of small windows across the whole potential range of voltage heights, 0 to 10 volts. This amounts to a data binning that can be displayed graphically to show exactly how many counts are occurring in a given time interval for each voltage bin.

Other instruments not included in these descriptions for the sake of brevity include a high voltage power supply, Canberra model 2000 Power supply, NIM bin, Rutgers P1075 scaler/timer, and a Canberra model 1466 Coincidence Module. The power supplies are of course used to power the rest of the instruments mentioned, the NIM bin is simply a rack for mounting the various devices, the scaler/timer to measure SCA counts in a preset time interval, and the coincidence module to

record the occurrences of gamma pulses hitting either scintillator simultaneously. The value of these last two instruments will be made clearer in the data and analysis section.

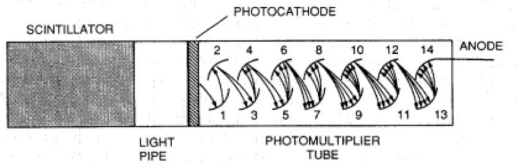

Figure 1: *The inner chambers of a standard scintillation detector*

III. Procedure

i. Basic Setup

Conducting experimentation involves minor augmentations to the following procedural outline. I begin by mounting the scintillators to a radial apparatus, pictured below in Figure 2. The faces of these detectors need to be equidistant from the yellow colored sample button seen at the center of Figure 2.

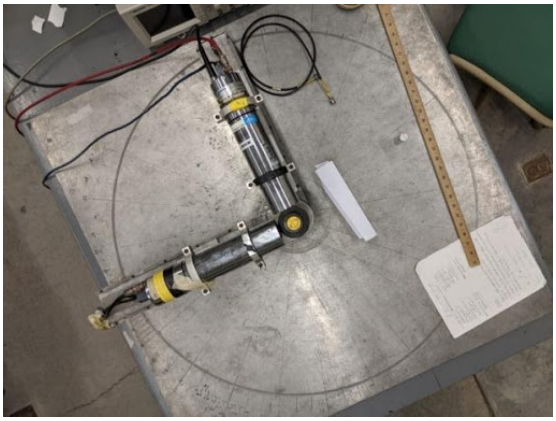

Figure 2

Once these have been mounted, the current wires extending out the rear of either scintillator are connected to the back of the high voltage power supply and to their respective SCA's. The connection of one of the scintillators to the 'AMP IN' port of its SCA is shown here in figure 3.

Figure 3

The SCA's may then be connected, one at any given time, via their 'AMP OUT' ports to the MCA input and via their 'SCA OUT' ports to the MCA Gate, shown below in Figure 4.

Figure 4

This MCA is then connected to the computer via USB, and the software "Meastro" used to run it. This setup alone will generate an energy spectra on our software once the instruments

have been turned on and supplied with power. Apart from what has been mentioned up until this point, it is only important to remember to turn the buffer setting in Meastro over to MCB in order to render the active count collection on screen.

From here there are various additions and changes that must be made in order to conduct different parts of the experiment.

ii. SCA setup

In the case where the SCA must be used manually without the incorporation of software, the 'SCA' port of the SCA must be connected to the '1' port of the Rutgers scaler/timer, shown in figure 5. This scaler/timer can then be preset to a 1, 10, 100, or 1000 second data collection interval. In this interval the scaler will collect counts in the voltage pulse height range preset on the SCA. This range is set by adjusting the knob for 'E lower' to the lowest magnitude pulse height the user is interested in collecting, and then adjusting 'ΔE' for the size of the range desired. To illustrate, if the desired observation range is from 6V to 7V, 'E lower' would be set to 6V and 'ΔE' to 1V. From here, a time interval of say 1000 seconds might be set, and the button 'start' hit. The data collection would reach its timely conclusion and a number of counts would be displayed on the digital face of the unit. In figure 5 this was 5861 counts in 1000 seconds.

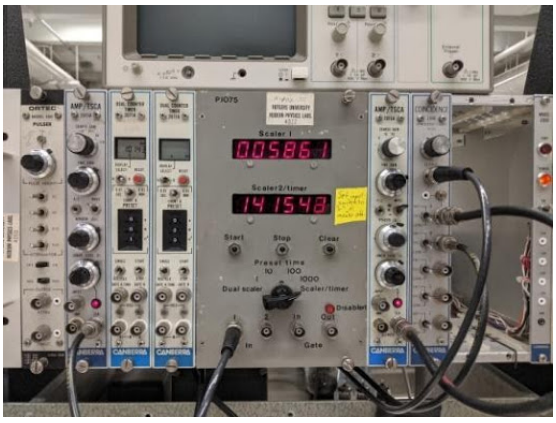

Figure 5

iii. Coincidence Setup

When using the coincidence module, both SCA ports on the front of their respective units are toggled to the front of the coincidence module, which is then connected, from the front, to the Rutgers scaler/timer. From the rear, the coincidence module is connected to the MCA in the same manner as would be done with either SCA.

iv. Calibration

Here I outline the calibration done on the hardware already pictured with the "Maestro" software. This calibration is to be done once at the beginning of the experiment, and the settings achieved left constant for the rest of the experiment. Any change of these settings will distort the relationship between prior and subsequent data collection.

To do this, we use our basic setup, with a sample of Na-22 placed on the central column of the radial apparatus, and begin collecting the data through Maestro. By toggling the 'Gain' knob on the SCA, I can change the horizontal positions of the energy readings in Maestro. The 'Fine Gain' knob must be adjusted such that the 1.2746 MeV Photopeak for Na-22 rests on channel 1500 in Maestro. It is also necessary to take the peak value at channel 0. To do this, I place the marker on channel 0 and then press 'insert' to select 'ROI.' Then I select calibration in the drop down menu, and enter the energy found at this peak. This process is repeated for channel 1500 at the 1.2746 MeV photopeak.

Following this I can verify the calibration by replacing the Na-22 with Cs-137 on the central tier and checking to see if the 0.6616 MeV photpeak for Cs-137 registers a consistent value according to the calibration. Provided this checks out, I save the file and the calibration setup it contains for Maestro. It is, however, then necessary to calibrate the second SCA as well. This can be done backwards by adjusting the 'course' and 'fine gain' settings on the SCA until they match the peak values established in Maestro. This concludes calibration.

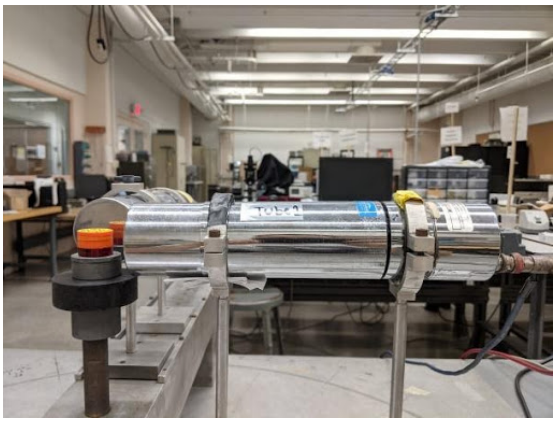

Figure 6

v. MCA Decay Spectra

Starting from the basic setup first outlined, the data output given in Maestro will render the MCA decay spectra. There are a few things, however, that can be manipulated in the analysis. To increase hit count, for example, I can add more samples of a particular isotope to the central column, seen in Figure 6. I can also move the scintillators closer to the sample, or use newer samples.

Figure 7

In Figure 7, the dates of production can be seen for the three different samples of isotopes. Once I begin, data collection must persist until 10,000 counts have been recorded to ensure that accuracy can be guaranteed to within 1% of the actual value. More on this in data and analysis. Upon completion, I note the number of decays as well as the elapsed time, and then save. This process must be completed for all three isotopes.

vi. SCA Decay Spectra

Starting again from the basic setup, I attach the front of the SCA module to the scaler/timer seen in Figure 4. As mentioned before, the SCA renders the counts, for one window at a time, on the scaler/timer. Beginning at the first window, I set the time interval to 100 seconds and begin collection by pressing the start button, all seen in figure 4. I then move the window up by increasing 'Lower E' by the value fixed for 'ΔE.'

This means that if lower E is set for 0V and ΔE is set for 0.5V for the first data collection period, the second period will be set to a lower E of 0.5V with δE remaining a 0.5V. Lower E during the third period of collection will be 1.0V, in the fourth period 1.5V, and so on up through the whole spectrum, in this case a maximum of 10V, with ΔE remaining at 0.5V throughout the process. The hit count is recorded on paper at the end of each collection period, and, ultimately, a graphical rendition of the data can be produced by plotting the hit counts against their respective values for 'Lower E.' This plot should be directly comparable to the plot produced in Maestro by the MCA.

vii. $\gamma-\gamma$ Coincidence

Here I begin to reference the gamma rays as γ. Again, starting from the basic setup, the concern here is to measure the rate at which rays from the same gamma decay event hit both scintillators simultaneously. This is referred to as '$\gamma-\gamma$Coincidence' and can be measured using the coincidence module previously mentioned. To do this, I must first tune the SCAs to a window encapsulating only the annihilation peak of the sample. I then connect both SCAs to the coincidence module and connect the coincidence module to the scaler/timer. I set the coincidence module's 'events required knob' to

2, and then collect. I then collect and record the count of coincidences in 100-second intervals for every 5° difference in relative scintillator position from 90°-270°.

IV. Data and Analysis

Each gamma-ray pulse spectra will follow the same format pictured in Figure 8 as a histogram where energy increases from left to right. There will be a low energy rise from the background. A full energy photopeak will occur at and will produce both a backscatter peak and a Compton edge. There may be more than one full energy peak depending on the source, but each one will produce its own backscatter and Compton edge.

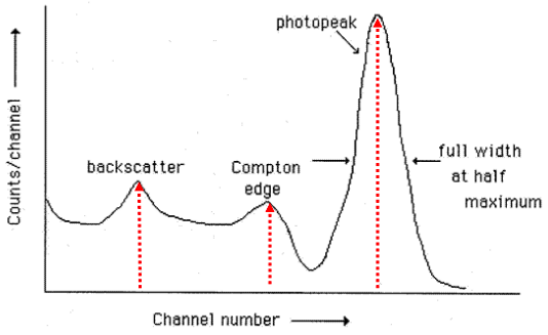

Figure 8

By taking additional points for calibration, the Maestro program can use an interpolation method to fine tune that calibration. The MCA was calibrated according to the gamma ray, annihilation, and zero value peaks taken from the Na22 sample, and the following values for the gamma rays of each material were found. Using these values along with the values for the Compton edge of each material, the maximum value for the scattered photon energy can be found. These are seen on the next page in Table 1.

Given that nuclear radiation is isotropic, through calculation I can estimate the minimum amount of radiation coming from a sample. By measuring the solid angle the detector takes relative to the sample, and the number of counts recorded over the given time interval, a minimum value for the curies produced by a given source can be calculated. To ensure that background did not disrupt the calculations, it was recorded as well. The counts were at least six orders of magnitude smaller than the sample material and was therefore determined to be negligible.

Because of the probabilistic nature of radioactive decay, these values can only be an estimate of the minimum activity; the value of recorded decays can always be higher or lower in a given time interval.

Also of concern is the solid angle of the scintillator face to the radioactive source. Here we use the formula, solid angle $\Omega = A/r2$, where A is the surface area of the face and r is the distance between the radioactive source and the outer perimeter of the face.

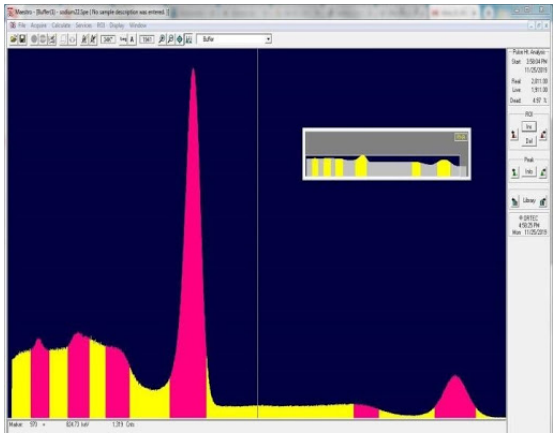

Figure 9

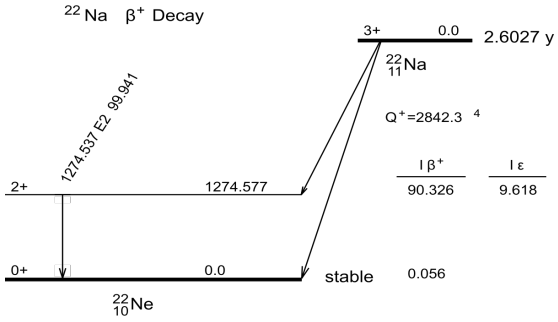

Figure 10

Table 1

Source	Gamma [keV]	Scattered Electron Energy [keV]	Scattered Photon Energy [keV]
Na^{22}	1274.1	990.1	283.4
Co^{60}	1169.7	890.6	279.1
Co^{60}	1332.0	1044.2	287.7
Cs^{137}	650.0	415.7	234.3
Cs^{137}	1318.9	992.6	326.4

Table 2

Source	Counts	Live Time [s]	Counts/s	Estimated decays/s	Curies
Na^{22}	$2.58633*10^{6}$	607	4260.8	23134	$6.25*10^{-7}$
Co^{60}	$2.19314*10^{6}$	704	3115.3	16914	$4.6*10^{-7}$
Cs^{137}	$1.28114*10^{7}$	702	18249.9	99085	$2.6*10^{-6}$
Background	259805	3337	78	-	0

The nuclear transmutation that occurs in Na-22 produces a positron and, as a result, should reveal an annihilation peak visible at 511 keV. This energy is equivalent to the half the total rest mass of the electron and positron from which it was produced. Although not exactly 511 keV, I found the energy of the annihilation still falls within the acceptable range using these methods, and occurs at 510.71 keV. There is a second gamma emission which occurs 0.05% of the time and has an energy of 2.84 MeV. Because of its low incidence and high energy, I did not capture this value.

The angular dependence of the photons produced in the electron positron annihilation can be seen in Figure 11. When the annihilation occurs, conservation of momentum dictates that the two photons must expulse from the annihilation in exactly the opposite direction from one another and with an energy equal to 511 keV.

The Cobalt gamma emission produces two gamma rays. Their photopeaks are clearly visible in the spectra given in Figure 11. Because of their close proximity, the two peaks should be spaced further out than they appear. The histogram would suggest that the first emission occurs more frequently than the second,

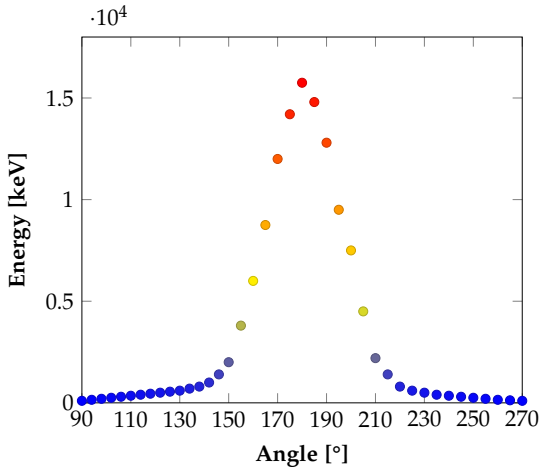

Figure 11: $\gamma-\gamma$ *coincidence energy by scintillation angle*

but this is only because the Compton scattering caused by the second peak is inflating the count number of the first peak.

The defining features of the Cs137 spectra that set it apart from the other samples are the small second gamma photo peak for the 1180 MeV transmission and the Ba K x-ray. The small second peak only occurs about 5% of the time and is easy to miss. To find the Compton edge for the second peak of Cs137, an estimate was made using a variation in the slope of the

Table 3

Na^{22}	Measured Energy [keV]	Predicted Energy [keV]
Low energy Rise	78.9	Consistent
Backscatter Peak	180.46	200 - 250
$\gamma-\gamma$ Compton edge	307.46	340.41
$\gamma-\gamma$ Annihilation	510.71	511
γ Compton Edge	990.1	1061.25
γ	1274.07	1274.6

Table 4

Co^{60}	Measured Energy [keV]	Predicted Energy [keV]
Low energy Rise	78.55	Consistent
Backscatter Peak	225.66	200 - 250
$\gamma-\gamma$ Compton edge 1	890.6	959.98
γ 1	1169.67	1173.56
$\gamma-\gamma$ Compton edge 2	1044.2	1117.56
γ 2	1331.94	1332.5

right tail of the first gamma photopeak and the left tail of the second photopeak. The Ba k x-ray was easily identified by its energy, which was very close to the expected value. It was also clearly discernible from both the low energy rise photopeak and the backscatter peak. The low energy rise being consistent across all the samples and the Ba k x-ray peak being far too small to be considered backscatter.

A second plot of the Cs137 spectra was created using the SCA. It has the major features seen in the original plot made with the MCA, but is less Gaussian in its distribution for the maximum photopeak. The lack of symmetry may be due to the lack of post processing power. Alternatively, the asymmetry on the left side of the distribution for the maximum photopeak could be a product of the inelastic collisions occurring in the sample before making its way to the detector, as was suggested in figure 3.6 b from Hastings A. Smith, Jr., and Marcia Lucas. Collection of the values for the SCA spectra was limited by our fine-tuning of the SCA. If we were able to be more precise in our incremental adjustments, the spectra produced by the SCA and MCA (theoretically) would become almost identical provided they had the same bin width (ΔE) and number of samples per bin.

Since the gamma ray produced during radioactive decay has a definite and singular value, it is odd that I did get a distribution as opposed to the same value over and over again. This is likely a consequence of the detectors limitations. When the gamma ray leaves the nucleus of the atom from, it would have the same value as any other gamma ray being produced by the same mechanism in another atom of the same isotope. Once it leaves the nucleus, it would experience some inelastic collisions on its way to the detector. This in turn could cause a slight left tail on the otherwise vertical line we expected to receive in the detector. Looking at the plot above it is apparent that the resolution of the detector decreases as energy increases, as the literature suggests. This must be the result of energy being lost during the ionization process in the scintillating

Table 5

Cs^{137}	Measured Energy [keV]	Predicted Energy [keV]
Ba-K x-ray	34.65	32.2
Low energy Rise	79.99	Consistent
Backscatter Peak	193.57	200 - 250
$\gamma-\gamma$ Compton edge 1	415.65	466.58
γ 1	649.99	661.6
$\gamma-\gamma$ Compton edge 2	992.55	1104.9
γ 2	1318.93	1180.0

material, likely due to the generation of heat within the crystal. In short, the more energy being detected, the more energy lost, the more Gaussian the gamma ray value appears.

V. Conclusion

The methods described above were successful in finding results consistent with the accepted values for gamma ray emission from the samples despite the limitations of the NaI(TI) detector.

Learning how to take advantage of the region of interest (ROI) commands in the Maestro program reduced guesswork and sped up the process of calibration and the recording of data. It would be interesting to use a solid-state detector to compare the results. I also found it very helpful to use all of the available samples for the same radioactive isotope together during data collection. Increasing the sample size increased hit count, speeding up the process considerably without distorting values.

References

[Melissinos, Adrian, 2003] Experiments in Modern Physics

[Smith, Hastings A. and Marcia Lucas, 1997] Gamma Ray detectors