Physics 307 Laboratory Experiment #1
Elements of $\gamma$-ray Counting and $\gamma$-ray Spectroscopy

The purpose of this experiment is to exhibit the properties of the response function of a sodium-iodide NaI(Tl) crystal to gamma rays, to introduce the student to methods of pulse counting, and to perform $\gamma$-ray Spectroscopy on an (unknown) $^{60}\text{Co}$ source using the (known) $^{137}\text{Cs}$ source for calibration.

References:

“Foundations of Modern Physics” by Tipler 2.1, 3.4, 3.5, 10.4 (pp 447-451).

“Data Reduction and Error Analysis...” by Bevington, Ch. 1, and Ch. 4.

“Experiments in Modern Physics” by Melissinos, 2.5, 5.2.5, (5.4.1), 5.4.2.

“Experimentation” by Baird, Ch.1 (Best estimate of standard deviation.)

Abbreviations:

This is the first of a series of experiments using $\gamma$-ray sources and detectors. The following symbols will be used throughout.

HV - High voltage (power supply)
AMP - Amplifier
SCA - Single channel analyzer
LLD - Lower level discriminator
ULD - Upper level discriminator
CRM - Count rate meter
FC - Frequency counter
NIM - Nuclear instrument module
MCA – Multichannel analyzer

Theory:

The gamma ray source contains radioactive nuclei of $^{137}\text{Cs}$ which slowly (over decades) Beta decays to form $^{137}\text{Ba}$ nuclei. Some of these Ba nuclei are in an excited state which quickly (in minutes) decay by the emission of 662 keV gamma rays. Some of these photons interact with the electrons in the NaI crystal through the processes of photoionization and/or Compton scattering. In both cases an energetic electron is released which proceeds to lose its kinetic energy by collisions with neighboring atoms. These electron-atom collisions result in further ionization and excitation of the atoms in the crystal. The final result is a pulse
of light that occurs when the ionized atoms become neutralized and return to their ground states. All this happens very quickly so that each light pulse corresponds to a single gamma ray scattering or absorption event. The light pulses are detected by a photomultiplier and converted into voltage pulses, where the amplitude of the voltage pulse is proportional to the amplitude of the corresponding light pulse. The amplitude of the voltage pulse is therefore representative of the interaction of a single gamma ray with the NaI(Tl) crystal. The spectrum of voltage pulses is determined by the original gamma ray energy, the type of crystal, and the type of interaction the gamma ray suffered in the crystal. Two types of $\gamma$-ray interactions are important for this experiment:

a) Photoionization - In this case the gamma ray is absorbed by an atom in the crystal, and during this process an energetic electron is released with the kinetic energy of about 662 keV. The light pulse and thus the voltage pulse that is detected when this electron is stopped has an amplitude that is characteristic of the 662 keV $\gamma$-ray.

b) Compton Scattering - In this case the 662 keV gamma ray is scattered by a loosely bound electron, and the scattered gamma ray now has less than 662 keV of energy with the energy of the released electron making up the difference. The spectrum of voltage pulses that correspond to these “Compton electrons” will range from zero amplitude to a maximum amplitude that is less than the photoionization peak mentioned above.

The energy of the scattered $\gamma$-ray, $E_{\gamma'}$, is related to the energy of the incident $\gamma$-ray, $E_{\gamma}$, by the equation

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

where $\theta$ is the scattering angle of the $\gamma'$-ray, $c$ is the speed of light, and $m_e$ is the mass of the electron.

Equipment:

1. Bertran Associates 215 power supply: 0-3000 V
2. Tektronix oscilloscope w/dual trace amplifier
3. Frequency counter (modified)
4. BNC portable NIM Bin
5. Mech-Tronics Model 500 AMP
6. ORTEC Model 406, 406A, or 550 SCA
7. Mech-Tronics Model 506 or 515 delay AMP
8. Mech-Tronics Model 776 CRM
9. Mech-Tronics Model 450 base and preamp
10. 2" × 2" NaI (Tl) crystal mounted on an RCA 8053 photomultiplier tube
11. Various cables
12. Personal computer with a SPECTRUM Universal Computer Spectrometer 30 (UCS 30) module and associate UCS 30 software.

Procedure:

**PART I. Response of NaI(Tl) crystal to γ-rays:**

1. Place $^{137}$Cs source about 10 cm in front of NaI crystal.
2. Connect DC power supply to HV of detector and set voltage to +900 V.
3. Connect Output of detector to Channel #1 of oscilloscope.

   **Scope Settings:**
   - Trig: Ch1/Ch2; Edge; negative slope
   - Sweep: 2 µs/div
   - Sensitivity: 20 mV/div

4. Sketch the waveform of the persistent pulses. Indicate the amplitude and full width at half maximum. The persistent pulses are the Cs 662 keV gamma ray scintillations from photoionization events.

5. Note the many pulses of lesser and seemingly random amplitude. These are the Compton scattered gamma ray scintillations. Note the gap, or lack of pulses, between the maximum Compton scintillations and the 662 keV scintillations. From the oscilloscope, estimate the maximum amplitude of the Compton pulses, and thereby determine the energy of the Compton edge. That is, determine the energy in keV of the maximum energy Compton electron.

6. Connect the Output of detector to Input of amplifier, and the Output of amplifier to Input of Channel #1 of the oscilloscope.

   **Amplifier Settings:**
   - DC Input
   - Normal
   - Integ. Out
   - Clip 2 Out
   - Gain 32 (about)
7. Adjust the amplifier so the 662 keV gamma ray photoionization (or photopeak) pulses are 6 Volts amplitude. What is the amplitude gain of the amplifier? Again note the Compton scintillations and the Compton edge. **Put Clip 2 in.** This shortens the pulses and helps prevent pulse overlap. It also enables the SCA (see part II) LLD (lower level discriminator) circuitry to operate quickly and uniformly. **Leave Clip 2 in and readjust the amplifier gain for 6 Volts amplitude. Sketch the waveform as seen on the scope screen, showing the 662 keV pulses and the Compton pulses.**

**PART II. Elements of Pulse Counting:**

1. Starting with set-up as in Part I (6) (with the clip in), connect amplifier output to both SCA Input and oscilloscope channel 1.

   **SCA Settings:**
   - ULD 10
   - LLD 0
   - NORMAL MODE

   Connect SCA Output to CH 2 of scope and set Trigger source to CH 2. Display the channel 2 signal. Sketch the waveform of the SCA Output showing both the amplitude and duration.

   Now display both the output from the Amplifier and the SCA (i.e., channels 1 and 2).

2. Raise the Lower Level Discriminator (LLD) and describe what happens to the channel 1 display.

3. Return LLD to zero, and now lower the Upper Level Discriminator (ULD) and describe what happens.

4. Describe the relationship between the SCA output pulse and the detector signal.

5. Set SCA to WINDOW MODE, ULD to 5 (or 0.5 Volts) and LLD to 2 (or 2 Volts). Scan LLD up and down and describe what happens.

6. Set LLD to about 2, ULD to 2 (Window Mode), and from the scope measure the range of pulse amplitudes that are displayed on the scope. Does this check with the ULD setting?
7. Does the relationship between the SCA and detector pulse described in part c still hold?

PART III. γ-ray SPECTROSCOPY

1. Using the SCA as set up in Part II(f), connect the SCA output to the Linear Rate Meter and position the Cs source so that a count rate of about 500 per second is measured.
   Linear Rate Meter Settings. Range 1K
   % Std. Error 3
   Input 2V/Pos

2. Prepare a table of count rate versus LLD setting as the LLD is varied from 0.40 to 10.00 in steps of 0.2. Graph your results and compare with figure 5.28 of Melissinos. On your graph, note the positions of the photoionization peak and the Compton edge. Determine the energy of the Compton edge from this data.

3. Connect the output of the PMT (or, equivalently, the detector) to the input BNC on the back of the SPECTECH UCS 30 computer interface box. Set an appropriate amplifier gain using the UCS 30 software. Record γ-ray spectrum of the $^{137}$Cs source using the computer as a MCA. (Instructions for using the computer as a MCA can be found on the attached pages.) Again note the positions of the photoionization peak (or photopeak) and the Compton edge, and determine the energy of the Compton edge.

4. Use the Compton formula from the theory section of this write up to determine the electron energy for the Compton edge and compare with your measured results from Part I (e) and Part III (b) and (c).

5. Record spectra of the $^{60}$Co and $^{137}$Cs sources using the same photomultiplier voltage and the same amplifier settings. If your Cs PI peak is centered at a channel bin in excess of 512 then you may not even see the PI peaks from your Co source. In this case you may decrease the course gain by a factor of two. Use the 662 keV photopeak and Compton edge from the $^{137}$Cs source to calibrate the spectra and determine the energies $^{60}$Co γ-rays. Include uncertainty estimates with your Co results.
Final Questions to be answered as part of the laboratory report for this experiment (You may discuss these with your lab partner(s) but the final answer should be your own work.):

1. The NaI scintillation crystal is 2" thick and 2" in diameter. On the basis of the total attenuation coefficient for NaI, what is the probability that an axially directed 0.662 MeV gamma ray will be absorbed or scattered within the crystal?

2. Of all the 0.662 MeV photons that are scattered or absorbed within the crystal approximately what fraction undergo Compton Scattering?

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

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

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

6. When voltage pulses are presented to the input of the Single Channel Analyzer, the SCA determines which pulses are acceptable, and then the SCA converts the acceptable pulses into standard sized pulses available at its Output for counting. If the ULD setting is 5 and the LLD setting is 3, what are the acceptable voltage pulses:
   in the NORMAL MODE?
   in the WINDOW MODE?

7. The MCA is equivalent to 1024 SCA’s operating simultaneously. For bin number 512 of the MCA, what would be the corresponding LLD and ULD settings of the SCA:
   in the NORMAL MODE?
   in the WINDOW MODE?
Personal Computer as a Multichannel Analyzer (or Multichannel Scalar)

A Personal Computer in combination with a SPECTECH UCS 30 module and associated software becomes a 1024 channel multichannel analyzer. (It also serves as a multichannel scalar in Experiment 3.) The built-in amplifiers of the UCS 30 module enable you to analyze pulses from the PMT without using external amplifiers. The following abbreviated instructions are intended only to help you get started using the computer and UCS 30 module. More detailed instructions are available by clicking ‘Help’ after loading the UCS 30 program.

Getting Started:

1. Check that the USB cable from the UCS 30 module is connected to a computer USB port and that the UCS 30 module has power before starting the UCS 30 software.

2. Click on ‘Mode’. Click on ‘PHA-amp in’.

3. Click on ‘Settings’. Click on ‘Amp/HV’. Set the ‘High Voltage’ to ‘OFF’ because you are using an external high voltage source for the PMT. Set the ‘Conversion Gain’ to ‘1024’. Set the ‘Course Gain’ to ‘64’. Set the ‘Fine Gain’ to ‘2.0’. Set the ‘LLD’ to ‘2.0’. This LLD setting discards the lowest amplitude background pulses. Set the ‘ULD’ to ‘102.3’ which is the highest setting possible.

4. Turn on your gamma ray detection system as described in steps 1-3 of Part I. The photop eak pulses should be no more than about 35mV for the above gain settings. You should have already connected the PMT output directly to the input on the back of the UCS 30 module and USB module output to an input on the front of the PC.

To Acquire Data

5. Turn on your gamma ray detection system as described in steps a-c of Part I. Then click on the green circular ‘Go’ icon on left.

To Stop Acquiring Data

6. Click on the red octagonal ‘Stop’ icon on left

Vertical Scale Changes

7. Click and drag the slide at the right edge of the display or use the up and down keys.

Channel Marker

8. The flashing channel marker is moved across the screen using the left/right arrows (← / →) or by clicking and dragging the marker. The channel position of the marker and the data contents of that channel are displayed under the origin of the plot.

Regions of Interest - Analysis of Peaks in the Spectrum
9. The centroid of a peak, its full width at half-maximum, and the integrated counts under the peak can all be displayed using the 'Region of Interest' function. To set up a peak as region of interest, move the channel marker to the lower or upper edge of the peak. Click on ‘ROI’s’. Click on ‘Set ROI’. Click and drag the channel marker to the other edge of the ROI.

To clear all ROI’s, click on ‘Settings’. Click on ‘ROI’s’. Click on ‘ClearAll’. To clear individual ROI’s, set the channel marker on the ROI. Click on ‘Settings’, did on ‘ROI’s’. Click on ‘Clear ROI’.

Erase

10. Click on the ‘Eraser’ icon on the left to erase the displayed data.

Printing

11. Click on ‘File’. Click on ‘Print’.

Analysis

12. Many students are already quite familiar with Microsoft Excel. Other data analysis software programs are available in the lab, but we will emphasize Excel because so many students are already familiar with it. To move your data to Excel, start up Excel and UCS 30 simultaneously. Save your data from the UCS 30 software as a tab separated or *.tsv file. Open the *.tsv file from Excel.

NOTE The preceding abbreviated instructions are intended only to help you get started using the computer.