Multichannel *γ*-ray Spectroscopy

Objectives: This experiment is designed so you will be able to:
1. Calibrate a multichannel analyzer and use it to acquire gamma-ray spectra.
2. Locate primary photopeaks in *γ*-ray spectra and correlate these with nuclear decay schemes.
3. Analyze spectral features resulting from the interactions of "low energy" *γ*-ray photons.

Theoretical Background

SPECTRAL FEATURES

Gamma rays having energies of less than 1 MeV interact by either photoelectric or Compton processes. (Compton scattering results in a photon wavelength shift of $\Delta\lambda = (h/m_ec)(1-\cos\theta)$ where θ is the scattering angle; Compton scattered photons often escape the detector). When these processes occur in the NaI detector, four major spectral features result. These features are labeled on the counts vs. channel number graph for ^{137}Cs shown on the next page.

1. The Photoelectric Peak: This is primarily the result of initial photoelectric interactions which is why it is referred to as the Photoelectric Peak or simply the photopeak. However, gamma photons that are initially Compton scattered (and thus lose energy), but do not escape the detector, can undergo subsequent photoelectric absorption and the total amount of light produced is the same as if the initial interaction had been photoelectric so a full energy pulse is observed. Thus, this peak is sometimes referred to as the total absorption peak.

2. The Compton Edge: This feature is due to photons that undergo Compton scattering with a scattering angle of 180° and then escape the detector. For a gamma ray photon of energy *E*, the energy, *E′*, of the 180° Compton scattered photon is given by:

$$E' = \frac{E}{1 + 2E/m_ec^2} \qquad (1)$$

   where $m_ec^2 = 511$ KeV is the electron rest energy. The energy, E_c, deposited in the detector by such an event is the maximum for Compton events and will be equal to the difference between the initial and the scattered (and escaped) gamma photon energies:

$$E_c = E - E'. \qquad (2)$$

   Since E_c is the maximum energy for Compton scattering but still less than the photopeak energy, the count rate falls off very rapidly for energies greater than E_c and an edge to the Compton continuum is formed in the spectrum.

3. The Valley: Pulses corresponding to an energy between E_c and E are infrequently produced. Thus, the region between the Compton edge and the photopeak should be void of pulses. However, due to the moderate resolution of the detector, the void is filled on either side resulting in a V-shaped depression known as the "valley".
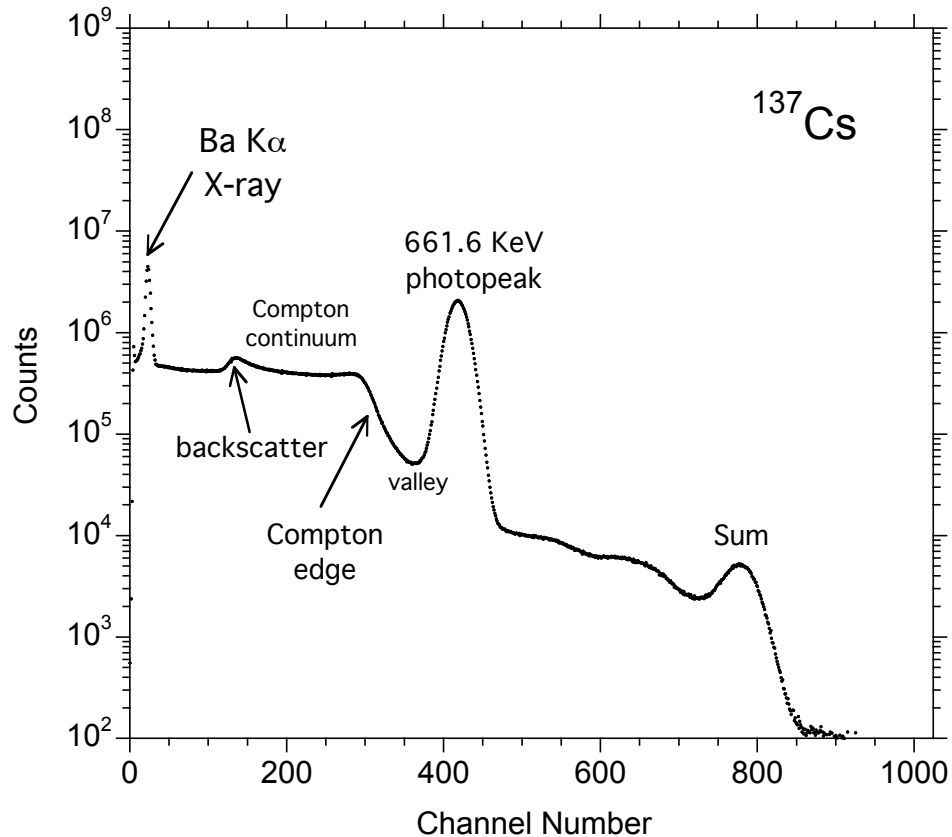
Fig. 1 Gamma spectrum of a ^{137}Cs source from a 3.8 cm x 2.5 cm NaI(Tl) scintillation detector without lead shielding.

4. The Compton Continuum: Compton interactions in which the Compton photons scatter at angles less than 180° and then escape the detector deposit less than E_c in the detector. The energy deposited decreases with scattering angle and since the angle can take any value, the resulting pulse heights range downward from that of E_c in an almost continuous manner producing a plateau-like feature in the spectrum.

5. Sum Peaks: Occasionally two gamma ray photons will be simultaneously measured in the detector. Such events give rise to measurable "sum peaks" associated with full conversion of both gamma rays.

Gamma rays entering materials and shielding near the detector can be Compton scattered into the detector or interact producing X-rays that can enter the detector. Such secondary photons produce the following spectral features:

1. High angle Compton scattering: The shape and level of the Compton continuum with respect to the amplitude of the photopeak is markedly influenced by the location and composition of the

materials surrounding the detector (and source). High angle (greater than 90°) Compton scattering will tend to increase the lower energy region of the continuum.

2. The Backscatter peak: This feature results from very high angle (close to 180°) scattering in material exterior to the detector which populates the spectrum in the vicinity of E'. The resultant peak is broad and unsymmetrical and quite unlike a true photopeak in this energy region.

3. Fluorescent X-rays: Gamma interactions with K-shell electrons of high-Z materials will produce fluorescent X-rays in the KeV energy range. Any lead placed near or around the detector can thus produce a small 72-KeV photopeak in the spectrum. (This feature does not appear on the spectrum shown above.)

Many radionuclides also emit X-rays through the processes of internal conversion or decay by electron capture. The photopeak of K X-rays of a higher-Z element is generally seen in the very low energy region of the spectrum. Depending on the setting of the MCA LLD (Lower Level Discriminator used to eliminate low level electronic noise), the photopeak for L X-rays may also be seen. For Cs-137, the K X-ray from Ba produced by internal conversion is 32.1 KeV and is a dominant feature of the low end of the spectrum shown above. The L X-rays from Ba have an energy of 4.5 KeV.

Experimental apparatus: You will be using a NaI crystal attached to a photomultiplier tube, similar to the SCA lab, but with a different detector and electronics system. This detector is connected to an interface board in a white box that contains an amplifier and an Analog-to-Digital converter (ADC). The ADC takes the voltage pulse in and sends out to the computer an integer between 0 and 1023. Zero is the measure for a voltage pulse less than a hundredth of a volt, and 1023 is the measure for a pulse larger than about 8 V (the largest pulse accepted by this ADC). Pulses between 0 and 8 V are proportionately given an integer measure between 0 and 1023. This measure is called the channel number. The computer acts as a multichannel analyzer (MCA) and records and displays these measurements as the number of gamma rays observed for each integer measure, or channel number. How does this compare to the SCA and the spectrum that you took in that lab?

Standard sources you will need are ^{22}Na, ^{137}Cs, ^{54}Mn, ^{57}Co, ^{60}Co, ^{133}Ba, and ^{116}In. Get the sources only when you need them. Your instructor will show you where they are located. The ^{116}In is in the neutron flux tank and must be retrieved by your instructor.

Part I: Energy Calibration

Experimental Procedure

1. If not done already, connect the high voltage cable between the detector's PMT and the interface board. Also connect the data cable from the interface board to the PMT.
2. Turn the box power on before starting the program.
3. Start program by going into Programs → SpecTech →UCS20.
4. Once in the program, either using a button or by going to Settings→Amp/HV/ADC, set the high voltage to 550 V (click "on"), the coarse amplifier gain to 4, the fine amplifier gain to about 1.5, the conversion gain to 1024, and the LLD to 0. Look at Mode Menu to be sure Pulse Height is checked. Also check the Display Menu to be sure Calibration and ROIs are both unchecked. In the Settings menu, Clear all ROIs and Uncalibrate if a calibration is present.
5. Set the counts scale (y-axis) to logarithmic (Look for the button).
6. Get the ^{22}Na source from the lead brick box and place it directly under the crystal end of the detector (label side away from detector). Take data by pressing the Go button. Once you get well-defined peaks (including the small X-ray peak, due to lead, near the left end of the spectrum) you can stop data acquisition.
7. If your spectrum does not look similar to the one shown below you will need to make adjustments to the gain settings. Increasing the gain will "stretch" the spectrum out while decreasing gain will contract the spectrum. Start with fine gain adjustments and if this is not sufficient, try changing the coarse gain by multiples of 2. If you need additional gain, you may need to adjust your high voltage (HV) in 25 V steps. To take a new spectrum erase the current spectrum and press Go.
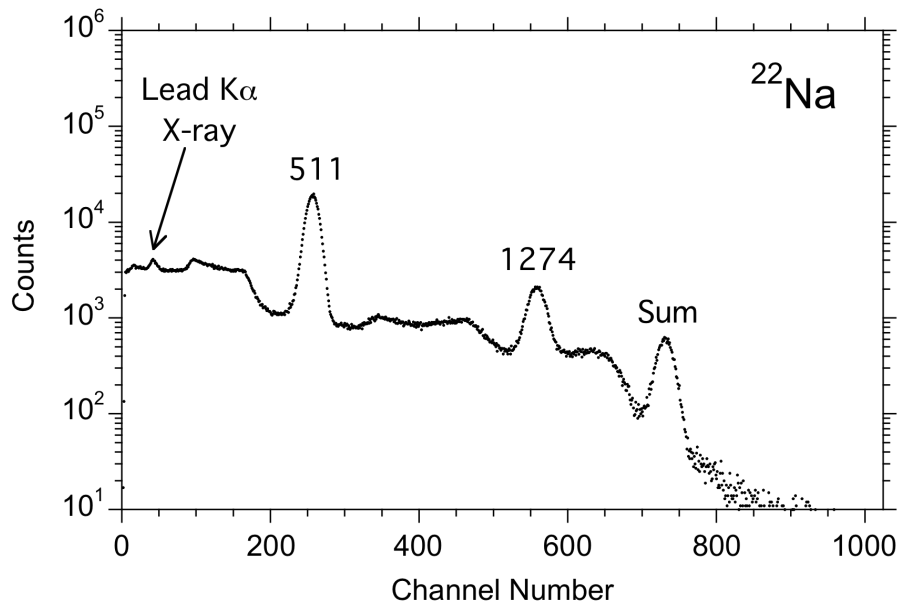

Fig. 2 Gamma spectrum of a ^{22}Na source from a 3.8 cm x 2.5 cm NaI(Tl) scintillation detector with lead shielding.

8. Once you have determined the appropriate gain settings for the ^{22}Na spectrum take a new ^{22}Na spectrum acquiring data until the largest photopeak reaches at least 16K counts.

9. Locate the centroid of each peak in this spectrum using an ROI analysis. To set a region of interest (ROI), go to Settings→ROI → Set ROI. You can then use your cursor to highlight your ROI. Place a ROI around each peak, recording the centroid and other information given at the bottom of the page.

10. To calibrate the MCA, go to Settings →Energy Calibrate → 3 point, and follow the computer's prompts. Use the 511 KeV and 1274.5 KeV ^{22}Na photopeaks and the 72 KeV Pb X-ray peak as the three calibration points.

11. To check the calibration, acquire a spectrum for ^{137}Cs and do an ROI analysis of the main photopeak located at 661.6 KeV. If your centroid result is not within 10 KeV of this value redo your calibration.

12. Your system is now energy calibrated. You should periodically recheck your calibration with the ^{22}Na source. BE PREPARED TO RECALIBRATE (it's not that hard to do)! You will probably need to recalibrate every time you restart your computer and certainly you must recalibrate if you change any gain or detector bias (voltage) settings.

## Part II: Backscattering, shielding, and detector resolution

Experimental Procedure (**Use only a 5μC ^{137}Cs source for this part of the experiment.**)

1. Mount the detector in its vertical position with its lead shield around it.
2. With all sources put away, take a five-minute background spectrum.
3. Mount the ^{137}Cs disc source so that it is held close to the end of the detector. (Note that the labeled side of the disc is the active side). Take a five-minute spectrum. The observed photopeak should be centered near 661.6 KeV. If it is not within 10 KeV of this value, recalibrate your system and start over.
4. Place an aluminum block directly below the source and take another five-minute spectrum. The aluminum will act as a backscattering material for the photons coming from the ^{137}Cs source.
5. Repeat 4 using a lead brick instead of the aluminum block as a backscattering material.
6. Without any backscattering material, carefully take a five-minute ^{137}Cs spectrum <u>without</u> the lead shield that holds the detector in place. Also take a five-minute background spectrum for this configuration.

Data analysis:

1. Subtract the relevant background from each of the plots using the Strip Background utility. Plot all four "stripped" graphs on the same plot to help emphasize the differences. (To make this combined plot you will need to save each of the spectra as a ".csv" or ".tsv" file and then import these into either Excel or Kaleidagraph).
2. Explain the features of the spectra with and without shielding and with aluminum or lead as backscattering material.

3. Using Eqs. (1) and (2), calculate the location of the backscattering peak E' and Compton edge E_c for the 662 KeV gamma rays from ^{137}Cs. How do these values compare with the features on your spectra?

4. Do you expect any X-ray peaks in your spectra? If so at what energies? Are these peaks present?

5. Resolution describes the ability of a spectrometer to distinguish the presence of gamma rays closely spaced in energy. The practical measure of resolution is the width of the photopeak at half its amplitude known as the Full Width at Half Maximum (FWHM). For NaI(Tl) scintillation detectors, the convention adopted is to define the resolution as the relative FWHM of the ^{137}Cs 662 KeV photopeak. Hence, the resolution will be the FWHM divided by the position of this photopeak centroid expressed on the pulse height (or channel number) scale as shown in the figure:
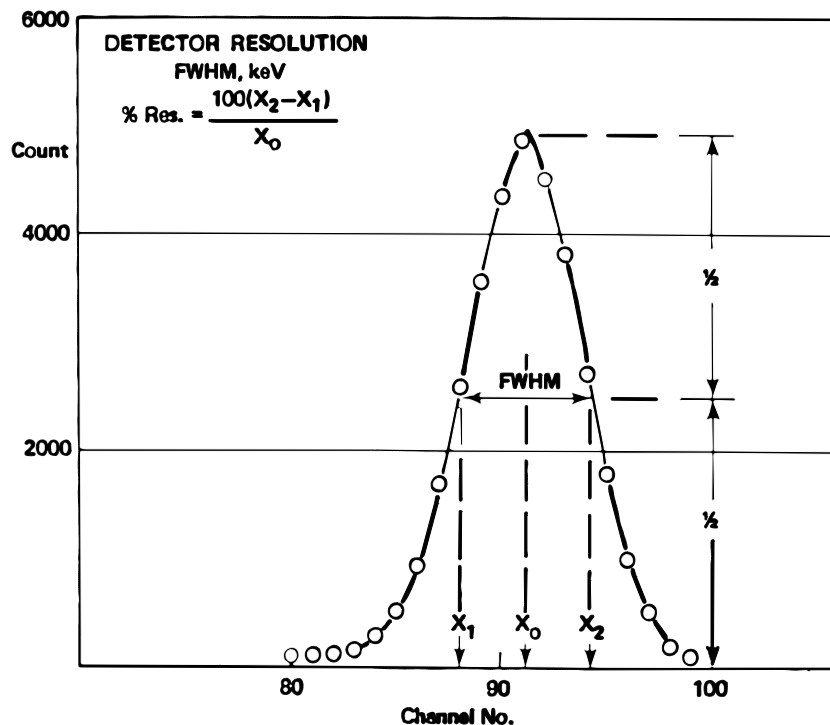
Expressed as a percent, the resolution of a good NaI (Tl) detector should be about 8%. This should be established for the particular detector in use to know about its limitations and also to monitor performance with time. An early indication of detector failure is loss of resolution. Use one of your ^{137}Cs spectra to determine the resolution of our detector.

Part III: γ-ray spectra and nuclear "decay" schemes

Experimental Procedure
    1. Start the MCA using the calibration of the previous part of the lab. Check the calibration with a

[137]Cs source. The observed photopeak should be centered near 661.6 KeV. If it is not within 10 KeV of this value, recalibrate your system.
2. Acquire a gamma spectrum for each of the following sources: [22]Na, [54]Mn, [57]Co, ^{60}Co, [133]Ba and the unknown source. Data acquisition should be for at least 10 minutes (longer is better). For each spectrum, determine energies of all spectral details (i.e., photopeaks, X-ray peaks, backscatter peaks, Compton edges, and sum peaks). You should have a printout of each spectrum annotated with these measured energies. Also, for each photopeak do an ROI analysis and determine the centroid energy, channel number, and Full Width at Half Max (FWHM).

Data Analysis:
1. Look up the nuclear decay scheme (see http://www.nndc.bnl.gov/mird/ and use pdf output) for each of the nuclei and make a list of all expected photopeaks. Compare your measured photopeak values with those expected. Do you actually find all the expected peaks? How well do the energy values agree?
2. Can you locate a Compton plateau and a backscattering peak for each photopeak? Do these features appear at the expected energies?
3. Do you observe X-ray and/or sum peaks in any of the spectra?
4. Explain how the 511 KeV photopeak is produced.
5. Determine the most likely isotope(s) in the unknown source by comparing observed photopeaks with those tabulated in the list of Commonly Observed Gamma Energies that was provided.
6. Graph the expected gamma energies of your photopeaks as a function of the channel number. Do the peaks follow a linear curve? If so, is it for the whole region? If not, where do they diverge?
7. Compute a quadratic fit. How does that compare to the linear fit? Why do we use 3 points for a calibration curve?

Part IV: A complex spectrum ([116]In)

Experimental Procedure
1. Recalibrate the MCA using the [22]Na source and the 511 KeV photopeak, 1785.5 KeV sum peak, and the 72 KeV Pb X-ray peak as the three calibration points.
2. Obtain the [116]In source from your instructor (these are the sources used for the half-life study in Intro Physics). Place the sample against the scintillation detector and acquire data for at least two half lives (longer is better).

Data Analysis
Determine the energy of all peaks in your spectrum. Consult the nuclear decay scheme for [116]In and make a list of all expected photopeaks. Do you observe all of these expected peaks in your spectrum? Do you observe any additional peaks?