

Gamma Ray Spectroscopy

Experiment GRS

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Objective

Techniques in gamma ray spectroscopy using a NaI scintillation detector are explored. You will learn to use a pulse height analyzer and be able to explain and identify the photopeak, the Compton edge, and the backscatter peak associated with gamma ray interactions. In addition, activity and half-life measurements are explored.

References

- Jerome L. Duggan *Laboratory Investigations in Nuclear Science*, 1988, The Nucleus.
- EG&G ORTEC *Experiments in Nuclear Science*, 1984, EG&G ORTEC.
- A. C. Melissinos, *Experiments in Modern Physics*, 1966, Academic Press.

Scintillation Detector

A block diagram for a typical scintillation detection system is shown in Fig. 1. The scintillation detector is illustrated in Fig. 2. Our detector has a 4×4 inch cylindrical NaI scintillation crystal which is activated with about 1 part in 10^3 thallium impurities. Through various processes, a gamma ray passing into the crystal may interact with it creating many visible and ultraviolet photons (scintillations).

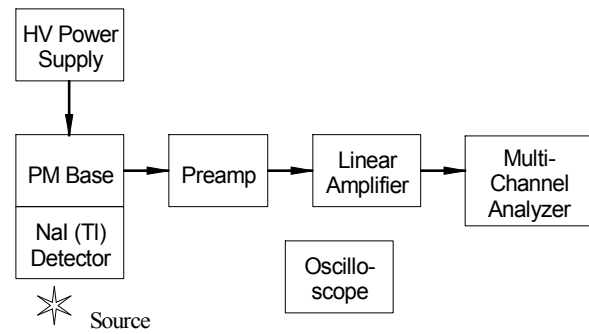


Figure 1: Block diagram for a scintillation detector system.

To detect the scintillation photons, the crystal is located next to a photomultiplier tube (PMT) and the scintillator/PMT (detector) is enclosed in a reflective, light-tight housing. To minimize the effects of background gamma radiation, the detector is surrounded by a thick lead shielding tube with the desired gamma rays entering at the scintillator end of the tube.

The PMT consists of a photocathode followed by a series of dynodes (6-10 is typical) followed by and ending with a collection anode. Scintillation photons striking the photocathode eject electrons via the photoelectric effect. A high voltage (HV) power supply and a resistor chain (not shown) bias the cathode, dynodes, and anode so as to accelerate elec-

trons from the cathode into the first dynode, from one dynode to the next, and from the final dynode to the anode collector. Each incident electron strikes a dynode with enough energy to eject around 5-10 (secondary) electrons from that dynode. For each initial photoelectron, by the end of the chain, there are on the order of 10^6 electrons reaching the anode.

The anode is connected to a charge-sensitive preamplifier which converts the collected charge to a proportional voltage pulse. The preamp pulse is then shaped and amplified by a linear amplifier before processing continues.

Because the amount of light (number of photons) produced in the scintillation crystal is proportional to the amount of gamma ray energy initially absorbed in the crystal, so also are the number of photoelectrons from the cathode, the final anode charge, and the amplitude of the preamp and amplifier voltage pulses. The overall effect is that the final pulse height is proportional to the gamma ray energy absorbed in crystal.

Pulse Height Analyzer

As the name suggests, a pulse height analyzer (PHA) measures the height of each input pulse. Special circuitry, including a sample and hold amplifier and an analog to digital converter, determines the maximum positive height of the pulse—a peak voltage as might be read off an oscilloscope trace. From the pulse height, a corresponding channel number is calculated. For example, for a PHA having 1000 channel capability and a pulse height measurement range from 0 to 10 V, a pulse of height 1.00 V would correspond to channel 100, one of 2.00 V would correspond to channel 200, one of 8.34 V would correspond to channel 834, etc. After the correct channel for

a given input pulse has been determined, the PHA then increments the count in that channel.

Our PHA can analyze pulse heights in the range 0-10 V and will be set up to sort them into 1024 channels.

After many pulses of various sizes have been processed, a plot of the counts in each channel versus the channel number can be displayed to show the distribution of pulse heights. With some caveats to be described shortly, the pulse height distribution from a scintillation detector can be interpreted as a plot of the number of gammas versus the energy of the gammas from the source, i.e., a gamma ray spectrum of the (radioactive) source. Spectra from pure isotopes can be found in references and compared with a source spectra to determine the nuclear composition of the source.

Gamma Interactions

To understand the pulse height distribution associated with the gamma rays from a radioactive source, it is important to realize that only a fraction of the gamma rays interact with the scintillator; many do not interact at all and simply pass right through. Furthermore, when a gamma does interact, the size of the pulse from the detector depends on whether all or only part of the gamma ray energy is deposited in the scintillator.

For a given amount of energy deposited in the scintillator, the output pulse height will be well-defined but every pulse will not be exactly the same size. Because of statistical variations in light production, photon collection, photoelectron production, and electron multiplication, the pulse heights will show a distribution of values with some pulse heights larger and some smaller than the average. Typical variations with our detector are in the range of 5-10 percent.

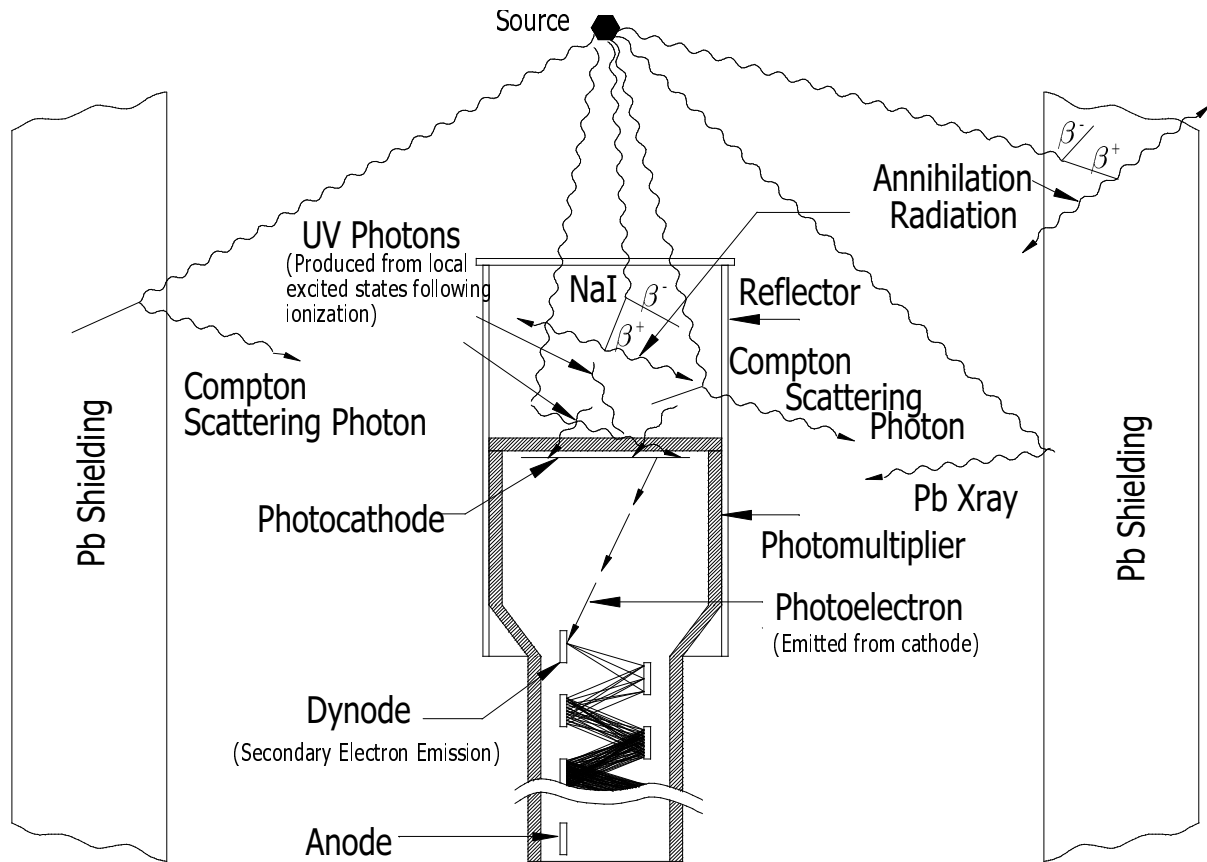


Figure 2: Schematic of a NaI detector and source showing various gamma ray interactions.

The pulse height distribution for a source emitting only single energy gamma rays typically appears as in Fig. 3. The large peak at the far right is called the photopeak and arises when all the gamma ray energy is deposited in the scintillator. Note the 5-10% width of this peak due to statistical fluctuations.

The most likely interaction to deposit 100% of the gamma ray energy is the photoelectric effect. The incident gamma essentially gives up all its energy to eject a bound inner shell electron from one of the crystal atoms. The ejected electron then has significant kinetic energy (the gamma ray energy less the small binding energy of the atomic electron, on the order of 10 keV) and loses this energy by exciting and ionizing more crystal atoms.

Compton scattering is another way gamma rays can interact in the crystal.

Exercise 1 *Compton scattering is a purely kinematic scattering of an incident gamma photon of energy E_γ with an electron (mass m) in the crystal that is either free or loosely bound ($E_e \approx 0$, $p_e \approx 0$). Use conservation of energy and momentum to show that when the gamma is scattered through an angle θ , its final energy E'_γ is reduced to*

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma/mc^2)(1 - \cos \theta)} \quad (1)$$

The small peak at low voltage (called the backscatter peak) arises when gamma photons first strike the lead shield and then Compton

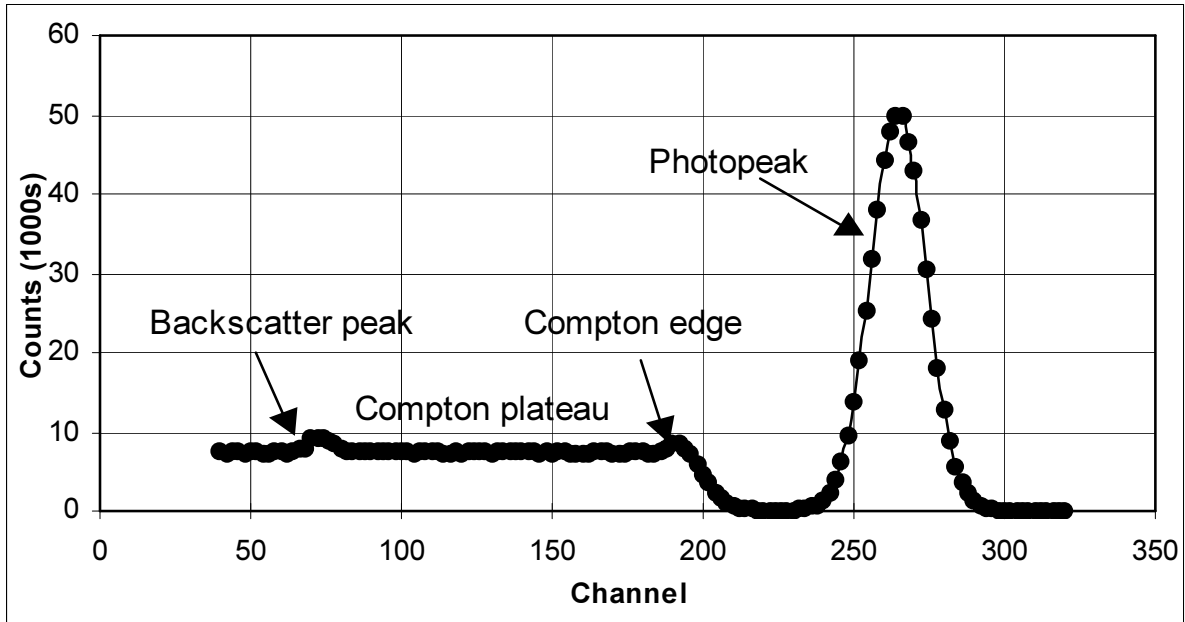


Figure 3: Pulse height spectrum for a monochromatic gamma ray source.

scatter back into the detector. The scattered photons, which are greatly reduced in energy, produce the backscatter peak. The Compton plateau—the relatively flat region extending from the Compton edge to lower energies—occurs when gamma rays Compton scatter in the scintillator. The recoiling electron’s energy is deposited in the crystal while the scattered photon exits the crystal undetected. The recoil energy varies from a maximum at the Compton edge when the photon backscatters, to zero when the photon is scattered in the forward direction.

Exercise 2 (a) Assume a 0.662 MeV gamma from a ^{137}Cs source Compton scatters in, and then escapes from, the scintillation crystal. What is the maximum energy that can be absorbed in the scintillator? (b) Assume the same energy gamma first Compton scatters from the lead shield and is then totally absorbed in the scintillator. What is the minimum energy that can be absorbed in the crys-

tal?

The third way gamma rays interact is through pair production. In the strong electric fields near crystal nuclei, a gamma ray can create an electron-positron pair as long as the gamma ray energy exceeds 1.022 MeV (the rest mass energy of an electron and positron). Any gamma energy in excess of this becomes kinetic energy of the electron and positron. This kinetic energy is quickly absorbed in the crystal and when the positron gets to low enough energy, it annihilates with an electron producing two 0.511 MeV gammas. The creation, energy loss, and annihilation effectively occur instantaneously. If both annihilation gammas are absorbed, the total energy absorbed will be the original gamma energy and the event would contribute to the photopeak. However, sometimes either or both of the annihilation gammas will escape from the crystal producing small peaks (called single or double escape peaks) 0.511 MeV or 1.022 MeV below

the photopeak.

Energy Resolution and Calibration

In addition to the gamma ray energy, and the way it interacts in the scintillator, electronic factors also affect the size of the pulses measured by the PHA. Of course, the preamp and amplifier gain will affect the overall size of the pulses. In addition, because of the many stages of electron multiplication, the pulse heights are very sensitive to the PMT supply voltage. Thus, the HV supply must be very stable. It is not normally adjusted to change the overall gain because the PMT typically works best over a fairly narrow range of voltages.

To perform an energy calibration on the PHA system, sources of well known gamma ray energies are used. The channel number C_γ for the center of the photopeak corresponding to each gamma ray energy E_γ is recorded and a plot of E_γ vs. C_γ is constructed and analyzed. For non-precision work, the relationship can be assumed linear with a small zero offset (intercept).

$$E_\gamma = \kappa C_\gamma + E_0 \quad (2)$$

where κ , called the energy scale, has units of energy/channel. A quadratic term is typically added to account for small nonlinearities.

Once the calibration is known, the energy of an unknown peak can be obtained through the center channel of its PHA photopeak. Because the HV and/or amplifier gain may change over time, it is wise to perform a calibration before any critical measurements.

The width of the photopeak is a measure of the energy resolution of the detection system. The smaller the width, the closer two gammas can become in energy and still be observed as separate peaks in the pulse height

spectrum. Consider a photopeak appearing in a pulse height spectrum at channel C and having a full width at half maximum of ΔC . The energy resolution R is commonly expressed by the ratio of the photopeak's full width at half maximum (in energy units) $\Delta E = \kappa \Delta C$ to its energy $E = \kappa C + E_0$. If, as is usually the case, the calibration offset E_0 is small, the energy resolution is easily obtained from the pulse height spectrum as

$$R = \frac{\Delta C}{C} \quad (3)$$

R decreases with increasing gamma ray energy and is nominally 5-10% for NaI detectors for the ^{137}Cs 0.662 MeV gamma.

The energy resolution will also depend on the PMT supply voltage. Furthermore, there is often a "focus" adjustment on the PMT base which changes the voltage between the photocathode and the first dynode producing small changes in the overall gain and energy resolution.

Nuclear Decay

The activity of a sample denotes the rate of nuclear disintegrations. An activity of 1 curie represents 3.7×10^{10} nuclear disintegrations per second. What happens after the disintegration depends on the nucleus.

For ^{137}Cs , the result is the formation of ^{137}Ba and a β particle (electron). Eight percent of the time the β carries away all the excess energy, and 92% of the time the ^{137}Ba is left in an excited state which decays to the ground state by the emission of 0.662 MeV gamma. Thus, the rate of 0.662 MeV gamma emission is 0.92 times the activity.

^{60}Co also decays by β emission to ^{60}Ni . The ^{60}Ni is left 99% of the time in an excited state 2.507 MeV above the ground state. This excited state decays by emission of a 1.175 MeV,

followed within a picosecond or so by a second 1.332 MeV gamma. Thus each of these gammas are emitted at a rate 0.99 times the source activity.

^{22}Na decays by β^+ (positron) emission (90% of the time) or by electron capture (10% of the time) to ^{22}Ne . Nearly 100% of the time the ^{22}Ne nucleus is left in an excited state, decaying within a few picoseconds to the ground state with the emission of a 1.274 MeV gamma. The high-energy positron thermalizes in the source (if it is thick enough) or the surrounding air within a few nanoseconds and then annihilates with an electron producing two 0.511 MeV gammas. Thus the rate of 1.274 MeV gammas is equal to the activity and 0.511 MeV gammas are emitted at 1.8 (2×0.90) times the activity.

^{54}Mn always decays by electron capture to an excited state of ^{54}Cr which then decays to the ground state with the emission of 0.835 MeV gamma.

Activity Determinations

If one has a source of known activity α_k , the unknown activity α_u of a source of the same isotope can be determined from the ratio of the count rate of the unknown R_u to that of the known source R_k .

$$\alpha_u = \alpha_k \frac{R_u}{R_k} \quad (4)$$

For this method, the unknown and known source must be measured under the same conditions. For example, the detection system should be the same and the sources should be placed identically.

Absolute activity determinations can be made if various “efficiencies” are known. For example, if a photopeak is well-separated in the source spectrum and the isotope responsible for the photopeak has been identified, the

activity α of the source (from the identified isotope) can be based on the observed count rate R_E in that photopeak. The activity determination would then require that the probability p that a nuclear disintegration results in a count in that photopeak be known.

$$R_E = \alpha p \quad (5)$$

In turn, p will be a product of the fraction f of the nuclear disintegrations which result in such a gamma, and a probability p' that the gamma will lead to a count in the photopeak.

$$p = fp' \quad (6)$$

Values for f for various sources is given in the section on nuclear decay or in reference books.

From the spreading out of the gammas we should expect p' to decrease as the detector-source distance increases. p' also decreases for higher energy gammas which are less likely to interact in the scintillator. In general, the dependence of p' (the absolute photopeak efficiency) on the gamma energy and on the detector-source geometry cannot be separated in any simple manner. However, the separation of $p' = G\epsilon$ into a geometry-only dependent factor G and an energy-only dependent factor ϵ is often a good approximation. G would represent something similar to the fraction of the gammas which enter the detector, e.g., $G = \Omega/4\pi$ where Ω is the solid angle subtended by the detector at the source. The intrinsic photopeak efficiency ϵ would then represent the probability that a gamma entering the detector produces a count in the photopeak. Various references show that ϵ typically decreases by an order of magnitude or so as the gamma energy increases from 0.5 to 2 MeV.

These considerations lead to the approximation

$$R_E = \alpha f G \epsilon \quad (7)$$

Note how this equation can also be used for a relative activity determination. By comparing

counts in the photopeak for a sample of known and unknown activity, the unknown activity can be obtained as long as the ratio of the various factors is known or can be estimated.

$$\frac{\alpha_1}{\alpha_2} = \frac{R_1 f_2 G_2 \epsilon_2}{R_2 f_1 G_1 \epsilon_1} \quad (8)$$

There is an interesting technique for making an absolute determination of source activity, but it requires that a single nuclear disintegration produce two simultaneous gammas of well defined energy, such as occurs for ^{22}Na or ^{60}Co .

We label the two gammas γ_1 and γ_2 . Let p_1 (or p_2) represent the probability that a nuclear disintegration leads to a γ_1 (or γ_2) whose full energy is deposited in the scintillator, such as might lead to a count in the photopeak. Let q_1 (or q_2) represent the probability that a nuclear disintegration leads to a γ_1 (or γ_2) having only partial energy deposited in the scintillator, such as might lead to a count in the Compton plateau or the backscatter peak.

Because the gammas are emitted simultaneously, if both are detected, the result would be a pulse height corresponding to an energy equal to the sum of the energies from each gamma. For example, sometimes both gammas give up their full energy in the scintillator and there appears in the spectrum a *sum peak*—a well defined feature that looks like an ordinary photopeak and occurs at an energy equal to the sum of the energies of the γ_1 and γ_2 photopeaks.

For some sources, e.g., the 1.274 and 0.511 MeV gammas from ^{22}Na , the two gammas are emitted equally likely in all directions so that p_1 and p_2 are statistically independent. For other sources, e.g., the 1.175 and the 1.332 MeV gammas from ^{60}Co or the two 0.511 MeV gammas from ^{22}Na , the outgoing directions of the two gammas are correlated. For independent gammas, the probability that

both γ_1 and γ_2 would deposit their full energy in the crystal (i.e., the probability of a sum peak count) would be $p_1 p_2$ and the rate of detection of sum peak pulses would be

$$R_{12} = \alpha p_1 p_2 \quad (9)$$

The probability of detecting a count in the γ_1 photopeak would now be $p_1(1 - p_2 - q_2)$. That is, γ_1 must deposit its full energy in the scintillator (hence, the factor p_1) and γ_2 must not deposit any energy (hence, the factor $1 - p_2 - q_2$). The rate of detection of counts in the γ_1 photopeak would then be

$$R_1 = \alpha p_1(1 - p_2 - q_2) \quad (10)$$

Similarly, the rate of detection in the γ_2 photopeak would be

$$R_2 = \alpha p_2(1 - p_1 - q_1) \quad (11)$$

In the experiment, you will measure R_1 , R_2 and R_{12} . Since there are five unknowns (α , p_1 , p_2 , q_1 , and q_2), with only three measurements, two more relations are needed. If the ratios $\delta_i = q_i/p_i$ are assumed known, (the procedure section will describe a measurement for a rough determination of these ratios) then the activity α can be determined from the three preceding equations.

$$\alpha = \frac{(R_1 + R_{12}(1 + \delta_2))(R_2 + R_{12}(1 + \delta_1))}{R_{12}} \quad (12)$$

Note that p_1 and p_2 can also be determined

$$p_1 = \frac{R_{12}}{R_2 + R_{12}(1 + \delta_1)} \quad (13)$$

$$p_2 = \frac{R_{12}}{R_1 + R_{12}(1 + \delta_2)}$$

Procedure

^{137}Cs Spectrum

A ^{137}Cs source is known to emit a single gamma ray of energy 0.662 MeV and should

produce a pulse height spectrum like that of Fig. 3 except that the backscatter peak, which is affected by the significant lead shielding around our detector, will be bigger and broader.

1. Turn on the NIM electronics supply rack.
2. Check that the PMT HV power supply is set to positive polarity. The switch is on the back. Set the PMT HV supply to 800 V. Turn on the supply.
3. Set the preamplifier on the $\times 1$ setting. Set the amplifier input to negative and output to unipolar. Set the amplifier coarse gain at 4.
4. Place a $1\ \mu\text{C}\ ^{137}\text{Cs}$ disk source about 10 centimeters from the front of the detector. Look at the preamp output with the oscilloscope—sensitivity 1 V/division, 1–20 μs /division time base. Describe what you see on the oscilloscope.
5. Look at the amplifier output with the oscilloscope. Describe what you see. Switch the amplifier to bipolar output. How do the pulse shapes change? The zero-crossing of bipolar pulses will be more precisely correlated with the time at which the original gamma interacted in the detector, while the amplitude of unipolar pulses will typically be more precisely correlated with the energy of the original gamma. Thus, the bipolar setting is normally used when one is interested in the timing of the gamma and the unipolar setting is normally used for spectroscopic analysis. Set the amplifier for unipolar output.
6. Turn on the Ortec PHA-equipped computer. Start the MAESTRO software. Select **Acquire|MCB Properties|ADC** and set the **Gain** to 1024 and the **Gating** to **Off**. Select **Presets** in this menu and clear all values or set them to zero. Select **Calculate|Calibration** and, if not grayed out, select **Destroy Calibration**. In the right-most item of the tool bar, select from the drop-down menu the detector (2 L1249-F MCB 1, and not the buffer. Select **Display|Full View** so you will display the entire 1024 channel spectrum on the main display. There are several ways to zoom in. If needed, learn these on your own. Select **Acquire|Clear** to erase the current detector spectrum. Select **Acquire|Start** to begin data acquisition.
7. Do the pulses viewed on the oscilloscope have a range of amplitudes? How do the scope traces demonstrate that all pulse amplitudes are not equally likely and there are more pulses at some amplitudes than at others. How does this correlate with what is observed on the PHA display?
8. Adjust the amplifier gain so that the photopeak pulse heights are around 6 V. Select **Acquire|Start** to begin data acquisition. After acquiring a spectrum, select **Acquire|Stop**. Set a region of interest (ROI) over the 0.662 MeV photopeak and then click inside this region. The software performs a fit to a Gaussian profile and supplies the peak center and the full width at half maxima (FWHM). Record these and determine the energy resolution.
9. Check how things change with count rate. The ^{137}Ba generator ($\approx 10\ \mu\text{C}\ ^{137}\text{Cs}$ source) is good for this part of the experiment. Move it close to the detector for high count rates, farther away for lower count rates. You may want to switch to

the 1 μC disk source to get to the lowest count rates. Check how the following change and explain what you find:

- (a) Resolution. Hint: look at the preamp pulses. The amplifier works off the derivative of the leading edge of the preamp pulse.
 - (b) Gain. What happens to the position of the photopeak? **Below what count rate or dead time does the gain become constant?**
10. In the next few steps, you will look for the dependence of the gain and resolution on the PMT high voltage setting. Retake a ^{137}Cs spectrum (at the current 800 V setting) with the source far enough away from the detector that the photopeak position and resolution should be unaffected by the counting rate. Leave its position fixed throughout these measurements. Measure and record the peak position and FWHM and calculate the resolution. Also record the amplifier coarse and fine settings.
 11. Being careful not to touch the 500 V selector switch (leave this at 500 V at all times), increase the high voltage to 850 V. Adjust the amplifier gain to get the position of the photopeak to roughly the same position as in the previous step. Measure and record the peak position and FWHM and calculate the resolution. Also record the amplifier coarse and fine settings.
 12. Repeat the previous step at a PMT high voltage of 750 V.
 13. Discuss the results.
 14. Set the PMT high voltage back to 800 V.

Dead Time

Note how the dead time percentage increases for high count rate conditions. Dead time is time the PHA is busy processing a pulse and not able to look at additional pulses coming in from the detector. Were you to measure spectra for a fixed time (called the *real time*) for both low and high count rate conditions, the effective time would be lower for the higher count rate because the acquisition would be “dead” for a greater fraction of the time. The Maestro PHA software can largely correct for this by providing the *live time*. The software effectively runs the live time clock only when it is not busy processing pulses.

15. Take a spectrum for a minute or so with the ^{137}Ba generator up against the detector noting the dead time percentage. Set one ROI over the entire spectrum. Click in it and record the total counts. Also record the live time and the real time. The difference between the real time and the live time is the time the PHA was busy processing pulses for this spectrum. Determine how long the PHA is dead for each pulse it analyzes.
16. Repeat the determination of this pulse processing time with the source backed away from the detector such that the dead time is about 10%.

Exercise 3 Show that, because of dead time, the measured count rate R_m would be lower than the true rate R (the rate that would be measured were there no dead time) according to the relation

$$R_m = \frac{R}{1 + RT} \quad (14)$$

where T is the dead time associated with each measured pulse, (i.e., as determined in Steps 15 and 16).

Background Correction

The detected gamma rays come not only from the source one is trying to measure, but from other sources as well. Since you will be working with several sources, it is important to move those not being studied far from the detector. Even with such precautions, there will still be detected gammas from cosmic rays, naturally occurring radioactivity in the building materials and from other sources. For some measurements it is wise to take into account these “background” gammas.

One of the simplest ways to do this with our system is via a *background subtraction*. To subtract out a background, first save your spectrum to the buffer using **Acquire|Copy to Buffer**. Next leaving all else unchanged, move the source away from the detector, and take a background spectrum. You want to take a long background to improve the precision of the correction, but you do not have to worry about differences in the collection times for the background and source spectrum. Any time difference will be scaled out in the subtraction. Save the background spectrum to disk and remember the name you give it. Select the buffer from the drop-down menu on the tool bar. You should be back to your source spectrum. Select **Calculate|Strip** and then select the previously saved background spectrum. The buffer should now contain the background-subtracted spectrum.

When in doubt, take a new background spectrum. It would change, for example, if you change the amplifier gain or move sources around.

Energy Calibration

As we will now be concerned with the relationship between the gamma energies and their photopeak positions, **all spectra should be taken with the sources placed far enough**

away from the detector that the gain reduction at high count rates is negligible. (See Step 9b.) Furthermore, while peak positions are generally insensitive to smoothly varying backgrounds, you should at least check one or two spectra to see if the photopeak positions change after a background subtraction.

17. Go back to using the ^{137}Cs disk source. Take a new, background-corrected spectrum. Record the channels at the photopeak center, the Compton edge and the center of the backscatter peak.
18. If the photopeak center channel is C_γ , a “quick and dirty” one-point calibration can then be performed assuming linearity and a zero offset. $E_0 = 0$, $\kappa = 0.662 \text{ MeV}/C_\gamma$. This step can be done manually or by the Maestro program by creating an ROI over the photopeak, clicking the cursor in the photopeak ROI, selecting **Calculate|Calibrate** and then entering the ^{137}Cs gamma energy of 0.662 MeV. From then on, the channel and energy will be displayed according to the one-point calibration. Print out the ^{137}Cs spectrum marking and labeling the channel value and energy at the photopeak, Compton edge and backscatter peak. Also supply on the graph, the value of κ . Roughly compare the Compton edge and backscatter peak energies with the predictions based on the Compton formula, Eq. 1.
19. Select **Calculate|Calibration** and destroy the one-point calibration.
20. Adjust the amplifier gain to make a 3 MeV gamma produce about a 10 V peak. That is, make the 0.662 MeV ^{137}Cs photopeak occur around channel 220. This step will make sure that the

highest energy peak (about 2.5 MeV) observed in this part of the experiment will be “in range.”

21. Take spectra for a ^{22}Na , ^{54}Mn , ^{60}Co , and ^{137}Cs sources. For each source, set the necessary ROI's and obtain the channel at the photopeak center. Make sure the count rate/dead time are low enough not to affect the gain. If in doubt, move the source farther away and check whether the peak position changes. Make an energy calibration table including the source isotope, the known gamma ray energy, and the photopeak center.
22. Make a plot of gamma ray energy vs. the measured photopeak center and perform a regression. Comment on the fit parameters and the fitting model (linear, or quadratic) and the “goodness of fit.”
23. Measure the spectrum of the unknown—a jar of white crystals that looks a bit like salt or sugar, but is neither. Just place the whole jar close to the detector. It is a naturally occurring mineral with a low natural abundance of a radioactive isotope. The spectrum will be weak and may need to be collected for over 30 minutes and stripped of the background. Use your calibration to determine the energy at the photopeak(s) and determine the isotope(s) present. Appendix A Section II of Duggan has a sorted list of gamma ray energies and isotopes.
24. Make the following measurements with the ^{22}Na , ^{54}Mn , and ^{137}Cs sources. Take background-corrected spectra for each source placing it along the centerline of the detector at distances of 0, 5, 15, and 30 cm.
25. Use the ROI feature to make tables of the **net** counts in each photopeak for all photopeaks, including the sum peak for the ^{22}Na source. For the ^{22}Na source make sure the acquisition time is long enough to get several thousand counts in the sum peak (except at the 30 cm source distance where the sum peak is too weak). For the ^{54}Mn and ^{137}Cs sources, also make a single ROI to cover both the Compton plateau and the backscatter peak for use in activity determinations described later. Record the **gross** counts for these ROI's. **For each spectrum, make sure you also record the live time.**
26. Check if the count rates behave (roughly) as expected with regard to distance. Are the ratio of the rates at the different distances consistent from source to source? What does this imply about the separability of the efficiency into a geometric and energy factor? Is the ratio of the counts at different distances reasonably related to an average detector solid angle at these distances? Keep in mind the detector is 4 inches long.

CHECKPOINT: The procedure should be completed to the previous step, including the regression analysis for the energy scale calibration.

Activity Measurements

These measurements are concerned with the overall count rates for the various sources. Thus, careful background subtractions will typically be important. All spectra in this section must be background-corrected.

27. Here you will determine the activities of the ^{22}Na source using the technique for simultaneous gammas. You will need an independent estimate of δ_1 and δ_2 . From

Step 24 you should already have the necessary data to determine δ 's for the ^{137}Cs and ^{54}Mn sources which produce single energy gammas (0.662 MeV for ^{137}Cs , 0.835 MeV for ^{54}Mn). These δ 's are simply the ratio of the counts in the ROI covering the Compton plateau and backscatter peak to the counts in the ROI covering the photopeak. Check how δ varies for the four source-detector distances measured and how it varies for the two sources, i.e., how it varies with gamma energy.

28. Use the two δ 's from the previous step to estimate the δ 's at the ^{22}Na gamma energies of 0.511 and 1.274 MeV
29. Use the appropriate ROI data for ^{22}Na and the live time to determine the count rates in the 0.511 and 1.274 MeV photopeaks and in the sum peak. Use Eq. 12, with these three rates R_1 , R_2 and R_{12} and the estimates of δ_1 and δ_2 of the previous step to determine the sample activity for the three source distances 0, 5 and 15 cm.
30. Compare the activities obtained in the previous step with each other and with the activity as determined by the original source activity, its age, and its half-life.
31. Most photopeak efficiency curves in the references show that in the energy range from about 0.2-2.0 MeV, p' falls off with energy E as E^{-q} with q around 0.9 for a 3×3 inch detector, increasing somewhat for smaller detectors. Determine q from the count rates for 0.511 and 1.274 MeV peaks for the ^{22}Na source. Use what you have learned to determine the activity of the ^{54}Mn source assuming the ^{137}Cs source activity was correctly labeled at the manufacture date.

Half-life of ^{137}Ba

The ^{137}Ba used for this experiment is a metastable excited state of a nucleus left behind when the ^{137}Cs isotope emits a beta particle. The ^{137}Ba is said to be the *daughter* of the *parent* nucleus ^{137}Cs . The 0.662 MeV gamma is emitted when the excited ^{137}Ba nucleus decays to the ground state. The excited ^{137}Ba decays with a short half-life while the ^{137}Cs decays with a much longer half-life. The barium will be chemically separated ("milked") from the cesium by forcing a mild acid solution through a container of powdered ^{137}Cs . Only the barium dissolves in the acid which will be collected in a dish and the detected gammas will be monitored over time to determine the half-life.

Nuclear decay is a homogeneous Poisson process¹ where Γ , the probability per unit time for the nucleus to decay (the decay rate) depends on properties of the nucleus and the particular excited nuclear state. For a nucleus in a given excited state at $t = 0$, the probability dP that it will decay between t and $t + dt$ follows the exponential probability distribution $dP = \Gamma e^{-\Gamma t} dt$. The mean or average lifetime for that excited state is then given by $\tau = 1/\Gamma$ and the half-life is given by $\tau \ln 2$.

Multiplying dP by the initial number of excited nuclei in a sample and by the probability that a decay will lead to a detected event gives the expected number of decay events in the interval from t to $t + dt$. Dividing this number by dt gives the rate of decay events at time t .

Adding in the constant average background rate occurring from other processes gives the predicted overall event rate as a function of time (uncorrected for detector dead time)

$$R = R_B + R_0 e^{-t/\tau} \quad (15)$$

¹See, for example, the addendum on *Poisson Variables* in the *Statistics* section of the lab homepage for additional information.

where R_0 is the event rate due to nuclear decay at $t = 0$ and R_B is the background rate.

The dead-time corrected rate is given by Eq. 14, $R_m = R/(1 + RT)$, with R given by Eq. 15. The predicted count C_p for the interval from t_i to t_f would then be the integral of the dead-time corrected count rate over the measurement interval

$$\begin{aligned}
 C_p &= \int_{t_i}^{t_f} R_m(t) dt \\
 &= \int_{t_i}^{t_f} \frac{R(t)}{1 + R(t)T} dt \\
 &= \int_{t_i}^{t_f} \frac{R_B + R_0 e^{-t/\tau}}{1 + (R_B + R_0 e^{-t/\tau})T} dt \\
 &= \frac{R_B(t_f - t_i)}{1 + R_B T} + \left(\frac{\tau}{T} - \frac{R_B \tau}{1 + R_B T} \right) \cdot \\
 &\quad \ln \frac{1 + R_B T + R_0 T e^{-t_i/\tau}}{1 + R_B T + R_0 T e^{-t_f/\tau}} \quad (16)
 \end{aligned}$$

Equation 16 is cumbersome and prone to numerical error. The formulation that follows is much simpler and gives quite reasonable results.

Although the source decays exponentially over the full course of the measurements, over the much shorter time scale of a *single* measurement interval, the detection rate can be assumed to change linearly. With this assumption, the average uncorrected event rate over an interval from t_i to t_f will be the value of R at the midtime of the interval: $t_{\text{mid}} = (t_i + t_f)/2$. Then, with every time interval set to give the same live time t_L , the count C_p in any interval will be that average rate multiplied by the live time.

$$C_p = C_B + C_0 e^{-t_{\text{mid}}/\tau} \quad (17)$$

where $C_B = R_B t_L$ and $C_0 = R_0 t_L$.

After milking the ^{137}Cs you will have to work quickly, so doing a dry run is definitely worthwhile. The basic principal is to take a

spectrum for some fixed live time and determine the total counts either over the photopeak and Compton plateau or just over the photopeak. These counts are obtained repeatedly as the activity of the sample decays.

Choose the **Services|Job Control** and select the JOB control program Decay.JOB. At this point just examine the program—don't run it. Here's what it looks like:

```

SET_DETECTOR 1
SET_PRESET_CLEAR
SET_PRESET_LIVE 10
LOOP 150
CLEAR
START
WAIT
FILL_BUFFER
SET_DETECTOR 0
REPORT "DECAY???.RPT"
SET_DETECTOR 1
END_LOOP

```

The **SET_PRESET_LIVE 10** command instructs the software to count for a live time of 10 seconds. The **LOOP 150** command repeats the following commands 150 times. The **CLEAR**, **START** and **WAIT** acquire another spectrum and the **REPORT** command creates a text file **DECAY???.RPT** (with the loop number for **???**) in the Maestro user directory. This file contains information about the acquired spectrum and the ROIs, in particular, the start time for the spectrum and the gross count within the ROI.

An Excel spreadsheet program will read the full set of report files made during execution of the Decay.JOB program and will produce columns containing the starting time, the gross count, and the net count and its uncertainty for each file.

For everything to work properly:

1. Make sure there is only one ROI set to include the photopeak and Compton

plateau and that it is in the detector spectrum, not the buffer.

2. Milk the ^{137}Cs cow with 1 cc of the acid solution letting the ^{137}Ba containing fluid fall into the aluminum dish. Place the dish next to the detector and leave it undisturbed through the rest of the measurements.
3. Chose the Tools|Job Control and select the Decay.JOB program. It will take 150 spectra, each for a live time of 10 seconds, and it will make reports on the ROI for each, taking about 30 minutes total. Over this time the sample activity will have decayed substantially.
4. Move the source away from the detector and take a long background count. You may have to reset the presets in the Acquire|MCB Properties tab list. Record the counts in the ROI and the live time.
5. When finished, dump the solution down the drain and wash out the dish. This violates no laws and is perfectly safe.
6. Activate the Excel spreadsheet program and click on the Read .RPT files (happy face icon) in the tool bar. First, click in the Data Table Location and select the top right cell address where the ROI data table will be written. Then click on the Get-Data button. From the file selection dialog box, find and select the first of the .RPT files—DECAY000.RPT. The program then reads all the files, and creates columns for the start time of the spectrum (as an Excel time stamp), the gross count, the net count, and the net count uncertainty.
7. Make a column for the starting time for the count—in seconds, starting at zero for the first count. This step can be performed with the spreadsheet formula $(\text{B10}-\text{B\$10})*86400$ and copying down (assuming the times start in cell B10). (The factor 86400 is the number of seconds in one day because Excel time stamps are real numbers in days since midnight, Jan. 1 1904.) Make a second column for the midtime of the data acquisition interval. You can take t_{mid} as the midtime between the start of one interval and the start of the next interval. There is a fixed delay of about 2-seconds while the Decay.JOB program writes the ROI information to the hard drive and starts taking data for the next interval. Thus, the delay would shift every t_{mid} by about 1 second, but any constant offset to all values of t_{mid} in Eq. 17 can be factored into the constant C_0 and would not affect any other parameters.
8. Make a graph of the gross count vs. the midtime of the counting period. Perform a properly weighted, least squares fit to your data using Eq. 17. Use “counting statistics” with the uncertainty in each measured count C_m taken as its square root $\sqrt{C_m}$. If significant, the starting time of an interval has an approximate uncertainty of ± 0.5 s.
9. Check if your results (χ^2 , and halflife) vary with the fitting region chosen. In particular, there may be significant errors at the beginning of the data set when the count rate is high and dead time corrections are most important. Discuss how the χ^2 and the lifetime vary as various amounts of this beginning data are left out of the fit. Compare the fitted halflife with the accepted value of 2.55 minutes.