

# Gamma Ray Spectroscopy

## Experiment GRS

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PHY4803L — Advanced Physics Laboratory

### Objective

You will learn about and use a scintillation spectrometer to study gamma rays and their interactions with matter. You will:

- Take a pulse height spectrum for a monochromatic source and identify the photopeak, Compton edge, and backscatter peak associated with the photoelectric effect and Compton scattering.
- Measure the dead time of the spectrometer and learn how to use the live time correction.
- Perform background subtractions.
- Measure the spectrometer resolution and study its energy dependence.
- Perform an energy calibration using a variety of known sources and then use the calibration to determine the energy of gamma rays emitted by an “unknown” isotope.
- Determine the absolute activity of a  $^{22}\text{Na}$  sample based on a sum peak analysis.
- Make and analyze half-life measurements of an excited nuclear state.

### References

1. Jerome L. Duggan *Laboratory Investigations in Nuclear Science*, 1988, The Nucleus.
2. EG&G ORTEC *Experiments in Nuclear Science*, 1984, EG&G ORTEC.
3. A.C. Melissinos, *Experiments in Modern Physics*, 1966, Academic Press.
4. G.A. Brinkman, A.H.W. Aten, Jr. and J. Th. Veenboer *Absolute Standardization with a NaI (Tl) Crystal—I*, Int. J. of App. Radiation and Isotopes, 1963, 14 pp. 153-157.

### 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  $4 \times 4$  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).

To detect the scintillation photons, the crystal is mounted against a photomultiplier tube (PMT) and the scintillator/PMT (detector) is enclosed in a reflective, light-tight housing. To

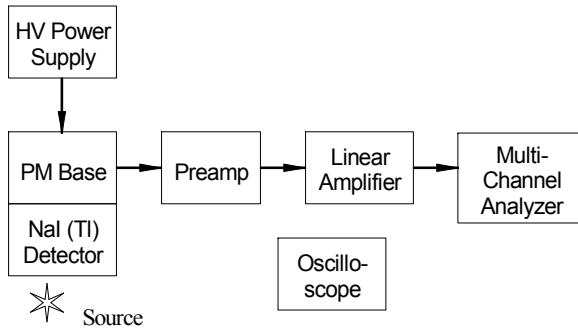


Figure 1: Block diagram for a scintillation detector system.

minimize the effects of background gamma radiation, the detector is surrounded by a thick metal shielding 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 electrons 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 crys-

tal 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 com-

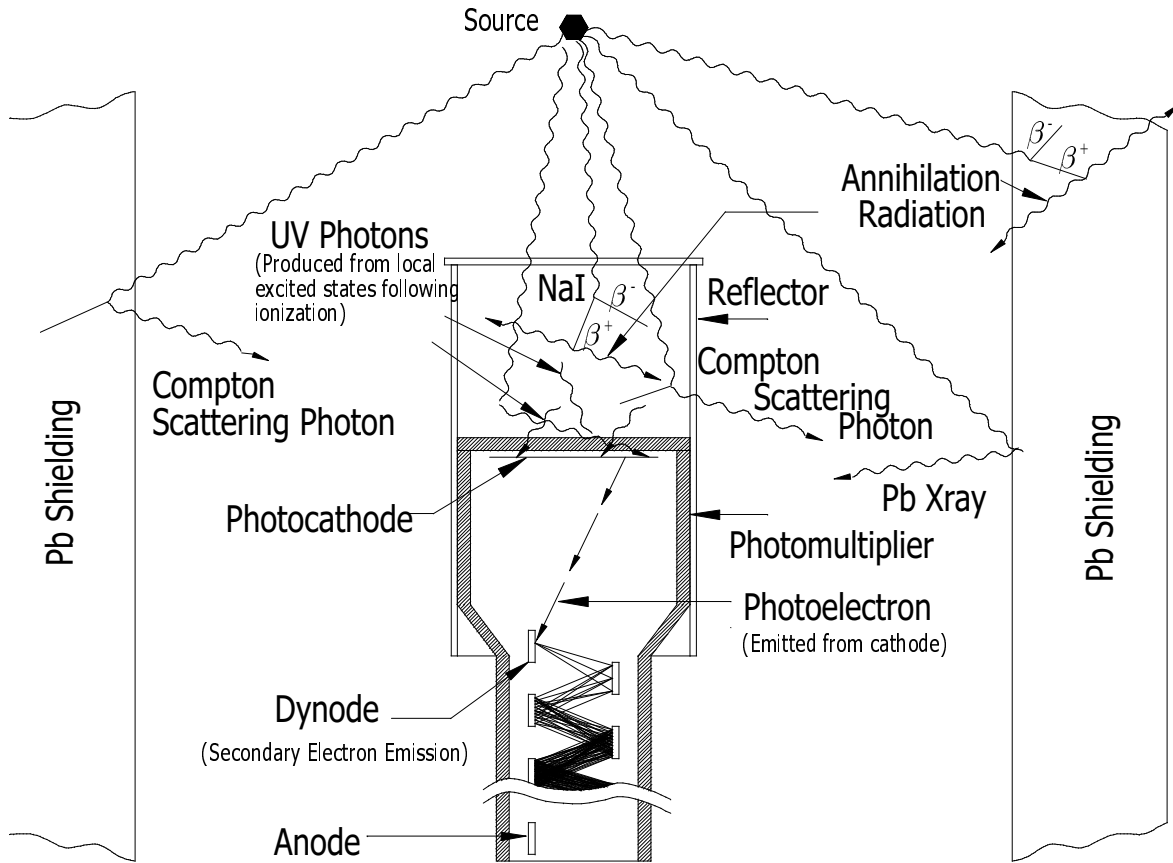


Figure 2: Schematic of a NaI detector and source showing various gamma ray interactions. From Reference 1.

pared 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. Moreover, there can be one or more interactions of a gamma and there may be multiple gammas emitted from a single nuclear decay. Usually, all energy depositions in the scintillator

from a single decay are effectively simultaneous; all interactions occur over a time scale that is small compared to the response time of the scintillator and electronics.

The size of the pulse from the detector depends on how much gamma ray energy is deposited in the scintillator. For a given amount of energy, the final pulse will have a well-defined average height, but because of statistical variations in light production, photon collection, photoelectron production, and electron multiplication, the pulse heights will have 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.

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  $E_\gamma$  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  $\theta$ , its final energy  $E'_\gamma$  is reduced to*

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

The peak at low voltage (called the backscatter peak) arises when gamma photons first strike the metal shield and then Compton scatter back into the scintillator at reduced energy. 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.

Occasionally, a gamma ray that Compton scatters in the scintillator may then interact again via the photoelectric effect thereby providing another mechanism for total absorption of the gamma energy.

**Exercise 2** (a) *Assume a 0.662 MeV gamma from a  $^{137}\text{Cs}$  source Compton scatters in the scintillation crystal and then escapes from it without further interactions. What is the maximum energy that can be absorbed in the scintillator?* (b) *Assume the same energy gamma first Compton scatters from the metal shield and is then totally absorbed in the scintillator. What is the minimum energy that can be absorbed?*

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) that are 0.511 MeV or 1.022 MeV below the photopeak.

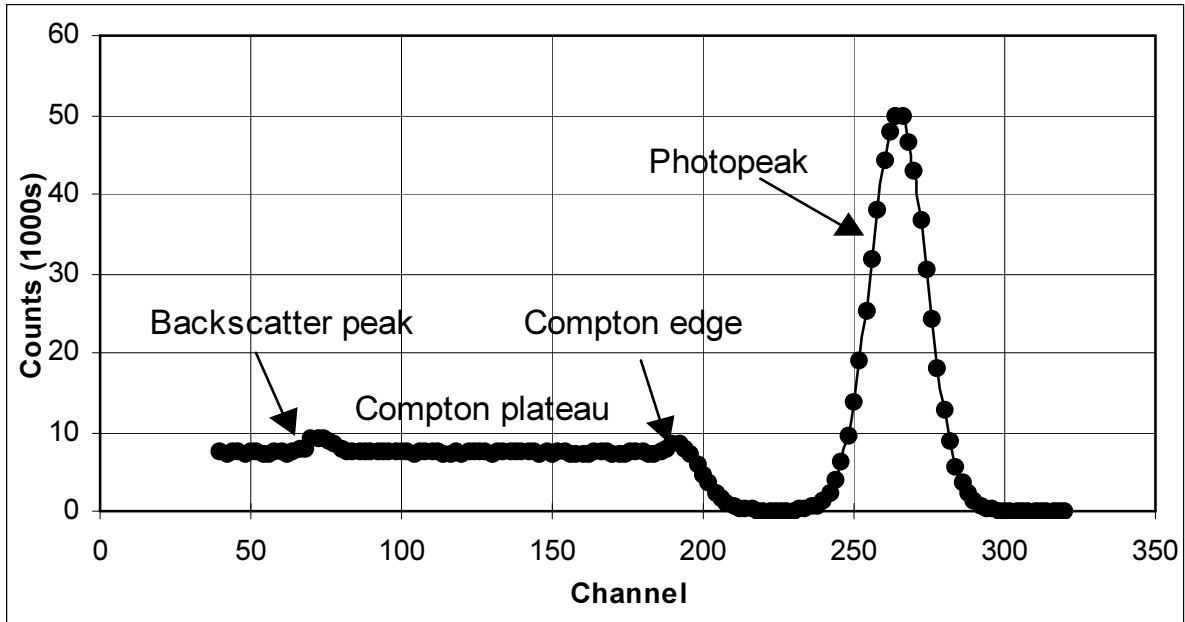


Figure 3: Pulse height spectrum for a monochromatic gamma ray source.

## Energy Calibration

Pulse processing electronics also affect the size of the pulses measured by the PHA. The preamp and amplifier affect the overall size of the pulses.

Because of the many stages of electron multiplication, the pulse heights are very sensitive to the PMT supply voltage and thus the HV supply must be very stable. Depending on the number of dynodes, their geometry, and other factors, the detector/tube manufacturer typically recommends operation over a limited voltage range that maintains proper operating conditions. Within the range, the voltage is typically optimized for best energy resolution.

To perform an energy calibration on the PHA system, sources of well known gamma ray energies are used. The channel number  $C_\gamma$  for the center of the photopeak corresponding to each gamma ray energy  $E_\gamma$  is recorded and a plot of  $E_\gamma$  vs.  $C_\gamma$  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  $\kappa$ , 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.

## Energy Resolution

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

Energy (keV)	Intensity (%)
121.8	25.6
244.7	7.6
344.3	26.5
411.1	2.2
444.0	3.1
778.9	12.9
964.1	14.6
1085.9	10.2
1112.1	13.6
1408.0	21.0

Table 1: Energies of the strongest gammas from a  $^{152}\text{Eu}$  source.

width at half maximum (FWHM) of  $\Delta C$ . The energy resolution  $R$  is commonly expressed by the ratio of the photopeak's FWHM (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

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

$R$  is nominally 5-10% for NaI detectors for  $^{137}\text{Cs}$  0.662 MeV gammas. Because of the Poisson statistics of light production in the scintillator and light detection in the PMT, the FWHM is expected to increase as the square root of the gamma ray energy. Consequently, the resolution  $R$  should improve (go down) as the square root of the energy.

The energy resolution will also depend on the PMT supply voltage.

## Nuclear Decay

The activity of a sample denotes the rate of nuclear disintegrations. An activity of 1 curie (1 Ci) represents  $3.7 \times 10^{10}$  nuclear disinte-

grations per second. What happens after the disintegration depends on the nucleus.

For  $^{137}\text{Cs}$ , the result is the formation of  $^{137}\text{Ba}$  and a  $\beta$  particle (electron). Eight percent of the time the  $\beta$  carries away all the excess energy, and 92% of the time the  $^{137}\text{Ba}$  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.

$^{60}\text{Co}$  also decays by  $\beta$  emission to  $^{60}\text{Ni}$ . The  $^{60}\text{Ni}$  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.

$^{22}\text{Na}$  decays by  $\beta^+$  (positron) emission (90% of the time) or by electron capture (10% of the time) to  $^{22}\text{Ne}$ . Nearly 100% of the time the  $^{22}\text{Ne}$  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 ( $2 \times 0.90$ ) times the activity.

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

$^{152}\text{Eu}$  decays by electron capture to  $^{152}\text{Sm}$  (72%) and by electron emission to  $^{152}\text{Gd}$  (27%). In both cases the daughter nucleus is left in an excited state which decays via emission of many different gamma rays. Those that can be observed with our apparatus are listed in Table 1.

## Activity Determinations

If one has a source of known activity  $\alpha_k$ , the unknown activity  $\alpha_u$  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  $\alpha$  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 knowing the probability  $p$  that a nuclear disintegration results in a count in that photopeak.

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

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 are given in the section on nuclear decay or in reference books.

Because the gammas spread out from the source,  $p'$  should 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  $\epsilon$  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  $\Omega$  is the solid angle subtended by the detector at the source. The intrinsic photopeak efficiency  $\epsilon$  would then represent the probability that a gamma entering the detector produces a count in the photopeak. Various references show that  $\epsilon$  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.

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

## Sum peak analysis

Reference 4 describes an interesting technique for making an absolute determination of the activity of a source that emits two simultaneous gammas of well defined but different energies, such as occurs for  $^{22}\text{Na}$  and  $^{60}\text{Co}$ .

Let  $p_1$  and  $p_2$  represent the probability that a nuclear disintegration leads to gamma rays  $\gamma_1$  and  $\gamma_2$ , respectively, whose energy is totally absorbed in the detector, i.e., that would be detected in their corresponding photopeak if the other gamma went undetected. Similarly, let  $t_1$  and  $t_2$  represent the probability

that a nuclear disintegration leads to  $\gamma_1$  and  $\gamma_2$  depositing energy anywhere in the spectrum—in the photopeak, Compton plateau, or 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  $\gamma_1$  and  $\gamma_2$  photopeaks.

For  $^{22}\text{Na}$  two 0.511 MeV annihilation gammas come out back-to-back— $180^\circ$  from one another. Because our flat-faced detector geometry only allows gammas to come in from a maximum of half of all possible directions (if the source is placed against the face of the scintillator) only one of any pair can ever be detected. Thus we can treat each decay as capable of producing a detected 0.511 MeV annihilation gamma and a 1.274 MeV gamma—either alone or in coincidence—in our scintillator. Their production mechanism— $e^+e^-$  annihilation radiation and direct nuclear emission—implies each of these two gammas would be emitted equally likely in all directions so that  $p_1$  and  $p_2$  are statistically independent; detecting one gamma of the pair does not change the probability of detecting the other.

For the 1.175 and the 1.332 MeV gammas from  $^{60}\text{Co}$  or the two 0.511 MeV gammas from  $^{22}\text{Na}$ , the outgoing directions of the two gammas are correlated and the equations would have to take the correlation into account.

For independent gammas, the probability that both  $\gamma_1$  and  $\gamma_2$  would deposit their full energy in the scintillator (i.e., the probability of a sum peak count) would be  $p_1p_2$  and the

rate of detection of sum peak pulses would be

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

The probability that a nuclear disintegration leads to a detected count in the  $\gamma_1$  photopeak would now be  $p_1(1 - t_2)$ . The factor  $p_1$  arises because  $\gamma_1$  must deposit its full energy in the scintillator, while the factor of  $1 - t_2$  arises because  $\gamma_2$  must not deposit any energy—otherwise the pulse would appear at an energy above the  $\gamma_1$  photopeak. The rate of detection of counts in the  $\gamma_1$  photopeak would then be

$$R_1 = \alpha p_1 (1 - t_2) \quad (10)$$

Similarly, the rate of detection in the  $\gamma_2$  photopeak would be

$$R_2 = \alpha p_2 (1 - t_1) \quad (11)$$

The total count rate  $R_t$  for a decay to lead a count detected anywhere in the pulse height spectrum is

$$R_t = \alpha(t_1 + t_2 - t_1 t_2) \quad (12)$$

where the final term takes into account that only a single count is recorded when energy from both gammas is detected simultaneously.

From the Eqs. 9-11, one finds

$$\frac{R_1 R_2}{R_{12}} = \alpha(1 - t_1)(1 - t_2) \quad (13)$$

And adding the last two equations gives

$$\alpha = R_t + \frac{R_1 R_2}{R_{12}} \quad (14)$$

## Procedure

### $^{137}\text{Cs}$ Spectrum

A  $^{137}\text{Cs}$  source emits 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 metal shielding around our detector, will be bigger and broader.



1. Turn on the NIM electronics supply rack. Set the PMT HV supply to 800 V—a dial setting of 267 (1/3 the desired voltage). Turn on the HV supply. It is recommended to allow at least 15 minutes warm-up time to reach a stable amplifier gain and operational voltage.
2. 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.
3. Place the  $^{137}\text{Cs}$  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  $\mu\text{s}$ /division time base. Look at both low and high count rate conditions (source farther or closer to the detector) and describe the shape of the preamp pulses. The preamp voltage  $V$  rises quickly as charge  $Q$  from a light pulse builds up on the final PMT anode;  $V = Q/C$  where  $C$  is the capacitance of the anode/connecting BNC cable to the preamp. The preamp has an input impedance  $R$  and thus charge and voltage then decay away like a charged capacitor in an  $RC$  circuit.
4. Look at both the preamp and amplifier pulses simultaneously. Describe the shape of the amplifier pulses and the relationship between the preamp and amplifier pulses under both high and low count rate conditions.
5. 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 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**, **Acquire|Start** or **Acquire|Stop** to erase, start, or stop data acquisition. Or, learn the keyboard shortcuts for these operations. For example, use **Alt-3** to erase a spectrum.
7. The amplifier pulses on the oscilloscope should show a range of amplitudes. There should be a noticeable group (darkened trace) of similarly sized pulses associated with the 0.662 MeV photopeak. Can you see this group on the oscilloscope? What is the approximate amplitude (in volts) of this group? Correlate this group with the photopeak displayed in the PHA display.
8. Adjust the amplifier gain so that the photopeak pulse heights are around 6 V. Start a new spectrum. Set a region of interest (ROI) over the 0.662 MeV pho-

topeak and then click inside this region. The software determines the channel for the *centroid* of the photopeak and its full width at half maxima (FWHM). Rather than fit to a line profile to find the center of the peak, the centroid is an alternate measure of the position. It is the channel where there is equal counts in the peak on either side. Record the peak position and the FWHM and determine the energy resolution.

9. Check how things change with count rate. The  $^{137}\text{Ba}$  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  $1 \mu\text{C}$  disk source to get to the lowest count rates. Dead time, discussed next, is proportional to the rate at which pulses are detected and processed into the PHA spectrum. It is found at the top right of the display and can be used as a measure of the count rate. Record how the following change with the count rate and explain what you find:
  - (a) Resolution. What happens to the FWHM?
  - (b) Gain. What happens to the position of the photopeak? Below what dead time does the gain become constant?

Hint for explanations: Look at the preamp pulses. The amplifier works off the derivative of the leading edge of the preamp pulse. For a given pulse shape, the derivative is proportional to the amplitude of the pulse. Note how, at low count rates, each pulse arrives and decays away before the next one is likely to arrive. At high count rates, note how the preamp pulses arrive on top of the RC decay of prior pulses. How would this affect the leading

edge? It is remarkable that the amplifier can put out relatively uniformly-sized pulses (for uniformly sized preamp pulses) even when the preamp pulses arrive on top of previous pulses.

### Dead Time

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.

10. Take a spectrum for a minute or so with the  $^{137}\text{Ba}$  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.
11. 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

$$R_m = \frac{R}{1 + RT} \quad (15)$$

where  $T$  is the dead time associated with each measured pulse, (i.e., as determined in Steps 10 and 11).

## 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 the PMT HV.

## High voltage dependence

In the next few steps, you will look for the dependence of the efficiency, gain, and resolution on the PMT high voltage setting. Be very careful with these measurements as applying a voltage in excess of 1000 V (a setting of 333 on the HV supply) can cause arcing inside the PMT that can destroy the tube.

12. Retake a  $^{137}\text{Cs}$  spectrum (at the current 800 V setting) with the disk 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, the gross and net counts in the photopeak and the gross counts in the entire spectrum.
13. Increase the high voltage to 900 V. Adjust the amplifier gain to get the position of the photopeak to nearly the same position as in the previous step. Repeat the previous step.
14. Repeat for PMT voltages of 700 and 1000 V.
15. Set the PMT high voltage back to 800 V.

Discuss what you learned from these measurements. Answer such questions as: What voltage gives the best resolution? How sensitive is the resolution to the voltage? Does the voltage affect the count rate? the gain?

## 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.

16. Go back to using the  $^{137}\text{Cs}$  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.
17. If the photopeak center channel is  $C_\gamma$ , 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  $^{137}\text{Cs}$  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  $^{137}\text{Cs}$  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  $\kappa$ . Roughly compare the Compton edge and backscatter peak energies with the predictions based on the Compton formula, Eq. 1.
18. Select Calculate|Calibration and destroy the one-point calibration. The energy calibration discussed next will be based on the photopeak center channels as determined by the Maestro software using ROI’s. It will not use Maestro’s calibration. Use only peak positions in channels from Maestro. Analysis must in per-
- formed in Excel or your favorite computer language.
19. Adjust the amplifier gain to make a 3 MeV gamma produce about a 10 V peak. That is, make the 0.662 MeV  $^{137}\text{Cs}$  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.”
20. Take spectra for  $^{22}\text{Na}$ ,  $^{54}\text{Mn}$ ,  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$  and  $^{152}\text{Eu}$  sources. For each source, set the necessary ROI’s and obtain the channels at the photopeak centers. 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.
21. Make an energy calibration table including the source isotope, the known gamma ray energy, and the photopeak center (in channels). The energies of the strongest gamma rays from  $^{152}\text{Eu}$  are given in Table 1. One of the  $^{152}\text{Eu}$  photopeaks in your spectrum is actually a closely-spaced (and thus unresolved) pair of photopeaks. For the known gamma ray energy of this photopeak, use an average of the two gamma energies weighted by their intensities.
22. Make a plot of gamma ray energy vs. the position in channels for each photopeak center and perform a regression. Fit to both a straight line and a quadratic polynomial. Do not use Excel’s trendline analysis. Discuss whether the quadratic fit is really any better than the linear 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 for the photopeak to become clear. 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. Don't forget to consider lifetimes. The jar has been on the shelf for years.

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

### Activity Measurements

As this section describes the use of measured counts in a photopeak with the live time to determine count rates in photopeak, you will need to know how to get this information. When you set an ROI and click in it, in addition to the peak position and FWHM, the software also supplies the gross and net counts in the ROI. The gross count is simply the sum of all counts in all channels of the ROI. The net count is the gross count less an estimate of the background contribution under the peak. The background contribution is obtained as the area under a straight line that extends across all channels of the ROI from one end to the other. The line goes through points connecting the second and next-to-last channels of the ROI at heights equal to the average of the counts in the first and last three channels of the ROI.

Since the Compton edge can run into (contribute to) the low energy channels of a photopeak ROI, setting the low energy side of the

ROI will take some thought to get the best estimate of the net count. For the net count to come out properly, you would want as many photopeak counts lost below the ROI as there are Compton edge counts occurring inside the ROI. Roughly, this should happen when the low energy side of the ROI is near the minimum between the photopeak and the Compton edge. Set the upper channel of the ROI where the photopeak appears to die off into the background.

24. Move all other sources away from the detector area and place the August 2014, 10  $\mu\text{C}$   $^{22}\text{Na}$  source about 10 cm from the detector. Adjust the gain so that the sum peak occurs around channel 800. Record the distance  $d$  from the source to the front of the detector.
25. Move the source far from the detector and take a background spectrum. Make sure the acquisition time is long enough to get good statistics when it is used next for a background correction.
26. Put sodium source back at the 10 cm distance and take a spectrum. Use the background spectrum from the previous step to make a background-corrected  $^{22}\text{Na}$  spectrum that will be used for the activity analysis.
27. Record the *live* time  $t_l$ . Its uncertainty is relative small and can be ignored in uncertainty calculations. Use the ROI feature to determine the *net* counts,  $C_1$  and  $C_2$ , in each of the two photopeaks and the net count  $C_{12}$  in the sum peak. Also record their uncertainties,  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_{12}$ , which are given with the other ROI information. Record the *gross* counts  $C_t$  in the entire spectrum and its uncertainty  $\sigma_t$  — the square root of its value:  $\sqrt{C_t}$ .

Use Eq. 14 to determine the sample activity  $\alpha$  and its uncertainty. This equation is more cleanly expressed in terms of the directly measure variables as:

$$\alpha = \frac{1}{t_l} \left( C_t + \frac{C_1 C_2}{C_{12}} \right) \quad (16)$$

where  $t_l$  is the live time.

For the uncertainty calculation, keep in mind that the three peak counts  $C_1$ ,  $C_2$  and  $C_{12}$  are all statistically independent from one another because they have no common counts. However, because the gross  $C_t$  includes the three peak area counts, there is a covariance between  $C_t$  and each of the peak counts equal to the variance of the peak counts. You should take these covariances into account in the uncertainty calculations.

Figure out how to determine the photopeak efficiencies  $p_1$  and  $p_2$ . Hint: Consider the definition of  $p_1$  (or  $p_2$ ) as the probability that a nuclear disintegration leads to the 0.511 (or 1.274) MeV gamma depositing all its energy in the scintillator. Consequently, the true number of 0.511 (or 1.274) MeV gammas that deposit all their energy in the scintillator is the counts in the corresponding photopeak plus the counts in the sum peak.

28. Repeat acquisition and analysis for this source placing it along the centerline of the detector at several other distances from 0 (source flat against detector face) to 30 cm.

Check if the ratio of  $p_1$  to  $p_2$  depends on distance. Check if  $p_1$  and  $p_2$  decrease with distance roughly as expected from a  $1/r^2$  behavior. Keep in mind that the scintillator is 4 inches in depth and its center is thus about 5-6 cm behind the protective shield.

29. We have several  $^{22}\text{Na}$  sources with different ages and activities. Use the sum peak

analysis technique for the activity for one or more them and check against a ratio-metric measurement and against the activity as determined by the original source activity, its age, and its half-life. Keep in mind, these sources are not calibrated and their activities are typically given by the manufacturer as  $\pm 10\%$ .

### Half-life of $^{137}\text{Ba}$

The  $^{137}\text{Ba}$  used for this experiment is a metastable excited state of a nucleus left behind when the  $^{137}\text{Cs}$  isotope emits a beta particle. The  $^{137}\text{Ba}$  is said to be the *daughter* of the *parent* nucleus  $^{137}\text{Cs}$ . The 0.662 MeV gamma is emitted when the excited  $^{137}\text{Ba}$  nucleus decays to the ground state. The excited  $^{137}\text{Ba}$  decays with a short half-life while the  $^{137}\text{Cs}$  decays with a much longer half-life. The barium will be chemically separated (“milked”) from the cesium by forcing a mild acid (elution) solution through a container of powdered  $^{137}\text{Cs}$ . 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 process<sup>1</sup> where  $\Gamma$ , 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

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

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)

$$R = R_B + R_0 e^{-t/\tau} \quad (17)$$

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. 15,  $R_m = R/(1 + RT)$ , with  $R$  given by Eq. 17. 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

$$\begin{aligned} C_p &= \int_{t_i}^{t_f} R_m(t) dt \\ &= \int_{t_i}^{t_f} \frac{R(t)}{1 + R(t)T} dt \\ &= \int_{t_i}^{t_f} \frac{R_B + R_0 e^{-t/\tau}}{1 + (R_B + R_0 e^{-t/\tau})T} dt \\ &= \frac{R_B(t_f - t_i)}{1 + R_B T} + \left( \frac{\tau}{T} - \frac{R_B \tau}{1 + R_B T} \right) \cdot \\ &\quad \ln \frac{1 + R_B T + R_0 T e^{-t_i/\tau}}{1 + R_B T + R_0 T e^{-t_f/\tau}} \end{aligned} \quad (18)$$

Equation 18 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.

$$C_p = C_B + C_0 e^{-t_{\text{mid}}/\tau} \quad (19)$$

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

After milking the  $^{137}\text{Cs}$  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:

30. Make sure there is only one ROI set to include the photopeak, Compton plateau, and backscatter peak, i.e., one big ROI covering the entire spectrum. As the photopeak (in fact, all features) will shift down at high count rates, set the upper end of the ROI to include the photopeak for low count rates. Then as the sample decays and the photopeak channel increases, the photopeak will stay in the ROI.

31. Use safety glasses and gloves for this part. However, the acid solution is quite weak. If any gets on your skin, simply rinse it off at the sink.

Fill the syringe with about 3-4 cc's of elution solution. Get rid of any air and fill the connecting tube attached to the syringe with the solution. Remove the end caps at each end of the  $^{137}\text{Cs}$  cow and place the filled syringe tube over the smaller end of the cow. Slowly force the solution into the cow, with the other end over an aluminum dish. When the solution just begins exiting the other end, stop forcing the solution through. (It may take very little solution to fill the cow if it was still almost full from the last use.) Then slowly push 2 cc's through the cow catching the outflow containing the  $^{137}\text{Ba}$  in the dish. Place the dish in front of the detector taking care to leave the small puddle undisturbed during the measurements. (Moving it around would change the detection efficiency.)

32. Re-cap both ends of the cow and move it far from the detector.

33. Choose 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.

34. When finished, carefully wash out the dish and syringe.

35. Activate the Excel spreadsheet program and click on the Read .RPT files (happy face icon) in the DATA tab of 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 GetData 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.

36. 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  $(B10-\$B\$10)*86400$  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  $t_{\text{mid}}$  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  $t_{\text{mid}}$  by about 1 second, but any constant offset to all values of  $t_{\text{mid}}$  in Eq. 19 can be factored into the constant  $C_0$  and would not affect any other parameters.

37. Make a graph of the gross count vs. midtime of the counting period. Using Poisson statistics, perform a properly weighted fit to your data using Eq. 19. If significant, the starting time of an interval has an approximate uncertainty of  $\pm 0.5$  s.
38. Check if your results ( $\chi^2$ , 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. Compare the fitted halflife with the accepted value of 2.55 minutes.