

Experiment 2K. PH 425 Winter 0708 MJM 2/23/07

Try to turn everything on (equipment rack, voltage (900v, not more) to the PMT) and leave it on for 10-15 minutes so that the gain will stabilize (it tends to increase a little from when it is first turned on.) Carry out Experiment 2K pretty much as written, skipping part D (unknown source). When you have questions, ask me.

Part A. Set up as requested. Read the discussion of the SCA in the Green Book to make sure how the dials for E and ΔE read. The counter timer is all connected so when you press Start on the timer, it will count for a preset time which you can set, and the results will show in the window of the counter.

To begin with, set E to 1 volt and ΔE to 1 volt and locate the photopeak by moving E up in steps of one volt. When you know roughly where the photopeak is, adjust the gain on the amplifier so that the photopeak is between 6 and 8 volts. (The scope should show you a bright peak among the others, which should of course be the photopeak.)

Now set ΔE to 0.2 v and gradually locate the photopeak value within 0.1 v or so of its true value by adjusting E and seeing what the count rate is at various E values. When you have a photopeak value in volts, calculate the value in volts for the backscatter peak by using the information in Fig. 4. Then set ΔE to 0.1v and try to locate the backscatter peak within 0.1v or so.

Do the same for the 'compton edge' and try to locate that experimentally.

In the red book by Tsoufanidis, read (or at least skim) chapter 6, on scintillation detectors. Then read through the first two sections of Chapter 12, and possibly the 3rd section. Note that the formulas in the book can be obtained from the Compton scattering formula $\lambda' = \lambda + hc/(m_e c^2) (1 - \cos \theta)$ and $E = hc/\lambda$.

Two effects are at work: the Compton effect and the photoelectric effect. Both come into play in Fig. 4 of the 2K writeup, and are discussed in Ch 12, especially figs 12.3, 12.4, and 12.5. Be prepared to intelligently discuss how these two effects interact, and which effect is responsible for what (which effect causes the photopeak, which the backscatter peak, which the Compton edge?)

For the values in Fig. 4, calculate both the Compton edge and also the backscatter peak and see if they agree with the numbers in Fig. 4.

Parts B, C and E (part D is omitted).

For the multichannel analyzer (MCA), we will be using the new ICS-PCI card in the Dell XP machine. There is no cable connection to the network, but **you can put a flash drive in one of the USB slots** and then set the realm (3rd line in login box) to PHOE-11 and log in as 'student' with password 'PHOE' as it says on the side of the computer. As a student, your writing privileges to the machine are nil, but you can save to a flash or maybe some other external drive.

There is a printed manual for the ICS-PCI card and it should stay right with the Dell XP.

With the new MCA card, all the electronics in the rack is bypassed ! !. You run a cable from the dynode output of the photomultiplier directly to the BNC connector in the back of the Dell. That's it. Click on

the ICS-PCI icon which is 2/3 of the way down the lefthand side of the screen (it think it is purplish blue). It's convenient to make the display full screen as soon as it opens.

It opens with a box for high voltage and gain settings. Leave the high voltage OFF. We are getting our own voltage from the supply on the lab bench. Try setting the coarse gain to 32 and set for 2048 channels.

Under 'Experiment' (see p. 25 in the ICS-PCI manual) you can tell it something about the conditions of the experiment. It will save this as part of the data file when you save the file. The saved data file will include the coarse and fine gains, the total time and live time, and other details, all right there in the file when you bring it back up.

I have been saving files as tab-delimited, and it gives them the extension .tsv. When I clicked on a tsv file, my computer wanted to know what app should open the file, and I told it Excel. Then when I double-clicked on the file, Excel opened it right away.

Once you massage a file and get a graph and stuff, you may want to save it as a .xls file in Excel. You can set a total time for taking data, and lots of other stuff (most of which I have not checked out) in the various menus.

To start taking data, press the green START button in the shape of a diamond. This is at the left just under the bar menu. Just below the start button, is an octagonal STOP button. Just below the stop button is the ERASE button.

The display starts as semi-log. At the righthand edge of the plot you will find a slider with the button all the way down. If you move the button on the slider up, you get various linear scales. To go back to the log scale, just move the righthand slider to the bottom.

For parts B, C and E, you will use the MCA to measure 'lines' from 3 gamma emitters: Cs-137 (0.662 MeV), Co-60 (1.17 MeV, 1.33 MeV), and Na-22 (0.511 MeV, 1.275 MeV), a total of 5 'lines'. For Cs-137 you may need only 5-10 minutes of real time data, but for the other two you may need 10-20 minutes of real time data collection.

For each of the 5 lines, you should measure

- The channel of the photopeak

- The 'full-width, half-maximum' (FWHM) of each peak, in channels

For *most* of the lines you should be able to measure

- The compton edge

- The backscatter peak

From this information, plot channel number vs energy and get what should be a straight line.

Calculate the compton edge and backscatter peak for all 5 lines, based on energy

Calculate the experimental compton edge and backscatter peak energies from their channel numbers.

Make a table comparing the theoretical and experimental backscatter and compton values

Discuss the origin of each effect.

Discuss the claim that backscatter energy plus compton edge energy equals photopeak energy.

Check this numerically, adding a column to your table above.

For each of the 5 lines, calculate the resolution R. R is supposed to be proportional to energy to some power: $R \propto E^n$. Read Tsulfandis to discover how the FWHM is supposed to depend on energy. Work out a way to plot your R and energy values to locate the value of the exponent n in E^n .

Report what the theoretical value of n should be, and what you found experimentally from your plot.

Some theory. **Start with $\lambda' = \lambda + hc/(m_e c^2) (1 - \cos \theta)$ and $E = hc/\lambda$, for gamma rays and show that the energy of a gamma of original energy E becomes (after scattering through an angle θ)**

$$E' = E/[1 + E(1 - \cos(\theta))/m_e c^2]$$

The maximum energy loss is in a head-on collision where $\theta = 180^\circ$, and then

$$E_{\min} = E/(1 + 2E/E_0),$$

where $E_0 =$ electron rest mass energy $= m_e c^2 = 0.511$ MeV.

E_{\min} is the energy of the 'backscatter peak'.

The scattered electron could get a maximum of $E - E_{\min} = E [2E/E_0/(1 + 2E/E_0)]$. This is the energy of the 'compton edge':

$$E - E_{\min} = E_{\text{compton edge}} = E [2E/E_0/(1 + 2E/E_0)].$$

The backscatter peak is fairly well defined in most spectra, but the compton edge (see Tsoulfanidis) is harder to pin down.

Skip part D. (Unknown source.)

Do part E sections 1, 2 and 3, as just discussed.

PH425 ADVANCED LABORATORY III

EXPERIMENT 2K: GAMMA-RAY SPECTROSCOPY USING A NAI(TL) SCINTILLATOR

Introductory

The purpose of this experiment is to acquaint the student with some of the basic properties of the NaI(Tl) (that is: sodium iodide, thallium-doped) scintillation detector, and its application to measurements of gamma rays. This is the most accessible and versatile type of general-purpose γ -ray spectrometer, although semiconductor detector far surpass it in precision and resolving power.

The emission of γ rays from a radioactive source follows the decay of a parent nucleus which leaves the daughter nucleus in an excited state. γ rays are high-energy photons emitted in the transition of the daughter nucleus from this state to one at a lower energy. For example, the beta decay of ^{137}Cs results in the emission of a photon of energy 0.6617 MeV, as indicated in Figure 1.

The scintillation detector is a single crystal of some transparent inorganic material (in this case, sodium iodide). Gamma photons entering the crystal can interact with electrons in a variety of ways - photoelectric absorption, Compton scattering, pair production - in which the photon energy is transformed into electron kinetic energy. The resulting fast electrons are quickly slowed down - they travel less than a millimeter - producing very many ionizing collisions with other electrons in the target material. In the next few nanoseconds, these ions and free electrons recombine, in the process producing flashes of visible and ultraviolet light. Thus a little flash of light - a "scintillation" - is produced in the detector in response to a γ photon striking the detector. Because the crystal is transparent, this flash can be detected photoelectrically from outside it. The usual scintillation detector consists of a crystal optically coupled to a photomultiplier tube. The photomultiplier detects the scintillation in the crystal and amplifies the resulting electronic signal to a level that external circuits can handle. Some of the processes that occur in a typical experimental arrangement are indicated in Figure 2 (next page).

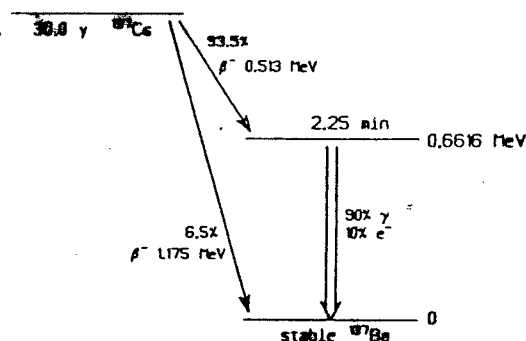


Figure 1 Cesium-137 decay scheme

The bottom line is this: a γ photon striking the crystal produces an output pulse from the phototube; the amplitude or height of the pulse is directly proportional to the energy given up by the primary photon to electrons in the crystal.

A. Single-Channel Spectrum

You've already encountered the NIM electronic module system, the linear pulse amplifier, and the single-channel pulse-height analyzer. Now we will use these instruments to look at the pulse-height spectrum produced in a scintillation

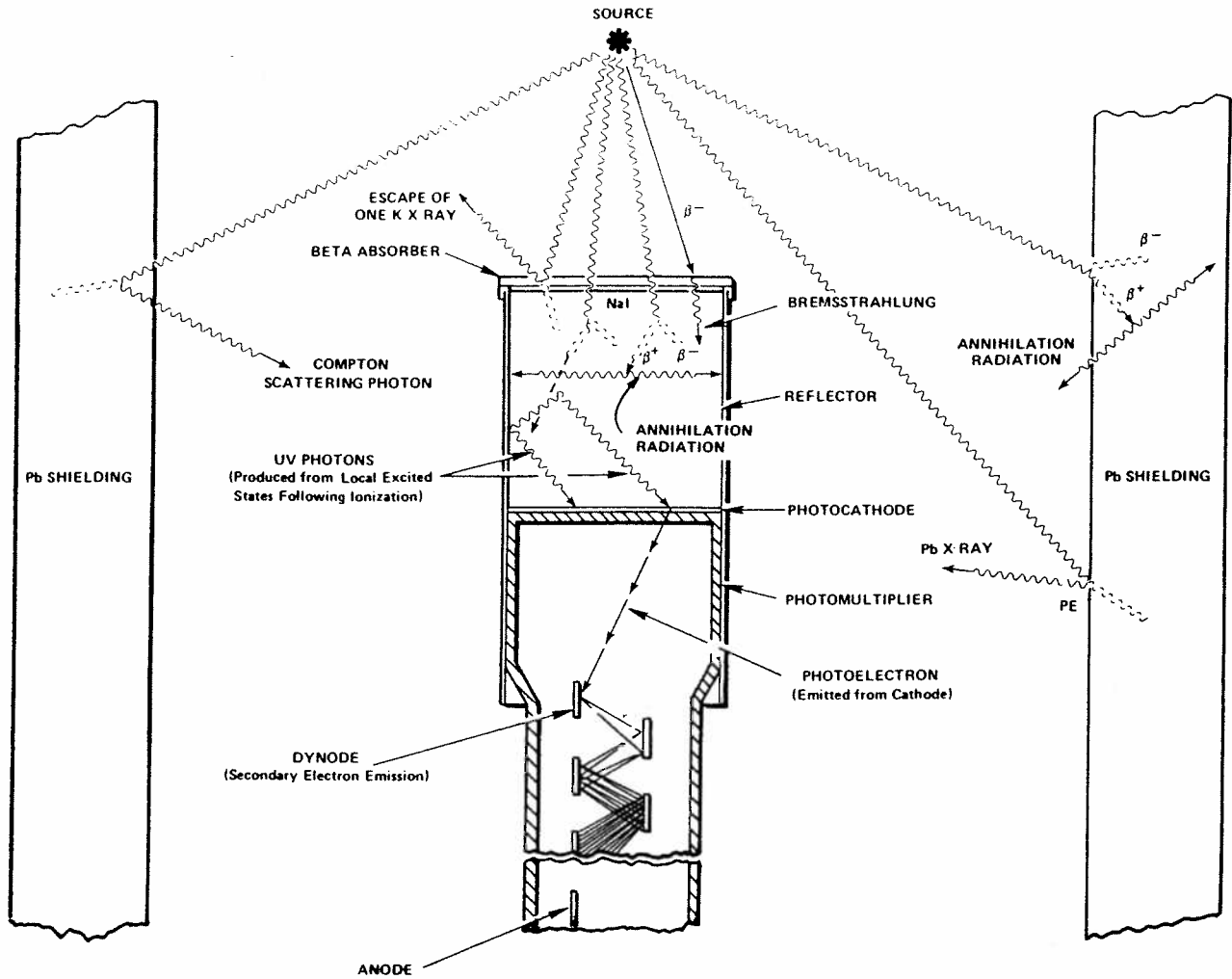


Figure 2 Various processes in a Typical Scintillation Detector Configuration

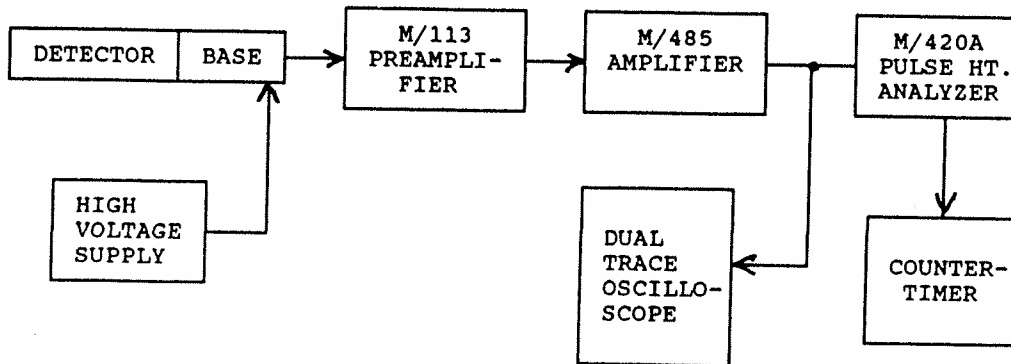


Figure 3 Experimental Setup for Single-Channel Analyzer Spectrum

detector by a monoenergetic gamma-ray source. Set up the equipment as in Figure 3.

Pulses produced in the scintillation detector pass through a preamplifier into the linear amplifier and are analyzed (as in Experiment 1) by the SCA. The radiation source I'll give you is one that produces monoenergetic γ rays; what their energy is isn't so important right now.

1. Place the source on the lab bench near the detector and on the detector axis, and leave it in the same position throughout the experiment. The high voltage supplied to the detector should be about 900 V positive. Adjust the amplifier gain until the bright maximum-height pulses on the oscilloscope are about 6 V high.
2. Set the SCA to DIFF and BI; set E to 0.40 V and DE to 0.20 V, and measure the count rate. Leaving ΔE set, increase E in 0.20 V steps, measuring the count rate at each setting, until E reaches 8.00 V.
3. Plot your data as a histogram (bar graph) showing the count rate in each 0.20-V pulse-height range from 0.40 to 7.20 V. Identify on your histogram the characteristic features of the detector spectrum from a monoenergetic gamma-ray source that are shown in Figure 4. Remember that the horizontal axis of these graphs - pulse height - corresponds to the energy transferred to the detector by a photon; the monoenergetic source does not produce a monoenergetic spectrum!
4. Give pulse height values from your spectrum corresponding to (1) the full-energy peak ("photopeak"), (2) the "Compton edge", and (3) the "backscatter peak".

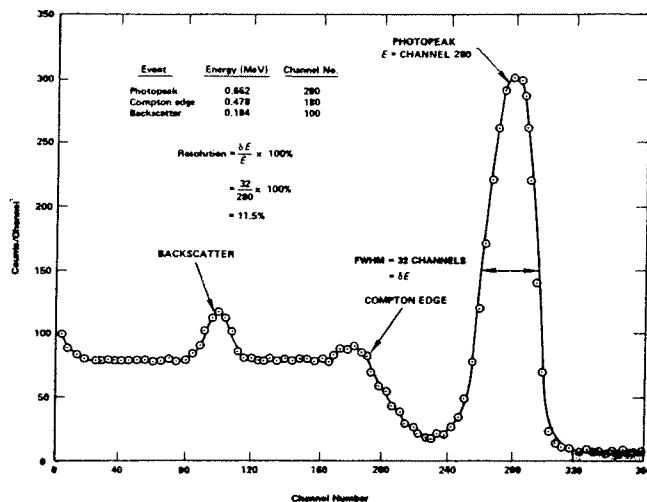


Figure 4 Nal(Tl) Spectrum of Cesium-137

In the rest of the experiment, you'll use a multichannel pulse height analyzer (MCA), an instrument which takes every incoming pulse and counts it in a memory location which is proportional to the pulse height, to do all this sorting out for you. (You've already used a multichannel analyzer, in the X-ray fluorescence lab in PH255.) Set this up now, as in Figure 5; all you really do is to replace the SCA and counter-timer with the multichannel analyzer.

B. Energy Calibration

In this section you will calibrate the detector system - that is, measure the relationship between channel number/pulse height and photon energy.

There are two parameters that ultimately determine the overall gain of the system: the high voltage supplied to the phototube, and the gain of the linear amplifier. The amplitude of the signal from the phototube is quite sensitive to the bias voltage: a rough rule of thumb is that a 10% increase in HV will double the gain. For the detectors you will be using, the setting should be around 900 V - think of 1000 V as an absolute upper limit. The bias voltage must be positive. Other settings:

preamplifier input from the first dynode output on the PM-tube base, not anode.

200 pf input capacitance on the M/113 scintillation preamplifier.

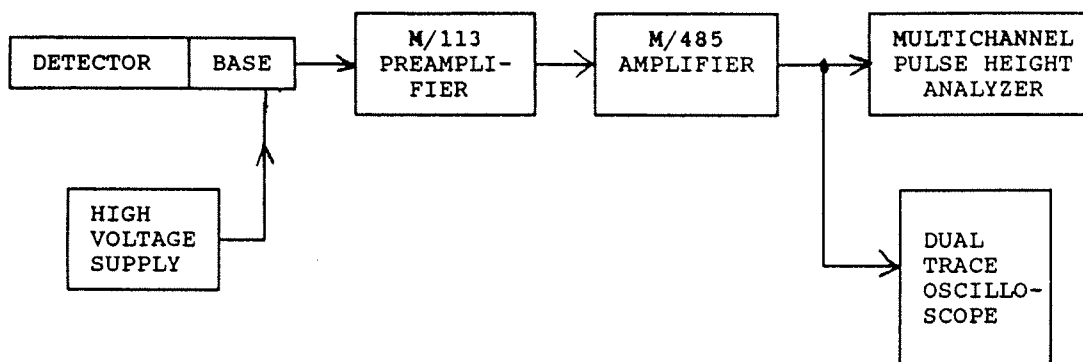


Figure 5 Experimental Arrangement Using Multichannel Analyzer

M/485 linear pulse amplifier: positive input, bipolar output. The gain will be adjusted as you go; start in the neighborhood of 50-100.

make sure the multichannel analyzer is set for the PHA, or analysis, mode.

1. Mount the detector vertically, so it is looking down at the source. Put a ^{137}Cs source on a stand or tabletop, a few cm from the detector.
2. Accumulate a spectrum in the MCA. Adjust the linear amplifier gain until the full-energy peak is approximately in channel 260. Since this peak is at 0.6616 MeV and the MCA conversion is linear, this means that 1 MeV falls about in channel 400, 2 MeV about in channel 800, etc. From this point on, leave the amplifier gain and the phototube high voltage fixed.
3. Accumulate a ^{137}Cs spectrum for a time period long enough so that the full-energy peak position is well defined. You'll see a spectrum like that in Figure 4. Record the spectrum in your notebook by sketching it clearly enough to show all the salient quantitative features - peak counts, channels, etc. - but don't take the time here to read out all 400 channel counts and graph them.
4. Identify and record the channels corresponding to the photopeak, the Compton edge, and the backscatter peak in the ^{137}Cs spectrum. (If the backscatter peak is not well defined, retake the spectrum with the source sitting on a heavy material, steel or lead or something. High-Z materials are more effective electron-scatterers.)
5. Accumulate and record a spectrum for a ^{60}Co source, which has two γ "lines" at 1.173 and 1.332 MeV. Do the same for ^{22}Na , with γ energies 0.511 and 1.275 MeV (the latter may be quite weak). These three nuclides are among the most common energy standards for calibrating a γ -ray spectrometer. As well as the photopeaks, record the positions of whatever Compton edges and backscatter peaks you can identify.
6. Make a graph of energy vs. channel number for the five full-energy peaks you have observed in these three radionuclides. The graph should be a good straight line. Perform a least-squares fit of the data to get an equation for the best straight line. Calculate the standard deviation (in energy units) of the points about the best-fit line.

The graph and equation you have produced enable you to measure the gamma-ray energy of unknown features of a spectrum. Note that when you do anything to change the gain of the system - turn it off and on again, change the amplifier gain or the phototube high voltage - you will have to redo the calibration before you can use it to make energy measurements.

C. Spectrum Analysis of Cobalt-60 and Cesium-137

In this experiment you will use the energy calibration you have just worked out to look at some of the features usually present in a pulse height spectrum – the Compton edge and the backscatter peak.

Compton scattering of a photon by an electron is one of the primary processes whereby high-energy photons exchange energy with matter. The amount of energy transferred to the scattered electron depends on the angle of the collision – the largest energy transfer in a head-on collision, less in a "grazing" collision. When the incoming photon Compton-scatters in the scintillation crystal, the electron kinetic energy is delivered to the scintillation. If the scattered photon escapes from the crystal without interacting again, then the detector produces a pulse corresponding to only part of the energy of the incoming photon. This is the reason for the continuum of pulse heights below the photopeak energy in the spectrum from a monoenergetic γ source (see Figure 4).

If a photon of energy E scatters through an angle of θ , the energy E' of the scattered photon is given by

$$E' = \frac{E}{1 + \frac{E(1 - \cos \theta)}{E_0}} \quad [1]$$

where $E_0 = 0.511$ MeV is the rest energy of the electron. In a "head-on" collision $\theta = 180^\circ$ (the photon is scattered directly back the way it came), and Equation [1] becomes

$$E' = \frac{E}{1 + 2E/E_0} \quad [2]$$

The remainder of the energy E is the kinetic energy of the scattered electron. Thus the largest energy that can be transferred to the electron is

$$E - E_{\min} = K_{e(\max)} = E - \frac{E}{1 + 2E/E_0} = \frac{2E^2}{E_0 + 2E} \quad [3]$$

If, for example, $E = 0.800$ MeV, then

$$E_{\min} = \frac{0.800}{1 + 1.600/0.511} = 0.194 \text{ MeV}$$

and

$$K_{e(\max)} = \frac{(2)(800)^2}{0.511 + 1.600} = 0.606 \text{ MeV}$$

In this case, Compton scattering in the crystal with loss of the scattered photon would give pulses of heights corresponding to any energy up to 0.606 MeV – that is, 0.606 MeV would be the energy of the "Compton edge" in the spectrum of a monoenergetic 0.800 MeV γ ray. Equation (3) is the energy of the Compton edge.

Likewise, Equation [2]) is the energy of the backscatter peak. These photons started from the source moving away from the detector and scattered, from an electron in the tabletop or whatever, back into the detector, scattered through angles of (nearly) 180° . For the gamma-ray energies of interest to us, backscattered photons have energies of 130-250 keV.

1. Calculate the energies of the backscatter peak and the Compton edge for the spectrum of ^{137}Cs . Use your calibration graph to calculate the channel number in which each of these features appears. How well do these agree with the ^{137}Cs spectrum you recorded? Are you within the experimental error of the calibration? Is there any ambiguity about just where the "Compton edge" is in your spectrum? The backscatter peak?
2. Make the same comparisons for whatever features you can locate in your spectra of ^{60}Co and ^{22}Na . You probably could only identify one Compton edge in the ^{60}Co spectrum. To which primary γ energy does it correspond? How come you don't

see the other one? You probably could only identify one backscatter peak in the ^{22}Na spectrum. How come?

- Note that the energies of the Compton edge and backscatter peak should add (in each case) to give the photopeak energy. Check this out.

The point here has been to use your calibrated γ spectrometer to measure some "known unknown" energies. You should come away with some quantitative sense of how precisely you can measure γ ray energies with your calibrated spectrometer.

~~D. Analysis of an Unknown Gamma Source~~ — DM IT

E. Energy Resolution

The resolution of any spectrometer is a measure of its ability to "resolve" or separate two peaks that are close together in energy. It is a very significant property! In some particular case, if a single photon energy produces a photopeak 60 keV wide, and you are trying to measure two different "lines" 25 keV apart in energy, you're out of luck.

"Width" of a peak always means full width at half the maximum height (FWHM). It can be estimated from the MCA display without bothering with numerical output: in your mind's eye, draw a smooth curve through the points and count off the number of channels between the points that are halfway between the off-peak "background" and the peak. With practice, you can do this to half a channel. Depending on how precisely you recorded the spectra in earlier parts of the experiment, you may need to retake spectra from ^{137}Cs , ^{60}Co , etc.

- Erase the multichannel analyzer. Check the energy calibration of your system using one or more known sources and, if need be, adjust or recalibrate.
- Measure the detector resolution for ^{137}Cs photons. "Resolution" can be expressed as

$$R = 100\% \times \frac{\text{FWHM}}{\text{peak } E} \quad (4)$$

For example, in Figure 4, the photopeak is at 662 keV and the FWHM is 73 keV, giving a resolution of 11% in Equation (4).

- Measure the resolution for several other photon energies. The resolution R is expected to depend on energy according to a power law:

$$R \propto E^n \quad (5)$$

Does this agree with your results? Estimate the value of n .

* $\text{Co-60} + \text{Na-22}$