

## 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  $\gamma$ -ray spectrometer, although semiconductor detector far surpass it in precision and resolving power.

The emission of  $\gamma$  rays from a radioactive source follows the decay of a parent nucleus which leaves the daughter nucleus in an excited state.  $\gamma$  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  $^{137}\text{Cs}$  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  $\gamma$  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).

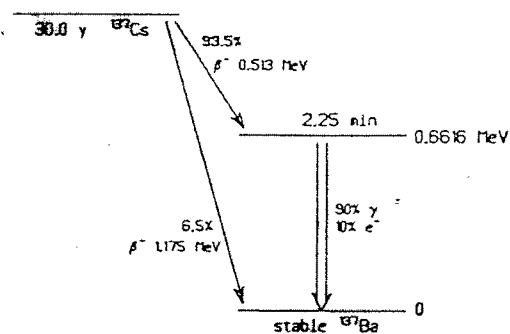


Figure 1 Cesium-137 decay scheme

The bottom line is this: a  $\gamma$  photon striking the detector 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.

The bottom line is this: a  $\gamma$  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

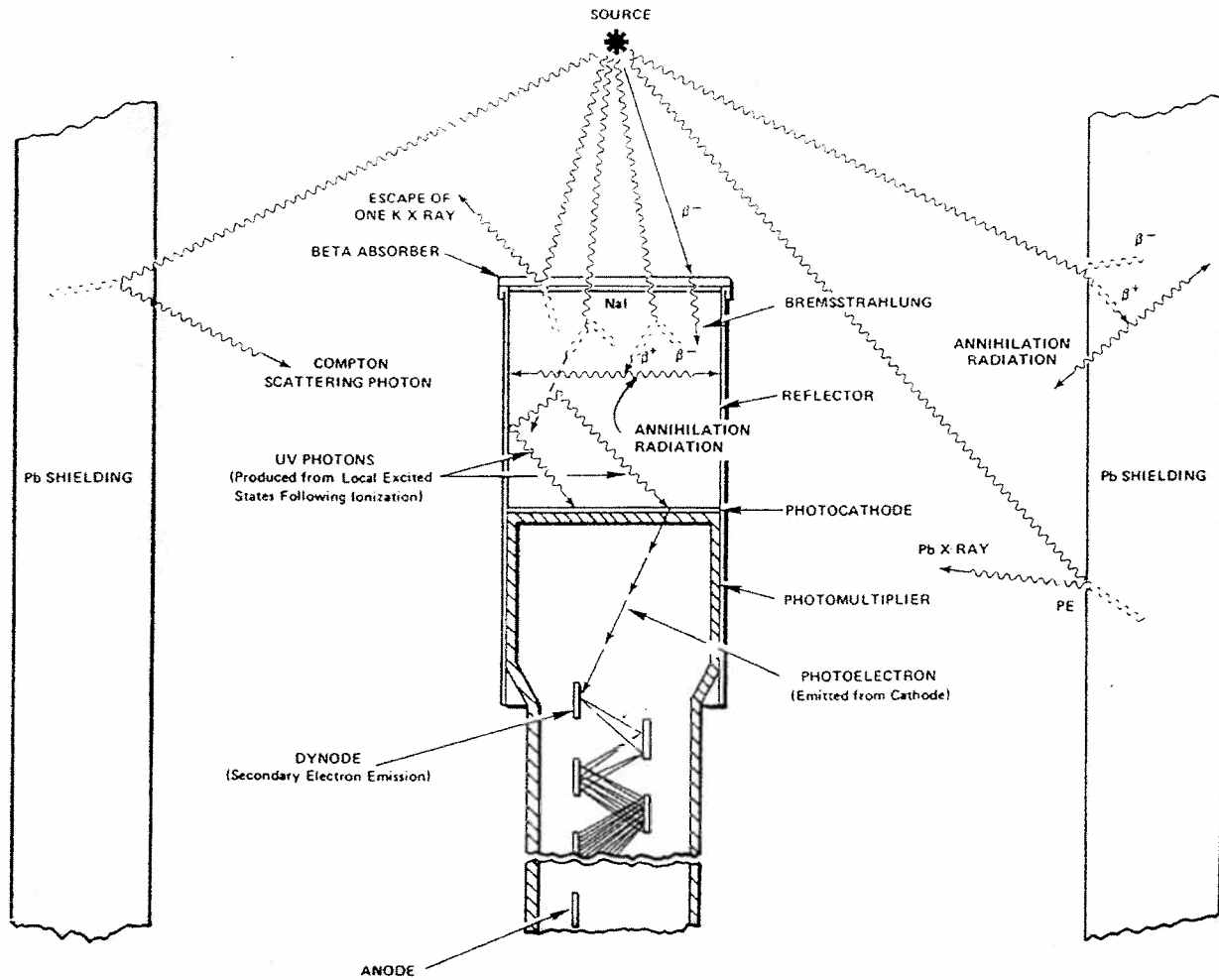


Figure 2 Various processes in a Typical Scintillation Detector Configuration

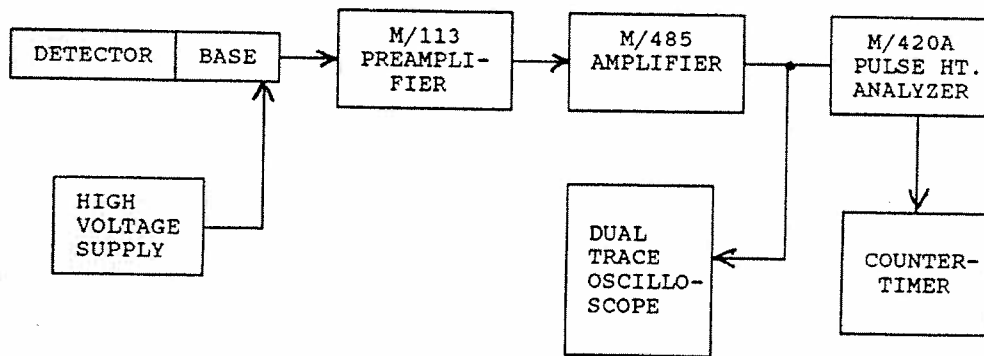


Figure 3 Experimental Setup for Single-Channel Analyzer Spectrum

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  $\gamma$  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  $\Delta E$  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".

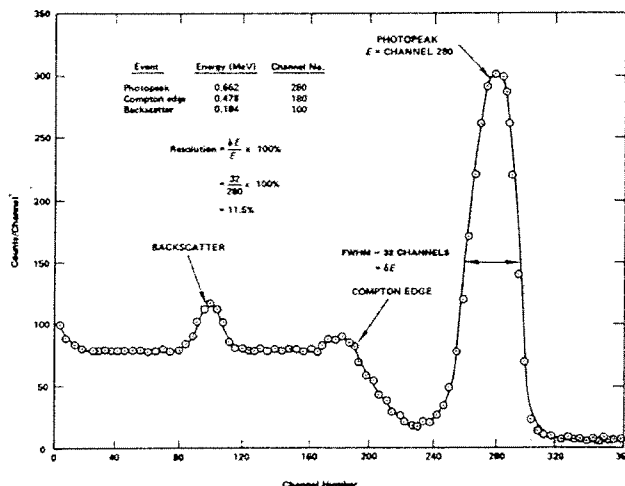


Figure 4 NaI(Tl) Spectrum of Cesium-137

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.

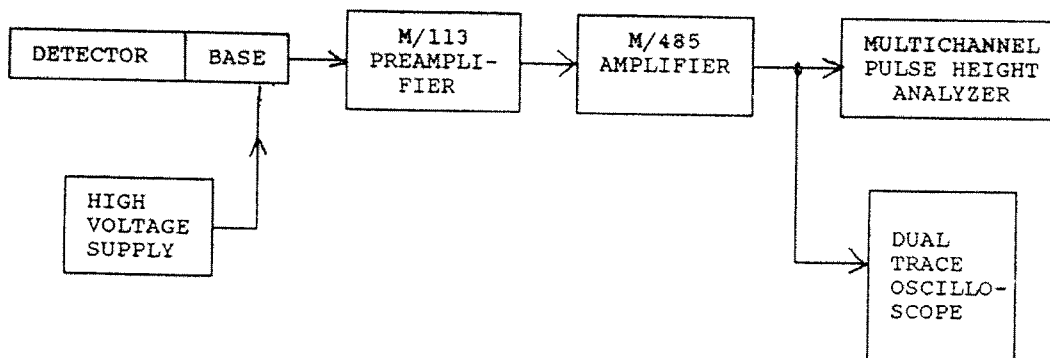


Figure 5 Experimental Arrangement Using Multichannel Analyzer

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  $^{137}\text{Cs}$  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  $^{137}\text{Cs}$  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  $^{137}\text{Cs}$  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  $^{60}\text{Co}$  source, which has two  $\gamma$  "lines" at 1.173 and 1.332 MeV. Do the same for  $^{22}\text{Na}$ , with  $\gamma$  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  $\gamma$ -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  $\gamma$  source (see Figure 4).

If a photon of energy  $E$  scatters through an angle of  $\theta$ , 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  $\gamma$  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)  $180^\circ$ . 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  $^{137}\text{Cs}$ . Use your calibration graph to calculate the channel number in which each of these features appears. How well do these agree with the  $^{137}\text{Cs}$  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  $^{60}\text{Co}$  and  $^{22}\text{Na}$ . You probably could only identify one Compton edge in the  $^{60}\text{Co}$  spectrum. To which primary  $\gamma$  energy does it correspond? How come you don't

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

3. 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  $\gamma$  spectrometer to measure some "known unknown" energies. You should come away with some quantitative sense of how precisely you can measure  $\gamma$  ray energies with your calibrated spectrometer.

#### D. Analysis of an Unknown Gamma Source

The purpose here is to use your calibrated system to measure the photopeak energy(ies) of an unknown  $\gamma$  emitter and so identify the unknown nuclide.

1. Erase the multichannel analyzer. Check the energy calibration of your system using one or more known sources and, if need be, adjust or recalibrate.
2. Obtain an unknown  $\gamma$  source from your instructor. Accumulate a  $\gamma$  spectrum from the unknown source for a time long enough clearly to identify the photopeak(s) in the spectrum. Record the spectrum in your notebook by sketching it clearly enough to show all the salient quantitative features. Plainly the question of how precisely you can infer a given photopeak energy is of great importance here.
3. Using references provided by your instructor, identify the unknown isotope(s).

#### 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  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ , etc.

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

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

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).

3. 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  $n$ .

4. I mentioned above that semiconductor photon detectors have much better resolution than scintillation detectors. Use our high-purity Ge detector to look at the spectrum from a  $^{60}\text{Co}$  source and a  $^{137}\text{Cs}$  source. (You'll need somewhat different electronic modules - consult your instructor. This spectrum may take quite some time - several hours, perhaps - because the efficiency is very low. Organize your work so that you can let this cook while working on something else, or overnight, or something.)
5. How does R at  $E = 1.332$  MeV compare with that of an NaI(Tl) detector? How does R compare at  $E = 0.6616$  MeV?
6. For the  $^{137}\text{Cs}$  spectrum from the Ge detector ( $E = 0.6616$  MeV), how does the fraction of all the counts that are in the full-energy peak (this fraction is called the "intrinsic peak efficiency" of the detector) compare with the corresponding quantity in the scintillation spectrum?