

## **Experiment VI**

### **Gamma Ray Spectroscopy**

#### **1. GAMMA RAY INTERACTIONS WITH MATTER**

In order for gammas to be detected, they must lose energy in the detector. Since gammas are electromagnetic radiation, we must understand how such radiation interacts with matter.

There are three distinct modes of interaction: photo-electric effect, Compton scattering, and pair-production.

##### **1.1 Photo-electric effect**

A gamma (or photon) strikes an electron, releasing the electron from its surroundings and giving it kinetic energy. The photon gives up its entire energy in this process.

##### **1.2 Compton scattering**

A gamma scatters from a free electron. The process produces a photon of reduced energy and an electron with kinetic energy. Note that **Rayleigh scattering**, or elastic scattering, may be considered a special case of Compton scattering with the electron replaced by a more massive object, e.g., a nucleus. Compton scattering is shown in Fig. 1.

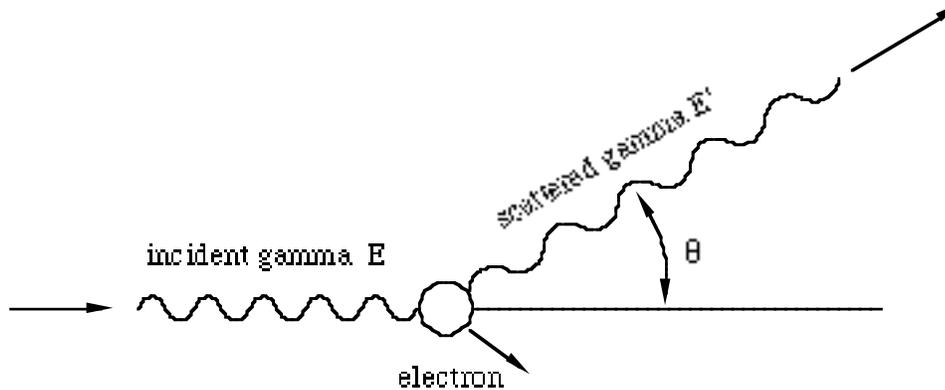


Fig. 1 Gamma of energy  $E$  scattered from an electron, showing the scattered gamma of energy  $E'$  and scattering angle  $\theta$

The relation between the incoming and outgoing gamma energies is given by the

**Compton scattering formula:**

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

where  $mc^2 = 0.511$  MeV, is the rest-energy of the electron and the other variables are defined in Fig. 1.

### 1.3 Pair production

A gamma passes near a massive nucleus. The energy of the gamma is converted to mass (an electron-positron pair) with kinetic energy. For this process to occur, the gamma must have at least twice the rest-energy of the electron, or  $2 \times 0.511$  MeV.

The cross-sections for each of these interactions in sodium iodide (NaI) as a function of gamma energy is shown in Fig. 2.

It is important to note that in each of the modes of interaction, the gamma's energy is converted to an electron having kinetic energy. The electron, and charged particles in general, traveling through matter, lose energy in a manner different from gammas.

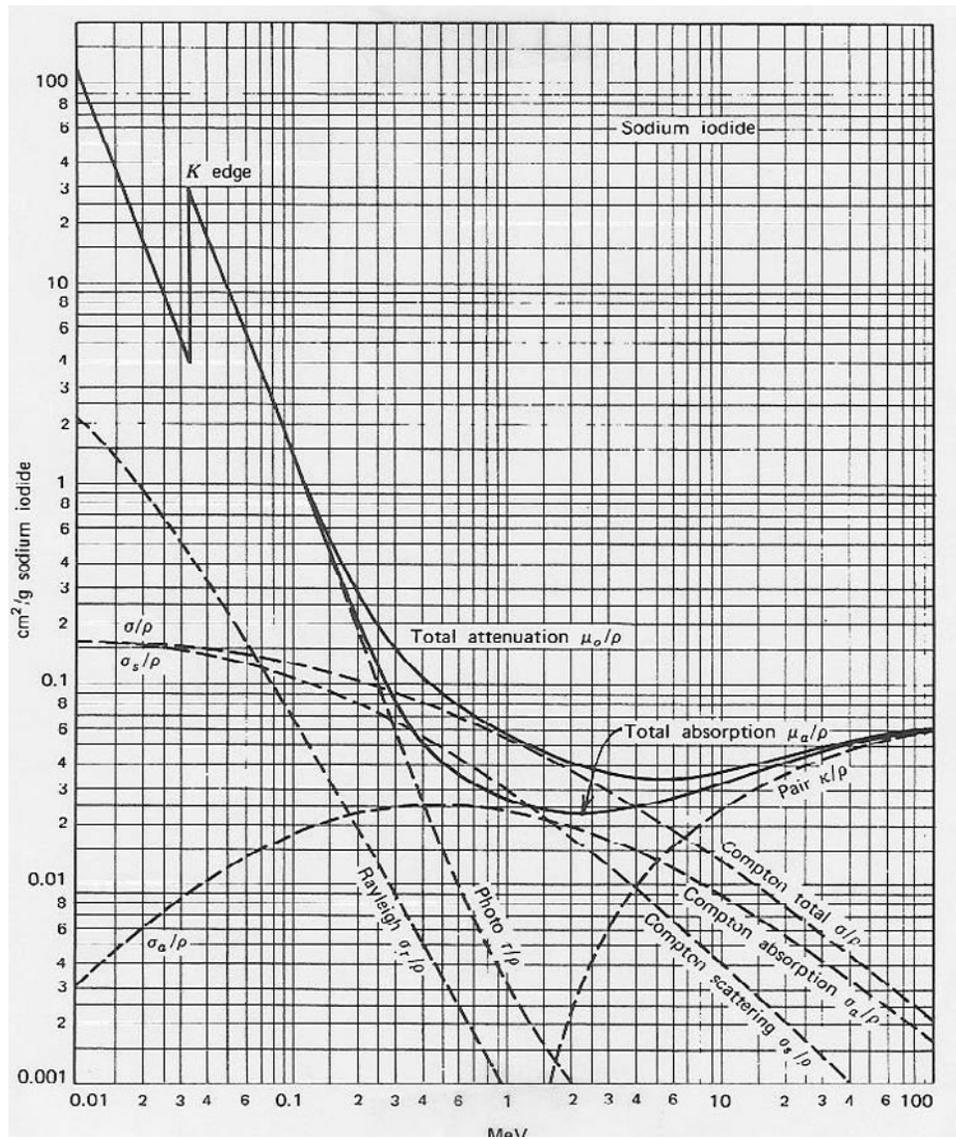


Fig. 2 Electromagnetic interaction cross-sections for NaI.

## 2. Electron interaction with matter

A vast majority of the volume of bulk matter contains electrons. Those electrons feel a Coulomb force as another electron moves through the bulk matter. The cumulative forces acting on the moving electron bring it to rest in a short distance. For example, if a 1 MeV gamma enters a NaI crystal, the most likely mode of interaction is Compton scattering (see Fig. 2). If the gamma undergoes a “head-on” collision with an electron in the crystal, the gamma will be scattered by 180 degrees. Applying eq.(1), show that this electron will have kinetic energy of about 0.8 MeV. Is this sufficient energy to kick the electron loose from the bound state in the crystal? Is this electron relativistic? Such an electron will move only about 1 mm in NaI before losing all of its kinetic energy. Approximate experimental values of the range of electrons in NaI as a function of electron energy are shown below:

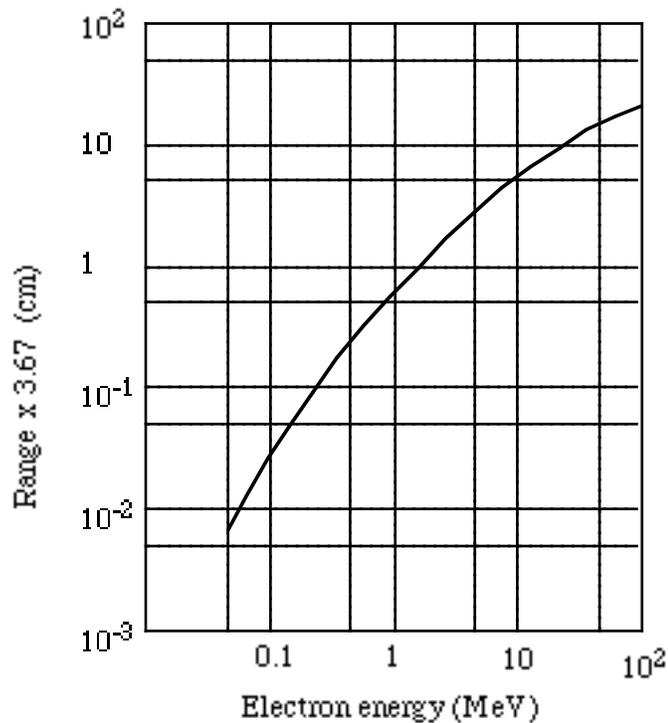


Fig. 3. Range-Energy relation for electrons in NaI

### **3. THE DETECTOR**

#### **3.1 Sodium Iodide (NaI) scintillators**

In this experiment the gammas are detected by a sodium iodide crystal doped with a small amount of thallium, NaI(Tl). The gammas entering the NaI crystal may undergo photoelectric effect, but more probably will Compton scatter from the electrons in the crystal (see Fig. 2).

There are two products of this scattering: a scattered electron and a gamma of reduced energy.

The electron loses energy very quickly in the crystal. The rate of energy loss,  $-dE/dx$ , is governed by the Bethe formula (see Knoll for details). In the process of moving through the crystal, the scattered electron excites electrons in the crystal's valence band into the conduction band, leaving a trail of electron-hole pairs. Holes migrate to the thallium impurity sites and ionize them. The ionized thallium atoms capture electrons, ultimately return to the ground state and give off visible light. Meanwhile, the remaining gamma moves through the crystal losing energy only when it scatters from another electron. With each successive scattering, the remaining gamma has less energy. At some point the gamma energy is small enough that the photoelectric cross section is dominant and the remaining gamma gives up its energy entirely to an ejected electron, which loses energy in the same manner as the electrons mentioned above.

#### **3.2 Photo-multiplier (PM) tube**

The light produced in the scintillator passes through a glass window and into the photo-multiplier tube where it liberates an electron by the photoelectric effect in the photo-cathode of the tube. The photo-electrons are accelerated through a series of metal plates called *dynodes*.

When an energetic electron strikes a dynode, several more electrons are ejected and are, in turn, accelerated to the next dynode. After typically 10 to 14 dynodes, the electron gain may be about

10<sup>6</sup>. The electrons are collected at the anode of the PM tube. What polarity (+ or -) would you expect at the dynode output? At the anode output?

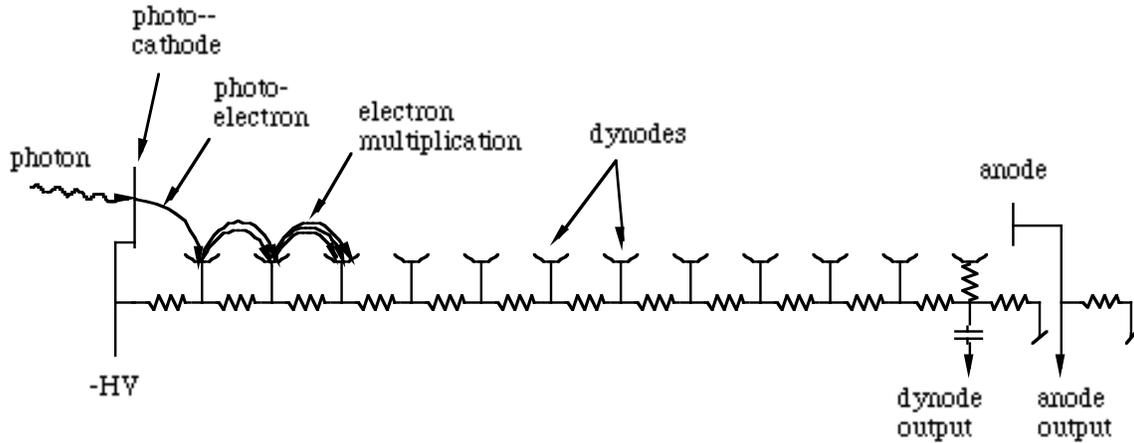


Fig. 4. Schematic of a photomultiplier (PM) tube

#### 4. NUCLEAR DECAY SCHEMES

At the end of this write-up you will find the nuclear decay schemes for the isotopes you will use in this experiment. Each column of horizontal lines represents the nuclear energy-levels of a specific isotope of some element. Diagonal arrows indicate the process involved in changing from one element to another. Vertical arrows indicate changes in nuclear energy-level within one element. Gammas are emitted when a nucleus changes from a higher to a lower energy nuclear state within the same isotope.

## 5. PROCEDURE

### 5.1 PM pulses on the scope

- a. Place a Cs-137 source near the scintillator. The PM tubes we will be using may be operated safely at (negative) 2000 volts, although we will generally use them at 1500 volts or less.
- b. Turn on the high voltage power supply. Note that there are two switches on the supply. Starting with both switches off, turn on the *power* switch. Wait a few seconds for a click and then turn on the *high voltage* switch. Adjust the high voltage to about  $-1500$  volts.
- c. Attach the 50 ohm terminator to an input of the scope, and attach a coaxial cable from the PM anode output to the terminated scope input.
- d. Adjust the scope's *gain*, *trigger slope* and *trigger level* until the PM pulses are clearly visible.
- e. Sketch the pulses in your lab notebook. What is the pulse polarity? Does this polarity make sense, given how the PM works? What is the duration of the pulses? What is the range of pulse heights? What are the rise and fall times of the pulses (see Fig.5)?

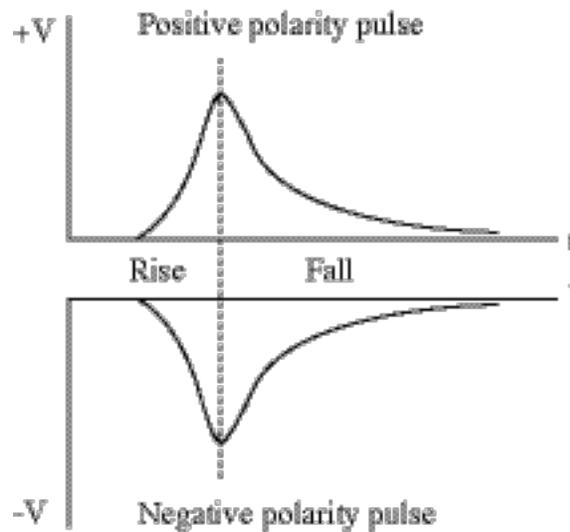


Fig. 5 Defining rise and fall for a positive and negative pulse.

## 5.2 Termination

- a. Remove the terminator and re-connect the cable directly to the scope. Look at the pulses again and try to measure their duration and height with no terminator at the scope input.
- b. The RG58-U coaxial cable you are using has a characteristic impedance of 50 ohms, (independent of its length!). On the other hand, the input impedance of the scope is 1 M $\Omega$ . This change in impedance from low to high at the cable-scope interface will cause a reflection of the pulse without a change in polarity. The pulses observed on the scope are the sum of the incident and reflected pulses. Using the terminator places 50 $\Omega$  in parallel with the scope's 1M $\Omega$  input impedance. What is the value of this parallel combination? How will the reflection be affected by the use of the 50 $\Omega$  terminator?

### 5.3 Pulse heights

Let us now try to make sense of the observed pulse heights. Make use of the following estimates to calculate the expected pulse heights from a Cs-137 source:

- a. The Cs-137 gamma energy is 0.662 MeV.
- b. The scintillation efficiency of NaI is about 10%, i.e., 10% of the gamma energy goes into visible scintillation light.
- c. The energy of each scintillation photon is about 4 eV.
- d. The light collection efficiency of the NaI-PM combination is about 70%.
- e. The photon to electron conversion (photo-electric) efficiency is about 10%.
- f. Each photo-electron at the entrance of the PM yields about  $10^6$  electrons collected at the anode.

Using these estimates and the pulse duration you measured earlier, calculate the expected pulse height for Cs-137. Hint: a-f above should give the charge in each pulse. Additionally, the duration should give the current. This current through the terminator's resistance should give the voltage.

Compare the estimated pulse heights with what you measured earlier.

### 5.4 Vary high voltage and gamma energy

Still using the Cs-137 source, vary the high voltage and record its effect on the pulse height. Return to -1500 volts and change the source. Use sodium-22 (Na-22), cobalt-57 (Co-57), Co-60, In each case sketch the pulses observed and record their pulse heights in your notebook.

## 5.5 Pulse height analysis

We would like to perform a quantitative analysis of the pulse heights. To do so, a histogram of heights may be created by using a *pulse height analyzer* (PHA). On the PHA the horizontal axis, channel number is proportional to pulse height. The vertical axis gives number of pulses having each height. Such a histogram is usually called a *spectrum*. The UCS-20 spectrometer may be used as a PHA.

## 5.6 PHA set-up

- a. Plug the coaxial cable from the photo-multiplier's (PM) anode into the pre-amp input on the rear panel of the UCS-20. This input is designed to take negative pulses from a PM tube without a 50 ohm termination.
- b. Turn on the UCS-20. Pull down the mode menu and select pulse height analysis. Quit the program and re-start it. (This action works past a minor bug in the software.)
- c. Start the UCS-20 software.
- d. Under the Settings menu, select *Conversion Gain, 2048*. This setting puts the pulse height range of 0 to 10 volts into channels 0 to 2047.
- e. Drag the LLD tab (lower level discriminator) to approximately the 5% position. This setting serves to eliminate low-level electronic noise pulses.
- f. Place a Co-60 source near the scintillator. Click the *start* box to start taking data. You may have to reduce the high voltage to get the entire spectrum on the screen. Note that for each source, there is a maximum energy gamma and therefore, an upper limit to the pulse-height. Thus, if the spectrum shows activity all the way to the upper (right) end of the

display, some of the spectrum must be off-scale to the right. In this case reduce the pulse heights by reducing the high voltage.

- g. Adjust the high voltage and/or the PHA gain so that both full-energy peaks appear near the upper end of the display. Refer to the nuclear decay schemes at the end of the manual to help identify the origin of the peaks. Leave the gain and HV set for the duration of the experiment.

## 5.7 Energy calibration

We wish to re-scale the horizontal axis of the PHA from *channel number* to *energy in MeV* (million electron-volts). To do so we will use two known gamma energies. Be sure to leave the HV and preamp gain fixed for the rest of the experiment in order to preserve your calibration.

- a. Look up the energies of the two gammas of Co-60. Using your spectrum of Co-60, determine which peak is due to the 1.33 MeV gamma.
- b. Use the mouse to move the PHA cursor to the 1.33 MeV peak position. Record the channel number for this peak.
- c. Erase the data and acquire a spectrum for Co-57. Identify its peaks and their energies from the decay schemes.
- d. Move the cursor to the 0.122 MeV peak and record this channel number.
- e. Under the *Calculations* menu, select *Energy Calibrate...*
- f. Place the cursor in the channel corresponding to the 0.122 MeV peak.
- g. In the calibration window, click the *Energy...* button and enter 0.122, and click *OK*.
- h. Click the *Units...* button and enter *MeV*.
- i. Repeat the above steps to enter 1.33 MeV at its appropriate channel.

- j. Click the *Calibrate* button. The horizontal axis should now be re-scaled and labeled in units of MeV.

### 5.8 Measure other gamma energies

- a. For the Na-22, Co-57 and Co-60 sources, acquire spectra and sketch them into your notebook. Measure the energies of the gamma peaks you observe and compare them to the decay schemes for each source.
- b. For each of the gammas, plot the energy vs. PHA channel number. How are they related? Does this relation make sense in light of the physical processes involved in the detection? Please explain.

### 5.9 Cs-137 spectrum

- a. Acquire a spectrum of Cs-137 with sufficient data to give a fairly smooth spectrum. Sketch the spectrum. Measure the gamma energy.
- b. Using the Compton formula, calculate the predicted energy of the *Compton edge*. Note that this feature represents the maximum energy given by the gamma to an electron due to a single, head-on collision. Move the cursor to the calculated energy of the Compton edge. Identify this feature on your sketch.
- c. Calculate the energy of the *backscatter peak*. This feature represents gammas which have undergone a large angle scatter outside the scintillator and then enter the scintillator, losing all of their remaining energy in the scintillator. Move the cursor to the calculated energy. Identify this feature on your sketch of the spectrum.
- d. and the full-energy peak?

### 5.10 Natural Line Width of the Cs-137 Transition (calculation)

From the Cs-137 decay scheme, determine the lifetime of the state which gives rise to the 0.662 MeV gamma. Use the Uncertainty Principle,  $\Delta E \Delta t \approx \hbar$ , to estimate its natural line-width.

### 5.11 Detector energy-resolution

The sources emit gammas with very well-defined energies. By contrast, the full-energy peaks displayed on the PHA have substantial width. The ability of the detector to resolve two closely spaced peaks is related to the peak widths. The widths are dominated by statistical fluctuations in the number of photo-electrons leaving the photo-cathode of the PM.

Poisson statistics tells us that if  $N$  photo-electrons are produced at the photo-cathode, the statistical fluctuation in that number will be in the range  $N \pm \sqrt{N}$ . From the estimates given in a-e above, calculate the expected number of electrons produced,  $N$  for each Cs-137 gamma. The *fractional* fluctuation is thus given by  $\sqrt{N} / N = 1 / \sqrt{N}$ . Using this expression, calculate the expected spread in energy (peak width). Measure the Cesium peak width and compare it to your calculation.

Compare the measured line width to the natural line width of the Cs-137 gamma, calculated above. Can you measure the natural line width with your detector?