Scintillation Detector and Compton Scattering

References:

G. F. Knoll, Radiation Detection and Measurement
N. Tsoulfanidis, Measurement and Detection of Radiation

Objective:
The objective of this experiment is to demonstrate the use of the scintillation detector and the multichannel analyzer (MCA) for the detection and spectrum measurement of gamma radiation. In addition the detector is used to study the effects of Compton scattering on gamma radiation. At the completion of this lab, you should fully understand how to use the scintillation detector and the MCA as well as be able to explain the changes that result in the energy spectrum from Compton scattering.

Introduction:
In the first portion of this experiment, the NaI(Tl) detector is introduced and used to measure the spectrum from various radioactive sources. The NaI detector, introduced in the 1950s, is very popular for gamma-ray spectroscopy because of its high efficiency and excellent linearity. A multi-channel analyzer (MCA) is used in conjunction with the scintillator to locate and identify the various features of the gamma-ray spectrum.

In each spectrum it should be possible to see photopeak(s), the Compton continuum, and the Compton edge. The Compton edge is formed by the maximum energy electron produced in Compton scattering with the scattered photon leaving the detector. This occurs when the scattering angle is 180°. The energy for this edge can be calculated as follows:

$$E_c = h\nu - E_e(\theta = \pi) = \frac{h\nu}{[1 + 2h\nu/m_0c^2]}, \tag{1}$$

where E_c is the energy of the Compton edge, $h\nu$ is the energy of the incident photon, and m_0c^2 is the electron rest mass energy.

The backscatter peak may also be discernable in the different spectra. The backscatter peak occurs for photons originating from the source which have their first interaction in the material surrounding the detector and are then scattered into the detector volume. From Fig. 1 it can be seen that as the scattering angle increases, the energy of the resulting photon converges to a minimum value. As a result, for scattering angles greater than about 110°, a peak will be seen in the spectrum at this energy. The energy of the backscatter peak can be calculated as follows:

$$h\nu'(\theta = \pi) = \frac{h\nu}{[1 + 2h\nu/m_0c^2]}, \tag{2}$$

where $h\nu'$ is the energy of the scattered photon.

In the ^{22}Na spectrum, a strong annihilation peak at 0.511 MeV will be displayed. This peak results from the detection of annihilation photons produced by positrons emitted in ^{22}Na decay. The resulting positrons then interact with a nearby electron and two 0.511-MeV annihilation photons are produced. One of these two annihilation photons can then interact in the detector.

For the size of detector used in this lab, one should also expect to observe single and double escape peaks for sources that emit gamma rays with energies above 1.022 MeV. These occur when pair production interactions take place within the detector and one or both of the annihilation photons escape. This results in a peak that is 0.511 MeV below the incident gamma-ray energy for single escape and 1.022 MeV below the incident energy for double escape. In this experiment, these may or may not be seen depending on the magnitude of the Compton continuum.

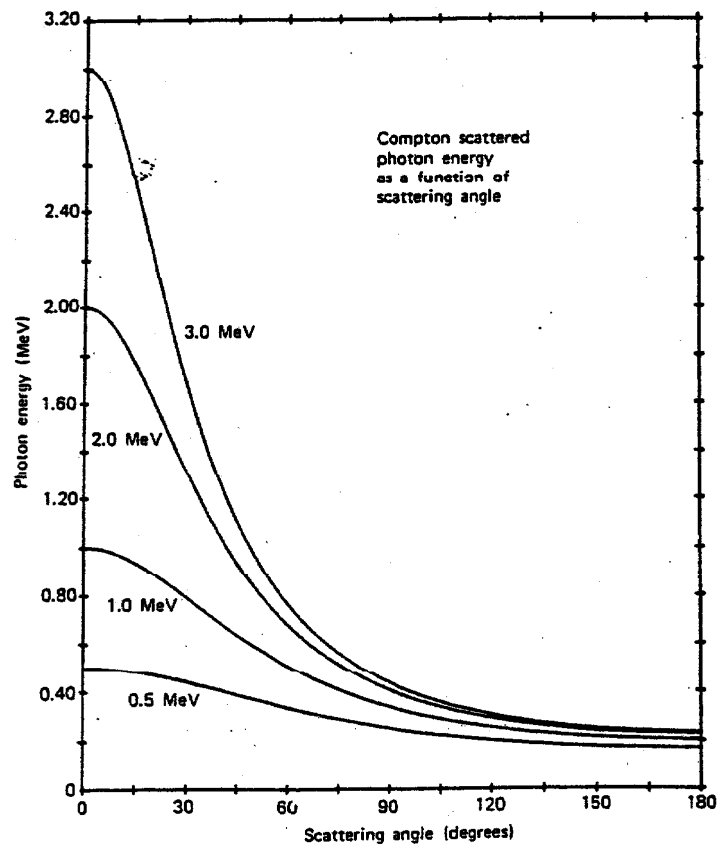

Fig. 1: Scattered Gamma-Ray Energy vs Scattering angle (Knoll p.23, 1st edition).

From the above discussion it should be obvious that there are many interactions taking place within the detector and the surrounding material. Figs. 2 and 3 depict some of these interactions schematically.

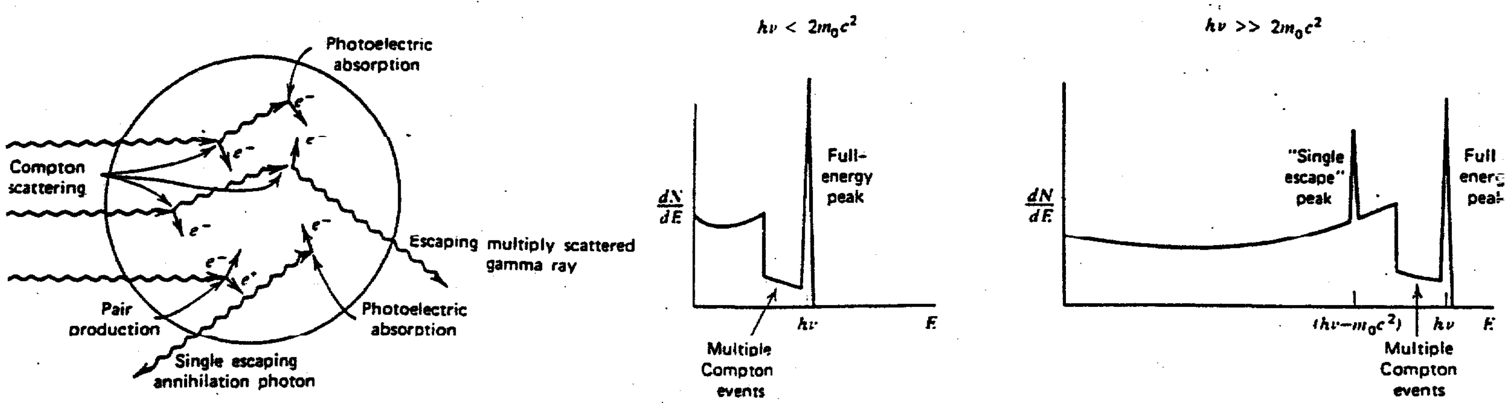

Fig. 2: Intermediate Detector Size in Gamma-Ray Spectroscopy. (Taken from Knoll, p. 317, 1st edition)

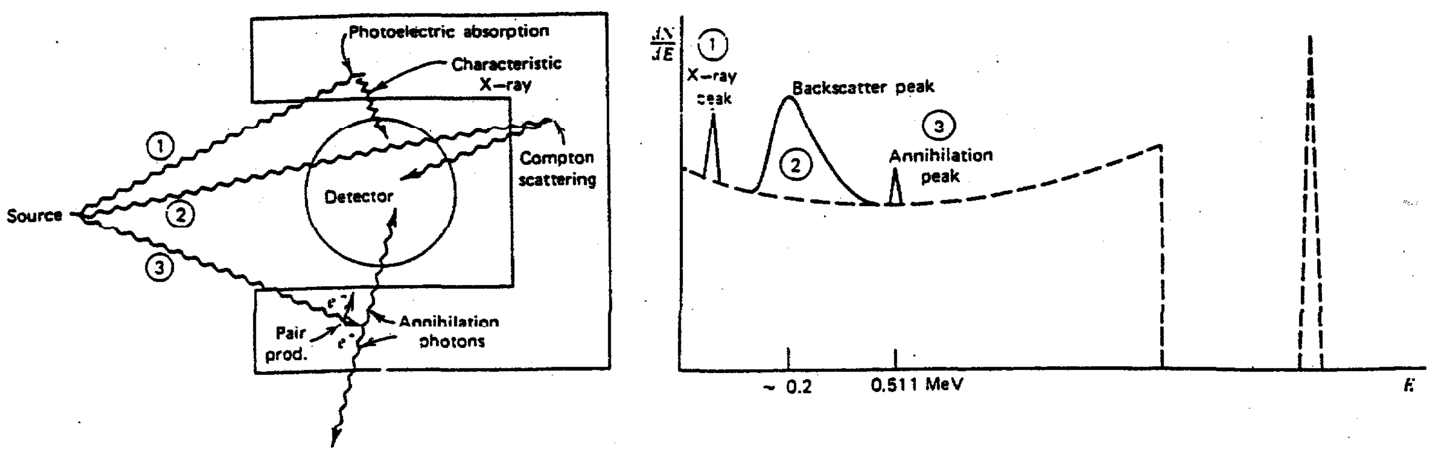

Fig. 3: Influence of Surrounding Materials on Detector Response (Taken from Knoll, p. 322, 1st edition)

One of the drawbacks of the NaI detector is that its energy resolution is poor when compared to semiconductor detectors. The resolution of the scintillation detectors is limited by the inherent statistical spread in the number of electrons produced in the photocathode. The resolution, R, is defined as

$$R = \text{FWHM}/E \tag{3}$$

where FWHM is the full width of the peak being analyzed in energy at half the maximum height, and E is the energy of the peak. In most cases it has been found that the statistical broadening of the peak is predominant over other sources of resolution loss. Because the FWHM is proportional to the square root of the gamma-ray photon energy, it can be shown that

$$R = \frac{k\sqrt{E}}{E} = \frac{k}{\sqrt{E}}, \tag{4}$$

where k is simply a constant of proportionality. Thus the energy resolution is inversely proportional to the square root of the gamma-ray energy.

Equipment:
The equipment is to be set up as depicted in Fig. 4 below. In addition to the electronics, the following items will be required:

1. Collimated 7 Ci ^{137}Cs source with lead shielding
2. Compton scattering table, including beam catcher, scattering pin, and movable extension arm for the detector
3. ^{137}Cs gamma-ray calibration source
4. ^{22}Na gamma-ray calibration source
5. ^{60}Co gamma-ray calibration source

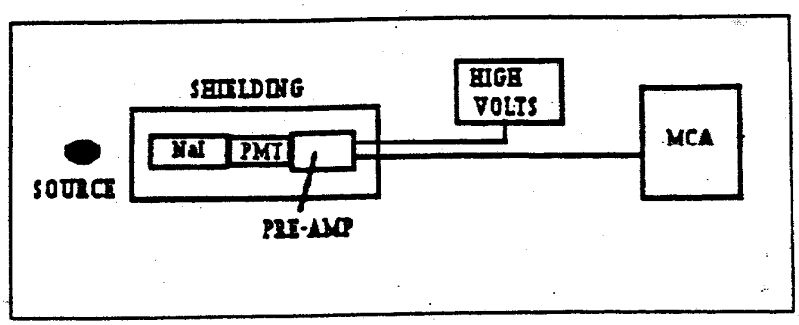

Fig. 4: Electronic Equipment Arrangement

Procedure:

Part I: Use of the NaI(Tl) detector

1. Identify and familiarize yourself with the equipment, especially the MCA. Do not allow the high voltage applied to the NaI detector to exceed 1000 V.

2. Place the ^{137}Cs source directly in front of the detector and begin counting with the MCA. Adjust the gain on the MCA until the photopeak falls at approximately one third of the full range of the analyzer. With this gain setting, obtain a spectrum long enough to get good statistics (about 100 seconds). Sketch the resulting spectrum, noting the channel numbers of any prominent features. Be sure to identify the photopeak, the Compton edge, and the escape peaks (if there are any). Record the central channel number of the photopeak, the uncertainty in determining the peak position, and the width at half the maximum photopeak height (in number of channels).

3. Replace the ^{137}Cs source with the ^{22}Na source. Using the same gain settings on the MCA, repeat the measurement of step 2. ^{22}Na should give at least two distinct peaks. Identify these peaks in your homework.

4. Construct a graph of the channel number vs. energy of the ^{137}Cs and ^{22}Na photopeaks. Plot the uncertainties in determining the peak channel number as error bars. This is now an energy calibration curve for your detector/MCA system. Calculate the energy per channel of the system. Calculate the energy resolution of the photopeaks in the two spectra using the FWHM's you determined.

5. A common method of checking the quality of scintillation systems is to analyze the ^{60}Co spectrum. Using the same voltage and gain settings as the previous cases, repeat the measurement of step 2 using the ^{60}Co source. Determine the ratio of the height of the 1.17-MeV photopeak to the height of the valley between the two photopeaks. A good scintillation system will give a ratio of about seven or eight, and exceptional systems will give ratios of nine or ten.

^{137}Cs
661.7 kev
^{60}Co
1.3325 Mev
^{22}Na
1.2745 mev
511 keV peak

Part II: Compton scattering

The geometry for this portion of the experiment is shown below in Fig. 5. A 7 Ci (intense!!) ^{137}Cs source is used to provide the gamma-ray photons. The beam is collimated to one-half inch and is heavily shielded. This beam is not to be opened until the actual scattering measurements are taken. The Teaching Assistant will control the shutter on the source and ensure that the local area radiation levels are safe for the experiment. While the shutter to the source is open, **DO NOT PLACE YOUR HAND IN THE BEAM!**.

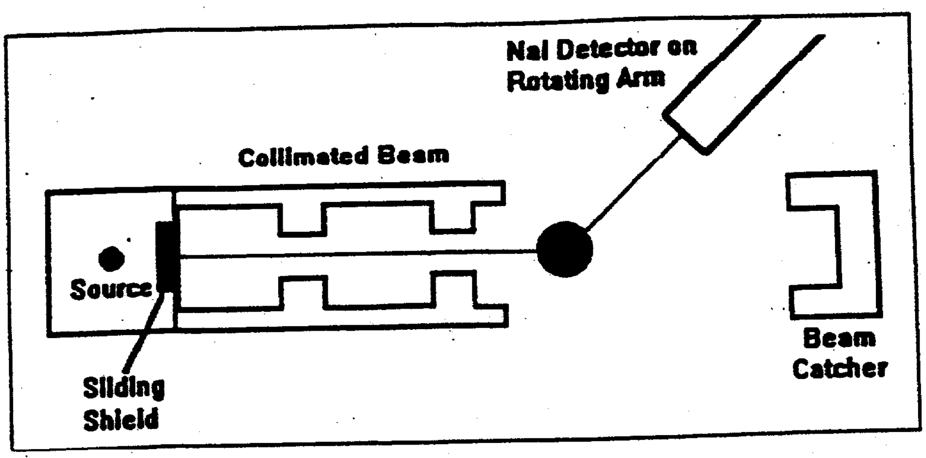

Fig. 5: Compton Scatterin Equipment Setup

At this stage we are ready to begin the actual data collection for the Compton scattering portion of the experiment. Ask the teaching Assistant to open the beam on the ^{137}Cs source. While the beam shutter is open,

DO NOT PLACE YOUR HAND IN THE BEAM!

The NaI(Tl) detector will now be used to measure the energy of the gamma rays that are Compton scattered from the scattering rod. The energy of the scattered photons can be found as follows:

$$h\nu' = \frac{h\nu}{[1 + h\nu(1 - \cos\theta)/m_0c^2]}, \tag{5}$$

where $h\nu$ is the energy of the incident photon, and $h\nu'$ is the energy of the scattered photon.

Use this equation to calculate $h\nu'$ for each of the indicated scattering angles on the table. Starting with a scattering angle of 40°, collect the resulting spectrum for 100 seconds. Record the channel number of the photopeak. Repeat this for all of the scattering angles marked on the table (10° increments). When rotating the lever arm, do it carefully and slowly. Repeat these measurements for the other scattering rod.

Homework:

Using the calibration curve you created in Part I, determine the measured values for $h\nu'$ at each angle. Compare the measured and calculated values of $h\nu'$. Do your experimental values agree with the theory? If not, why not? How do the results from the two different scattering rods compare? Why?