Gamma Rays

OBJECT:
To understand the various interactions of gamma rays with matter. To calibrate a gamma ray scintillation spectrometer, using gamma rays of known energy, and use it to measure the energy of an "unknown" gamma ray. To use positron annihilation radiation to determine the mass of the electron and to observe correlated gamma rays.

READINGS: The lab manual (see supplementary reading)"Experiments in Nuclear Science" AN34, EG&G ORTEC provides an excellent hands-on discussion of the background and techniques for a number of undergraduate level nuclear experiments. The equipment described resembles, with some variation, the equipment available in the laboratory. Additional readings are given at the end of this write-up.

APPARATUS: NaI:Tl scintillator and photomultiplier tube detector with integrated preamplifier (2), high voltage power supply, Canberra model 2000 power supply, NIM bin, Canberra 2015A amplifier/single channel analyzer module (2), Rutgers P1075 scaler/timer, Canberra model 1446 coincidence module, Nucleus Personal Computer Analyzer (PCA-II) board in CompuAdd 286 personal computer, Analyzer software, monitor.

BACKGROUND: In this experiment you will study the radioactive decay of a nucleus by detecting gamma rays emitted consequent to the decay. Gamma ray detection is a multi-step process: the gamma ray enters a NaI:Tl scintillator crystal where it produces a rapidly moving free electron that, in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways, one being emission of visible light (fluorescence). Thus a single high energy gamma ray entering the scintillator produces a flash of low energy photons. These photons are directed to the photosensitive surface of a photomultiplier tube, where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube, which in turn is proportional to the initial energy of the fast electron.

When a radioactive source is placed near the scintillator, the photomultiplier produces a series of pulses, each corresponding to the decay of a single nucleus. The amplitude of each pulse is related to the energy of the electron freed by the gamma ray. These pulses are studied using either a single- or multi-channel analyzer. A single channel analyzer (SCA) counts the number of voltage pulses whose height falls within a given (adjustable) window of values, while a multi-channel analyzer (MCA) sorts the pulses according to height and counts the number in each window to give a spectral (energy) distribution of the fast electrons. Figure 1 shows a typical MCA spectrum. In order to relate this spectrum to the nuclear decay, we need to understand how gamma rays interact with matter.

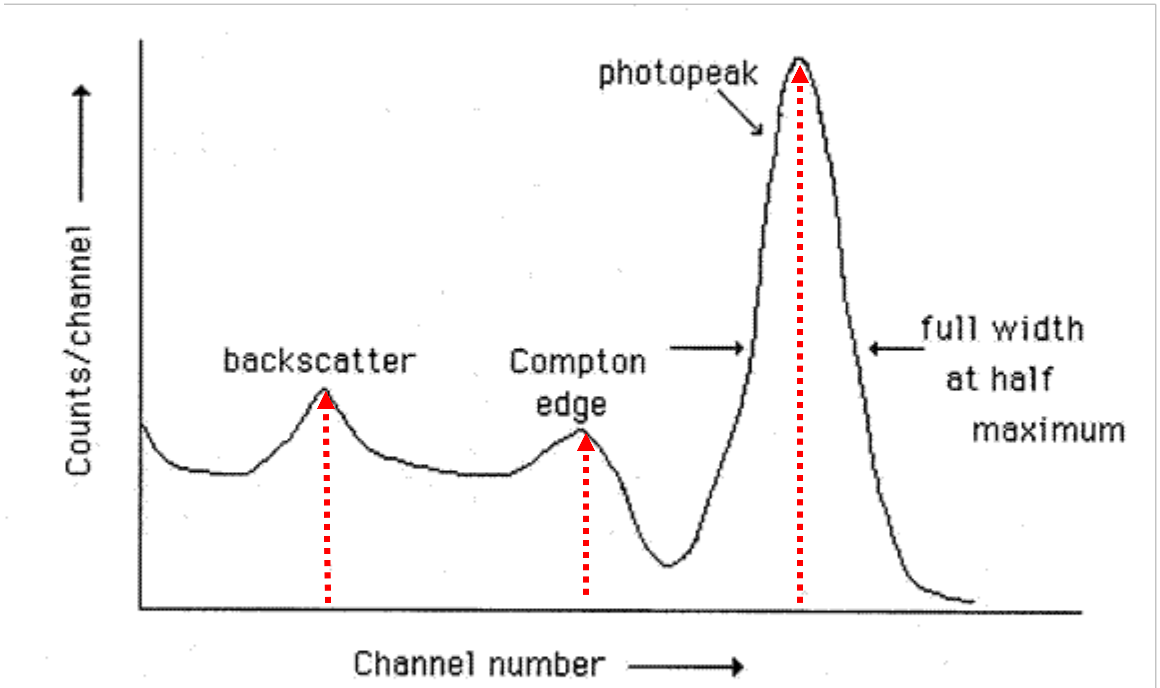

Figure 1. Na(Tl) Spectrum for Cs^{137}

DETECTION of gamma rays with NaI(Tl) detectors. Gamma rays are neutral, so that when entering the crystal they must first produce electrons in order to be detected. This conversion can occur by one of three processes: photoelectric effect, Compton effect and pair production. It is these fast electrons that give rise to scintillations. The observed spectral distribution will thus depend on the detailed interaction process of the gamma rays in the crystal. Below is a description of each of these processes.

Photoelectric effect. When a gamma ray strikes an ion in the crystal, it is absorbed and all of its energy is transferred to one of the bound electrons, which is freed and moves rapidly through the crystal. If for example an atomic K-electron is ejected as a result of the photoelectric process, its energy will equal the gamma ray energy less the electron binding energy in the K shell. Very shortly after, another bound atomic electron will "fall" into the K shell vacancy (or cascade down sequentially) with the subsequent emission of x-rays. These x-rays will have a large probability of producing light pulses in the scintillator by exciting other loosely bound electrons. These processes (initial photoelectron ejection and subsequent x-ray production and interaction with the crystal) will usually happen within the resolution time of the counter, so that these successive light pulses add and cannot be distinguished from one another. Therefore in the end the photomultiplier output pulse will correspond to the full gamma ray energy, if the photoelectron stops in the crystal and if no light escapes the crystal. Thus the photoelectric effect results in a peak, called the **photopeak**, at an energy equal to that of the incoming gamma ray.

Compton scattering. In this case the gamma ray is not absorbed, but rather scattered through an angle θ by an electron, which recoils and carries away some of the gamma ray's energy E. The scattered electron energy is then detected in the photomultiplier. (The scattered gamma ray escapes from the scintillator; the probability that a gamma ray Compton scatters in a typical size scintillator is quite small (1% to 10%), which means you are unlikely to detect a gamma ray that has undergone two Compton scatterings.)

The energy of the Compton-scattered gamma ray $E_{\gamma'}$ as a function of the scattering angle, θ, and the initial energy E_γ is given by:

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\theta)} \qquad (1)$$

where m is the mass of the electron and c is the speed of light. Prove this using the kinematics of energy and momentum conservation illustrated in Fig. 2.

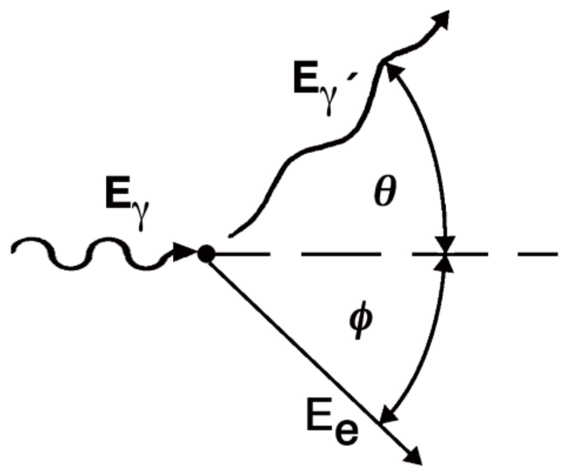

Figure 2. Angles and Energies Defined for the Compton

From this equation you can see that the energy of the scattered electron, which is the energy loss of the gamma ray, will vary from zero (when θ = 0⁰) to a maximum of $2E_\gamma^2/(mc^2 + 2E_\gamma)$ (when θ = 180⁰). This maximum energy is called the **Compton edge**. For comparing the predicted $E_{\gamma'}$ to the measured $E_{\gamma'}$ in this experiment, it is useful to rearrange equation (1) to the form:

$$\frac{1}{E_{\gamma'}} = \frac{1}{E_\gamma} + \frac{1-\cos\theta}{mc^2}$$

The energy distribution of Compton scattered electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost flat plateau from zero energy up to the Compton edge where it drops off sharply (at a rate limited by the energy resolution of the tube).

The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator (Figure 3). In this case the observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ. But cos θ varies only slowly with θ for θ near 180^0, which means [see Eq. (1)] that these gamma rays will have energies close to $mc^2 E_\gamma /(mc^2 + 2E_\gamma)$. The resulting energy peak is called the **backscatter peak**. It can be enhanced by placing a sheet of lead around the outside of the scintillator.

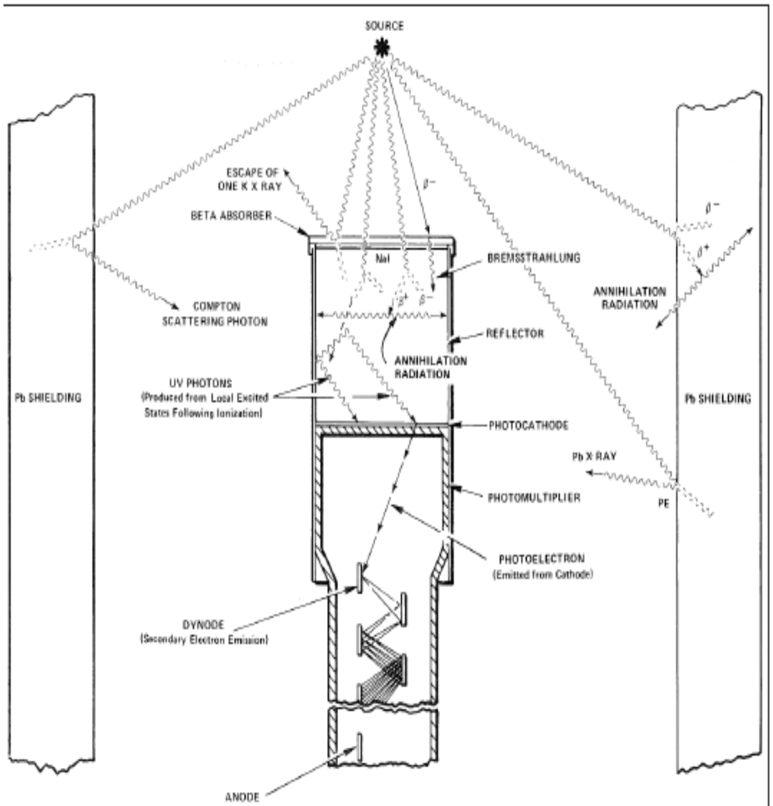

Fig. 3 The Structure of the NaI(Tl) Detector and Various Types of Gamma-Ray Interactions that Occur in the Typical Source-Detector-Shield Configuration.

Pair production. If the incoming gamma ray energy is above 1.02 MeV = $2mc^2$, the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy ($E-2mc^2$). The short lived positron will eventually annihilate with an electron, emitting two photons, each of energy mc^2. One of these may be absorbed in the crystal, and contribute a peak at energy mc^2 =0.511MeV. The annihilation may occur before the positron is completely stopped in which case the peak energy will be higher.

Additional peaks may appear if the positron annihilation occurs during the initial collection time of the photomultiplier. In this case the energy of the emitted photons will add to the signal produced by the slow-down of the electron-positron pair resulting in three peaks:

a. "Full energy" peak (E), when both annihilation photons are absorbed in the scintillator.

b. "One-escape peak" (E-mc^2) when only one annihilation photon is absorbed in the scintillator.

c. "Two escape peak" (E-2mc^2), if both annihilation photons escaped.

The final question to consider is that of the relative importance of the three interaction mechanisms, which depend in different ways upon the energy of the gamma ray. For low energy rays, the photoelectric effect predominates. Since the photopeak directly yields the energy of the gamma ray, most scintillators are designed to maximize the photopeak. In the NaI:Tl scintillator you will use, a small amount of the heavy metal thallium is added for this purpose when the crystal is grown. (The strength of the photoelectric effect depends strongly on the number of electrons bound to the ion.) As E increases, the photoelectric absorption deceases rapidly, while the Compton scattering decreases much more slowly and predominates above several hundred keV. The absorption coefficient for pair production rises rapidly above the threshold E = 1.02 MeV and exceeds the Compton scattering, while photoelectric absorption becomes negligible.

Energy resolution: The typical energy resolution that can be obtained with NaI(Tl) is ~7% for the 0.662 MeV ^{137}Cs gamma-ray line. For NaI(Tl) detectors, the resolution is a strong function of energy. The resolution is primarily controlled by the statistical fluctuation of the number of photoelectrons produced at the photocathode surface in the photomultiplier tube. The energy resolution (in percent) is defined as the ratio $R = 100(\delta E / E)$ where δE is the FWHM (full width at half maximum) of the peak at energy E. The resolution of NaI(Tl) detectors depends on energy: $R(E) \approx k \frac{100\%}{\sqrt{E}}$ where k is a proportionality constant characteristic of the particular detector. Thus you will note that the linewidth will become wider at higher energies.