Gamma-Ray Spectroscopy using NaI(Tl)*

Gamma Emission

Most isotopes used for gamma-ray measurements also have beta-emissions in their decay schemes. The decay scheme for the isotope typically includes beta decay to a particular level, followed by gamma emission to the ground state of the final isotope. The beta particles will usually be absorbed in the surrounding material and not enter the scintillation detector. The gammas, however, are quite penetrating, and will easily pass through the aluminum light shield.

The NaI(Tl) Detector

The structure of the NaI(Tl) detector is illustrated in Figure 1. It consists of a single crystal of thallium activated sodium iodide optically coupled to the photocathode of a photomultiplier tube. When a gamma ray enters the detector, it interacts by causing ionization of the sodium iodide. This creates excited states in the crystal that decay by emitting visible light photons. This emission is called a scintillation, which is why this type of sensor is known as a scintillation detector. The thallium doping of the crystal is critical for shifting the wavelength of the light photons into the sensitive range of the photocathode. Fortunately, the number of visible-light photons is proportional to the energy deposited in the crystal by the gamma ray. After the onset of the flash of light, the intensity of the scintillation decays approximately exponentially in time, with a decay time constant of 250 ns. Surrounding the scintillation crystal is a thin aluminum enclosure, with a glass window at the interface with the photocathode, to provide a hermetic seal that protects the hygroscopic NaI against moisture absorption. The inside of the aluminum is lined with a coating that reflects light to improve the fraction of the light that reaches the photocathode.

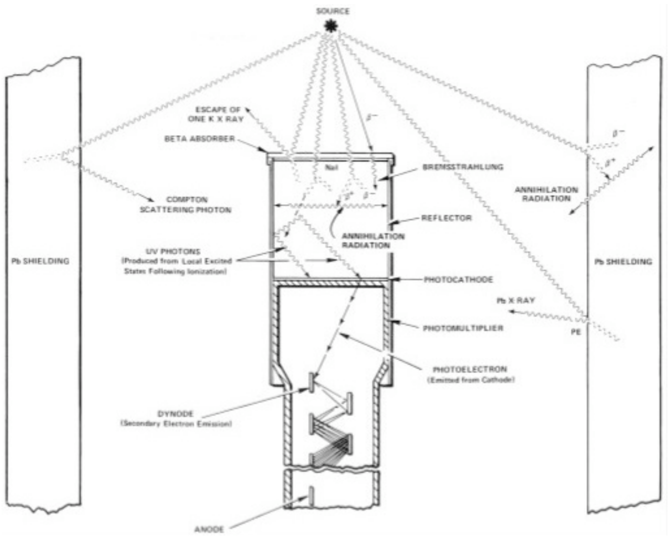

Figure 1. The Structure of the NaI(Tl) detector and various types of gamma-ray interactions that occur in the typical source-detector-shield configuration

* Experiment handout taken from Ortec's 'Experiments in Nuclear Science'

At the photocathode, the scintillation photons release electrons via the photoelectric effect. The number of photoelectrons produced is proportional to the number of scintillation photons, which, in turn, is proportional to the energy deposited in the crystal by the gamma ray.

The remainder of the photomultiplier tube consists of a series of dynodes enclosed in the evacuated glass tube. Each dynode is biased to a higher voltage than the preceding dynode by a high voltage supply and resistive biasing ladder in the photomultiplier tube base. Because the first dynode is biased at a considerably more positive voltage than the photocathode, the photoelectrons are accelerated to the first dynode. As each electron strikes the first dynode the electron has acquired sufficient kinetic energy to knock out 2 to 5 secondary electrons. Thus, the dynode multiplies the number of electrons in the pulse of charge. The secondary electrons from each dynode are attracted to the next dynode by the more positive voltage on the next dynode. This multiplication process is repeated at each dynode, until the output of the last dynode is collected at the anode. By the time the avalanche of charge arrives at the anode, the number of electrons has been multiplied by a factor ranging from 104 to 106, with higher applied voltages yielding larger multiplication factors. For the selected bias voltage, the charge arriving at the anode is proportional to the energy deposited by the gamma ray in the scintillator.

The preamplifier collects the charge from the anode on a capacitor, turning the charge into a voltage pulse. The pulse is transmitted to the supporting amplifier. At the output of the preamplifier and at the output of the amplifier, the pulse height is proportional to the energy deposited in the scintillator by the detected gamma ray. The Multichannel Analyzer (MCA) measures the pulse heights delivered by the digiBASE, and sorts them into a histogram to record the energy spectrum produced by the NaI(Tl) detector.

For an ideal detector and supporting pulse processing electronics, the spectrum of 662-keV gamma rays from a ^{137}Cs radioactive source would exhibit a peak in the spectrum whose width is determined only by the natural variation in the gamma-ray energy. The NaI(Tl) detector is far from ideal, and the width of the peak it generates is typically 7% to 10% of the 662-keV gamma-ray energy. The major source of this peak broadening is the number of photoelectrons emitted from the photocathode for a 662-keV gamma-ray. For a high-quality detector this is on the order of 1,000 photoelectrons. Applying Poisson statistics [2, 3], 1,000 photoelectrons limit the full width of the peak at half its maximum height (FWHM) to no less than 7.4%. Statistical fluctuations in the secondary electron yield at the first dynode and fluctuations in the light collected from the scintillator also make a small contribution to broadening the width of the peak in the energy spectrum.

The Multichannel Pulse-Height Analyser

The Multichannel Analyzer (MCA) is responsible for measuring the height of each pulse delivered by the linear amplifier. Over the period of time the gamma rays are counted, the MCA sorts the pulses, according to pulse height, into a histogram that represents the spectrum of gamma-ray energies intercepted by the NaI(Tl) detector.

The MCA in the set-up for this experiment uses software in a supporting personal computer to operate the instrument and display the spectrum. The MCA connects to the computer via a USB cable.

Spectrum Analysis of ^{137}Cs

At a given angle, the measured spectrum for the scattered gamma rays looks something like this in the Maestro software:

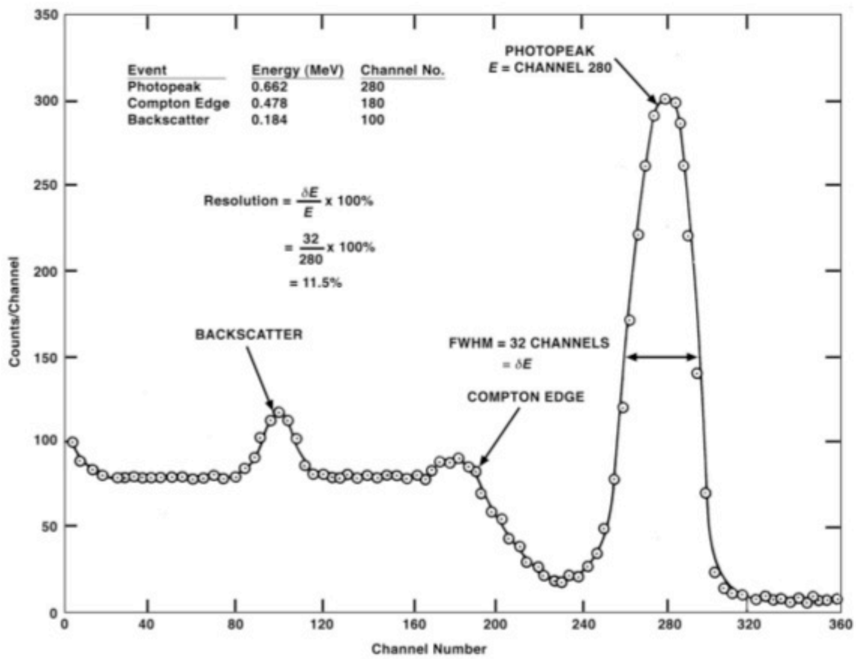

Figure 2. Na(I) spectrum for ^{137}Cs

The photopeak is created when the gamma-ray photon interacts in the scintillator via the photoelectric effect. The photon encounters an orbital electron that is tightly bound to a nucleus. The entire energy of the photon is transferred to the electron, causing the electron to escape from the atom. The gamma-ray photon disappears in the process. As the photoelectron travels through the scintillator, it loses its energy by causing additional ionization. At the end of the process, the number of ionized atoms is proportional to the original energy of the photon. As the electrons re-fill the vacancies in the ionized atoms, visible light photons are generated. This is the source of the scintillation, wherein the number of visible photons is proportional to the original energy of the gamma-ray. Consequently, the event populates the photopeak in the spectrum. This peak is often called the full-energy peak, because a two-step interaction, a Compton scattering followed by a photoelectric interaction, also contributes a small number of events to the full-energy peak.

The Compton interaction is a pure, kinematic collision between a gamma-ray photon and what might be termed a free electron in the NaI(Tl) crystal. By this process, the incident gamma-ray photon gives up only part of its energy to the electron as it bounces off the free electron. The recoiling electron loses energy by causing ionization as it travels through the crystal. Thus the number of visible photons in the resulting scintillation is proportional to the recoil energy of the Compton electron. The amount of energy transferred from the gamma-ray photon to the recoiling electron depends on whether the collision is head-on or glancing. For a head-on collision, the gamma ray transfers the maximum allowable energy for the Compton interaction. Although it involves a photon and an electron, the interaction is similar to a billiard-ball collision. The reduced energy of the scattered gamma ray can be determined by solving the energy and momentum conservation equations for the collision. The solution for these equations in terms of the scattered gamma-ray energy can be written as

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_o c^2}(1 - \cos\theta)} \qquad \text{(Eqn. 4)}$$

where

$E_{\gamma'}$ is the reduced energy of the scattered gamma ray, γ', in MeV;

θ is the scattering angle for the direction of γ' relative to the direction of the incident gamma ray, γ;

E_γ is the energy of the incident gamma ray, γ, in MeV,

$m_o c^2$ = 0.511 MeV is the energy equivalent energy of the rest mass, m_o, of the electron; and

c is the speed of light.

For a head-on collision, the gamma ray is scattered backwards along its initial trajectory, and θ = 180°. For this condition, the backscattered gamma-ray energy becomes

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma} \qquad \text{(Eqn. 5)}$$

where the convenient approximation, $(m_o c^2)^{-1} \approx 2$, has been used.

If this backscatter event happens in the detector, the maximum energy transferred to the recoiling electron will be

$$E_e = E_\gamma - E_{\gamma'} \qquad \text{(Eqn. 6)}$$

Thus the maximum energy that can be recorded in the spectrum for a gamma ray that interacts in the detector by Compton scattering is given by Equation 6. This defines the energy of the Compton edge in the above figure. For an initial gamma-ray energy of 1 MeV, Equations 5 and 6 predict that the Compton edge will occur at 0.80 MeV, and the energy of the backscattered gamma ray will be 0.20 MeV.

Because the gamma-ray photon can be scattered through any angle from 0 to 180°, and the scattered photon can escape the detector, the energy deposited in the detector can vary from the maximum at the Compton edge through all values down to zero. This is the genesis of the Compton continuum in the above figure.

Note that there is a small, but finite, probability that the Compton scattered photon will be subsequently absorbed in the crystal by the photoelectric process. This two-step interaction will generate a pulse that falls in the full-energy peak.

The backscatter peak is caused by Compton scattering from an entirely different location. Consider a gamma ray emitted by the radioactive source in a direction heading away from the detector. This gamma ray can encounter material in the neighborhood of the radioactive source and undergo Compton scattering. If the scattering angle is 180° the scattered gamma ray travels back towards the detector with an energy defined by Equation 5. If this lower-energy gamma ray interacts in the scintillator by the photoelectric effect, it will contribute to a photopeak at the lower energy. Typically this backscatter peak will be of low intensity, if there is minimal material behind the radioactive source. Usually, the backscatter peak is rather broad, because of the range of directions that can contribute to the peak. For an initial gamma-ray energy of 1 MeV, Equation 5 predicts that the backscatter peak will occur at 0.20 MeV.

Figure 1 illustrates some of the types of interactions that can take place in the NaI(Tl) detector and the surrounding shielding material.