Memorial University of Newfoundland
Department of Physics and Physical Oceanography
Physics 3900 Laboratory

Gamma Ray Spectroscopy

Objectives

To use a scintillation detector to record γ-ray spectra; to study and understand the various features of γ-ray spectra, including photopeaks, the Compton edge, and backscatter peaks; to identify the components of a radioactive source; to study the absorption of γ-rays by matter.

You should read up in the references to learn about the various interactions of γ-rays with matter, and about the scintillation detector, before you start the experiment.

Apparatus

NaI(Tl) scintillation detector
Computer with *Integrated Computer Spectrometer* card
set of γ sources
set of metal foils

Warning! All radioactive sources are potentially dangerous and must be treated with caution and respect. The γ sources you will use are intended for educational use and are quite weak, and so are relatively safe. Nonetheless it is important that you handle them carefully and use common sense when working with them. When not in use they must be stored in the lead container provided.

Introduction

An excited nucleus can emit one or more gamma rays as it decays to its ground state. In this experiment you will investigate gamma ray spectra from several radioactive sources using a sodium iodide scintillation counter.

The detector consists of a single crystal of sodium iodide “activated” with a small amount of thallium. A gamma ray absorbed by the crystal causes an electron to be ejected via the photoelectric effect, which then produces light as it loses energy to the crystal. This light falls on the photocathode of a photomultiplier, producing electrons. These electrons are then accelerated towards a special electrode, called a *dynode*, held at a positive potential V_1 with respect to the photocathode. On striking the dynode the electrons are sufficiently energetic to cause secondary electron emmission, and the secondary electrons formed in this way are accelerated towards a second dynode, at a potential V_2, where a similar process occurs. The result is a large pulse of electrons received at the anode of the photomultiplier. The size of the pulse depends on the energy of the original gamma ray.

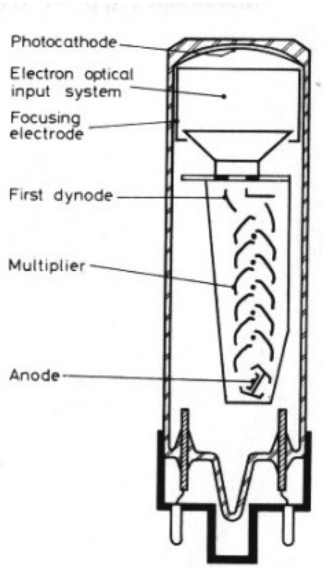

Figure 1: Schematic diagram of NaI dectector

If m electrons are emitted per electron incident on any dynode, and if there is perfect collection between dynodes and there are n stages, then the overall gain will be m^n.

The pulses of electrons are fed into a multichannel analyzer (MCA) which sorts them according to size, with bigger pulses going into higher numbered channels. Thus channel number is related to gamma ray energy. The resulting spectrum will contain one or more photopeaks at the energies of the gamma rays emitted from the source. A typical gamma spectrum is shown in the figure below. In addition to the sharp peaks, note the lower energy features, which result from scattering of electrons in the crystal by the incident gamma rays. Note that the spectrum you see is not just a spectrum of the γ-ray energies emmitted by the source, rather it gives the energies of the *photons* that eventually impinge on the photomultiplier. There are several types of interactions between the γs and the atoms or electrons in the detector that can affect the resulting spectrum. Be sure that you understand the process whereby a gamma ray incident on the scintillation crystal is recorded as a count in one channel of the multi-channel analyzer.

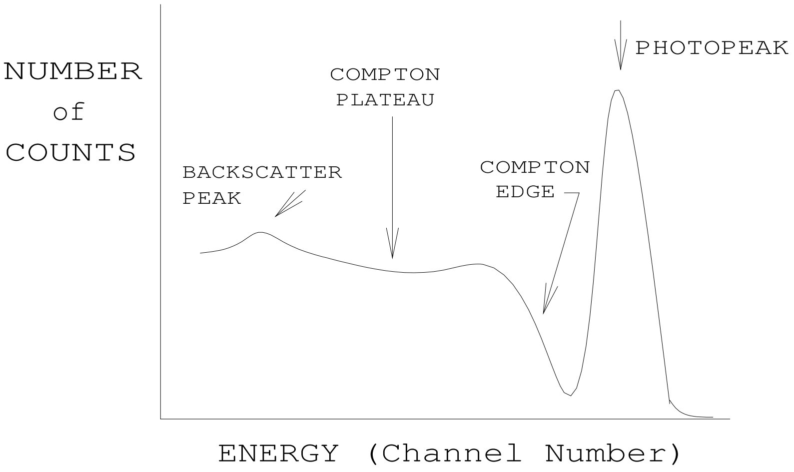

Figure 2: A Typical Gamma Ray Spectrum

The position of the photopeak depends on the gain, M, which is in turn proportional to V^n, where V is the applied voltage. Thus if write

$$M = kV^n \tag{1}$$

we can show that for a small change δV in the applied voltage Eq(1) becomes

$$M + \delta M = k(V + \delta V)^n$$

Expanding, neglecting second order terms and above,

$$M + \delta M = k(V + n\delta V)$$

so that

$$\frac{\delta M}{M} = n\frac{\delta V}{V} \tag{2}$$

The implication of Eq(2) is that if we want the gain of the photomultiplier to be stable to within x percent, the high voltage supply has to have a stability of (x/n) percent.

Photomultiplier Gain

Please see the ICS-PCI manual for a more complete description of the software. Note that you can save spectra in a data file — you are encouraged to do this often so that spectra can be retrived and used in other data analysis and plotting programs.

Click on the ICS-PCI icon to start. When the *Amp/HV/ADC* settings window appears, set the High Voltage to 600 volts and the Conversion Gain to 2048 (if you want to use all 2048 channels). Using the Cs^{137} source, obtain a spectrum and locate the position of the photopeak. Repeat, increasing the voltage by about 50 volts each time, up to a maximum applied voltage of 1000 volts. Plot a suitable graph to determine the value of n in Eq (1). What is its physical significance?

Calibration

- Reset the high voltage to 900 volts. Using the Na^{22} source, obtain a spectrum which fills the width of the screen. (You may need to adjust the gain and discriminator controls to display the best spectrum.)

- Select *Settings – Energy Calibrate – 2 Point Cal.* Locate each peak and enter their energies in the appropriate boxes (511 keV and 1274 keV). You may find that a 3 Point Cal using a third peak from another source gives a better calibration.

- What is the mathematical relationship between channel number and gamma ray energy?

- Using the remaining sources in the box, sketch each spectrum and confirm that the energy of each photopeak agrees with the values listed. Many isotopes emit a gamma ray of energy 0.511 MeV. This is often called *annihilation radiation* or *AR* which refers to 0.511 MeV photons created as a result of positron-electron annihilation.

Decay Products of Ra-226

Uranium-238 decays to lead-206 by processes of α and β emission, as shown in Figure 3. Many of the intermediate daughter nuclei are γ emitters, one of which is Ra^{226}. Obtain a spectrum from the Ra^{226} source. You may have to collect data for several hours to resolve the important features clearly. Determine the energies of as many lines as you can, and, using tables in the *CRC Handbook of Chemistry and Physics* as a guide (or other reference), identify the decay products and discuss the various modes of decay associated with Ra^{226}. You may need to adjust the gain control in order to see the highest energy peaks. If you do this, you will need to repeat the calibration.

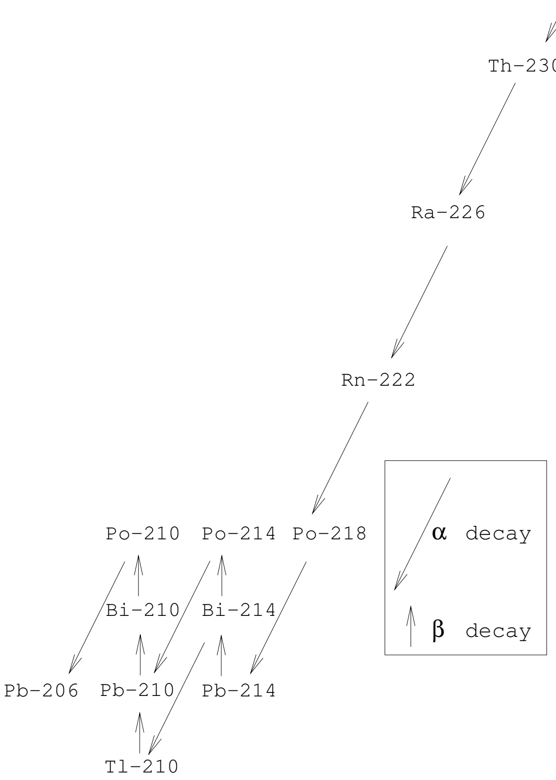

Figure 3: Decay Scheme of U^{238}

Compton Scattering

When γ-rays pass through matter they can be scattered by electrons they encounter along the way. This process is called *Compton scattering*. If the scattering is elastic, we can use conservation of momentum and energy (bearing in mind that the velocities involved are relativistic) to derive an expression for the energy E'_γ of the scattered γ-ray [1].

$$E'_\gamma = \frac{E_\gamma}{(E_\gamma/m_0c^2)(1-\cos\theta)+1}$$

where $E_\gamma = h\nu$ is the energy of the incident γ-ray, m_0c^2 is the rest energy of an electron, and θ is the scattering angle. The maximum transfer of energy to the electron — and hence the minimum energy of the scattered γ — occurs for *backscattering*, when $\theta = 180°$. Then the energy of the scattered γ is

$$E_{bs} = \frac{E_\gamma}{(2E_\gamma/m_0c^2) + 1}$$

and the energy of the electron is

$$E_{ce} = E_\gamma - E_{bs} = \frac{E_\gamma}{(1 + m_0c^2/2E_\gamma)}.$$

E_{ce} is called the Compton edge, and shows up as the high-energy end of the region of the spectrum due to Compton scattering in Fig (2), while the peak at the low-energy end has energy E_{bs}.

Look for the backscatter peak and Compton edge using the Cs_{55}^{137} and Mn_{25}^{54} sources. Use your results to determine the rest mass of the electron with its associated uncertainty. Note that it is unlikely that your spectra will be as clean as that in Fig. (2).

Energy Resolution

In theory, we expect gamma rays of a single energy to be recorded in one channel. In practice, each gamma ray appears as a peak, which can be approximated by a Gaussian function; the peak position corresponds corresponds to the energy of the gamma ray, while the width of the Gaussian tells us something about how precisely the NaI detector measures the energy of the gamma ray.

The standard definition of energy resolution R is:

$$R = \frac{\text{Full Width Half Maximum}}{\text{Peak Position}}$$

For a Gaussian distribution the position of the peak = mean, and Full Width Half Maximum (FWHM) is related to the standard deviation σ by $FWHM = 2.36\sigma$.

For each of the five peaks (2 from Na^{22}, 2 from Co^{60}, and 1 from Cs^{137}) estimate the FWHM and location of the peak in terms of the channel number and calculate the energy resolution. Make sure that you accumulate enough data for each sample by waiting until the spectrum has "smoothed" itself out. Can you establish a relationship between energy resolution and gamma ray energy?

Photoelectric Absorption

When a gamma ray interacts with matter, it can cause an electron to be ejected from the absorbing atom. This is the process which usually occurs in the NaI detector. The energy of the emitted photoelectron is

$$E_e = h\nu - E_b$$

where E_b is the binding energy of the electron. The probability of a photoelectric interaction (normally called the *cross-section*, σ) depends on the atomic number Z of the absorber and the energy of the γ. The cross-section is proportional to the absorption coefficient, μ, which is defined by

$$I(x) = I(0)\mathrm{e}^{-\mu x}.$$

Often the mass absorption coefficient $\mu' = \mu/\rho$ is used; then

$$I(x) = I(0)\mathrm{e}^{-\mu' \rho x}.$$

μ' has units cm^2/g. Typically μ has the functional form

$$\mu = KZ^n E_\gamma^m \tag{3}$$

where K, m and n are constants. m is usually around -3.

Using the .662 MeV gamma of Cs_{55}^{137} and a series of aluminum absorbers of different thickness, confirm the exponential dependence of absorption on thickness and determine the absorption coefficient for Al at this energy. Note that you will have to increase your counting time as absorber thickness increases in order keep the uncertainties small. The software will display the total number of counts under the photopeak. You will need to check that the Region of Interest (ROI) is set appropriately. Be sure to properly deal with uncertainties in your measurement.

Repeat this experiment using a higher energy gamma from either the Co^{60} or Na^{22} sources. What does Eq (3) predict about the variation of μ with gamma energy?

References

1. D.W. Preston and E.R. Deitz, *The Art of Experimental Physics*, (Wiley, New York, 1991), pp. 316–324 and pp. 376–385.

2. A. Beiser, *Concepts of Modern Physics*, 4th ed. (McGraw-Hill, New York, 1987), Ch. 12.

3. G.F. Knoll, *Radiation Detection and Measurement*, (Wiley, New York, 1979).