Gamma Ray Spectroscopy

1. Introduction

Gamma rays are high energy photons created in the decay transitions of radioactive nuclei. The gamma ray energy spectrum measures the energy levels of the nuclear states in the same way that visible line spectra measure atomic structure. In many modern applications the above logic is reversed, and gamma rays at characteristic energies are used to analyze, sometimes at trace levels, the composition of unknown samples.

In this experiment, you will measure the spectra of several well-known gamma emitters using a "scintillation counter", modular electronics, and some histogramming software. Observation of a gamma ray starts with an interaction that transfers energy to an electron, which then ionizes a trail of atoms. The *scintillator* is a material that converts the energy of such an ionization trail into visible or near-visible light. The small pulse of scintillation light is directed to a *photomultiplier* (PMT), which converts it into an amplified electrical signal. The voltages from the PMT are amplified and finally digitized by a computerized *Pulse Height Analyzer* (PHA). To the extent that all the stages have a linear response with energy, the amplitude of the signal is a measure of the gamma energy, which allows you to study nuclear spectra and, as a bonus, all the processes by which gamma rays interact with matter. Figure 1 illustrates some of these processes.

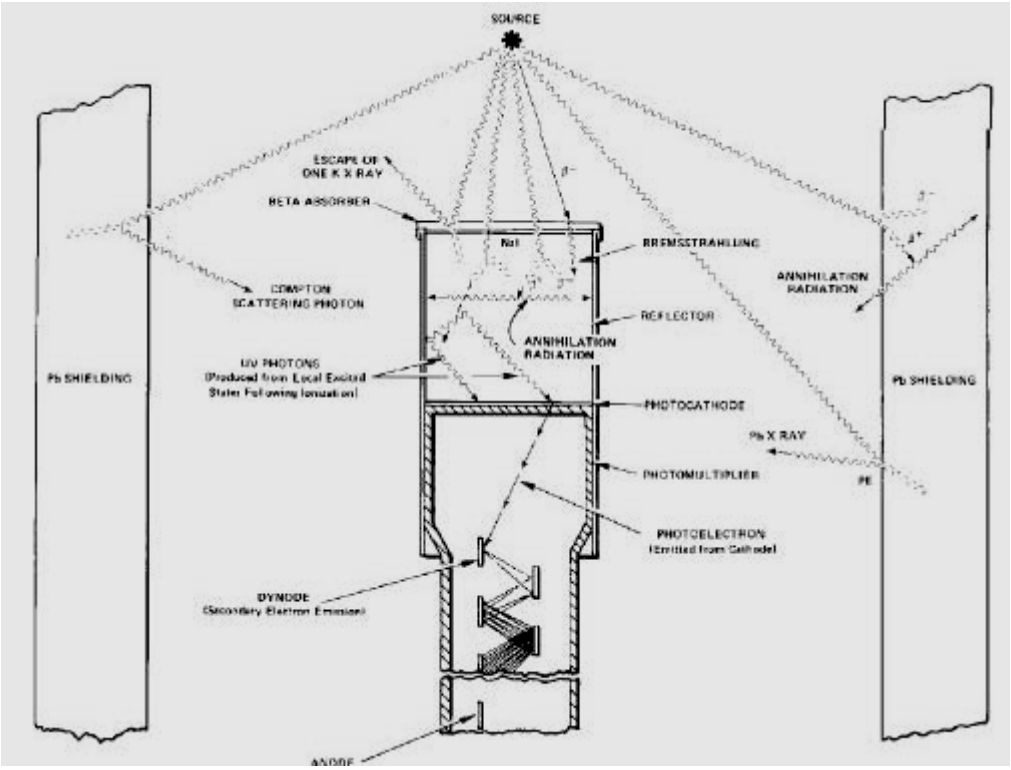

Figure 1 What goes on in the vicinity of gamma source and detector.

2. Origin of Gamma Rays and A Bit of Nuclear Physics

In Bohr's model for atomic line spectra, an electron makes a transition between quantized energy levels, and the energy lost by the electron appears in a photon of specific frequency, according to the deBroglie relation:

$$E_f - E_i = \Delta E = h\nu$$

Although we are accustomed to think of this as a change in state of a single electron, it is useful to think of the process as a change in the configuration of the whole atom: the nucleus and its collection of electrons find a lower energy state, and the excess energy is carried away by a photon. Now consider the nucleus, a multi-particle collection of protons and neutrons held together by the "strong" interaction, whirling about themselves in bound configurations with stationary wave-functions and quantized energies. There is no fixed attractive center (the nucleus does not have nucleus!), but the net effect of all the nucleons is to create an average nuclear potential in which the bound states of the individual nucleons are arranged in a shell scheme reminiscent of atomic structure. The configuration of all of the nucleons in this level structure is a collective nuclear state with a quantized energy. When a nucleus decays radioactively to a lower energy state, the excess energy is sometimes released as a photon, or "gamma-ray".

Several features of the nuclear environment make nuclear emission spectra more complicated than the atomic case.

a. In the nuclear system, each particle feels the force of every other particle. For large nuclei the spectrum of the multi-particle states can be very complicated. In addition, with two different kinds of fermions, protons and neutrons, the Exclusion Principle allows 4 particles in each state, and changes of state can therefore include changes in particle identity.

b. The strong interaction between protons and neutrons is independent of charge: the strong force between a neutron and a proton is the same as that between two neutrons or two protons. However, the electric Coulomb repulsion between the like-signed protons is still there and is a net destabilizing force for the nuclear state. This is the reason that the number of neutrons exceeds the number or protons Z, when Z is large. The excess of neutrons contributes enough strong binding energy to overcome the large internal Coulomb repulsion. In many heavy nuclei it is energetically favorable to emit a bound state of two neutrons and two protons (in effect, a helium nucleus), thus reducing the Coulomb repulsion in the remainder nucleus and gaining an additional binding energy contribution from the fact that helium is a very tightly bound nucleus. These changes of nuclear state are called radioactive α decays, and the emitted helium nuclei are still called α rays.

c. The weak interaction can change a proton into a neutron and vice versa, with the emission of a positron or electron and a neutrino or antineutrino. A free neutron is unstable and decays to a proton in 887 sec as $n \rightarrow p + e^- + \nu$. This happens to a free neutron because it has slightly more mass than the decay products, and thus the decay is energetically favorable. This does not happen, in general, to neutrons in the nucleus, because adding a proton would *raise* the energy due to the increased Coulomb repulsion. However, for some nuclei this is energetically possible because changing a particle identity circumvents a configuration restriction due to the Uncertainty Principle. The process $p \rightarrow n + e^+ + \overline{\nu}$ reduces the number of protons, and the lowered Coulomb repulsion can be

more significant than the mass difference between the proton and neutron, so that the overall energy is reduced. Both electron and positron emission are referred to as β decays, and the emitted electrons or positrons are called β rays.

e. The electromagnetic interaction can mediate a nuclear transition where the collective system drops to a lower electrical potential, releasing the excess energy in the form of a high-energy photon. These are called γ decays, and the photons are referred to as γ rays. The spectrum of nuclear gamma rays shows a rich line structure, and the situation is very reminiscent of atomic transitions, with the salient difference that nuclear states are separated by MeV scale energies. In many cases, γ decays occur right after α or β decay**s,** a kind of final electromagnetic cleanup rearrangement after the gross changes in atomic number and weight.

3. Interaction of Gamma rays and Charged Particles with Matter

Becquerel first detected gamma rays with photographic film even when thick material was placed between the radioactive source and the film. This proved that although they were very penetrating, they ultimately reacted with matter in a manner similar to light. To understand any technique for gamma detection, we have to start with the quantum interaction of light with matter, and the ways photon energy is transferred to the detector. In all cases, the photon transfers energy to electrons, and detection relies on sensing the ionization created as the high-energy electrons move through matter. We review the energy loss mechanisms here, and techniques for sensing the ionization in the next section.

a. The Quantum Interactions of Light with Matter.

We describe briefly here the three main mechanisms by which a photon transfers energy to an electron. More detail on the interaction of light with matter can be found in Melissinos 5.2.5 or Knoll, Chapter 2, Sec. III. As is generally done in the description of a particle scattering, the probability of an interaction is quantified by using a *cross section*, σ, which is an effective size of the target, as seen by the projectile. In some cases the cross section actually is related to the size of the target, in other cases it measures the range of the interaction between the scatterers. In all cases, though, just like throwing a ball at a barn, the bigger the cross section, the greater the likelihood of hitting the target. More detail on the derivation and meaning of cross-section can be found in Melissinos, Sec 5.2.1.

i) In the **photoelectric** effect, the photon transfers all of its energy to an electron and disappears. In our case, the electron gains an energy equal to that of the gamma ray minus the ionization energy of an atom of the scintillator. Since inner shell ionization potentials, typically KeV, are $\sim 10^{-3}$ of the gamma energy, we may consider that the electron energy measures the gamma energy. The cross section for the ejection of one electron from a K shell of an atom with nuclear charge Z is

$$\sigma_{photo} \approx \sigma_T Z^5 \left[\frac{h\nu}{mc^2} \right]^{-\frac{7}{2}}$$

where σ_T is the classic Thompson cross section for an EM wave incident on a free electron,

which is independent of frequency. Therefore, we see that the probability of a photoelectric interaction is steeply falling with gamma energy above 511 KeV, and increases very strongly with the charge of the target nucleus. The above expression is true for energies above the K shell ionization level. For lesser energies, the K shell ionization "turns off", and the drop in the cross section is known as the "K absorption edge".

ii) In **Compton scattering**, the photon is not absorbed, but instead scatters elastically with the electron, like a collision between billiard balls. In fact, the energy and momentum of the photon and electron after the scattering are exactly as if this is a collision between particles, and, as first measured by Compton, this was one of the early convincing evidences that light could behave as "a particle". The detailed calculation shows that if a photon of energy E is deflected from its original direction through an angle θ, the new photon energy E' is given by

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

In our case the scintillator records the energy of the recoiling *electron,* which obviously acquires the energy lost by the photon, $E_e = E'_\gamma - E_\gamma$

Since there is a continuum of scattering angles, there is a continuum of scattered electron energies up to a maximum at $\theta = \pi$, when the photon bounces straight backwards and the electron recoils in the original photon direction.

The cross-section for Compton scattering is given by the celebrated Klein-Nishina formula, which you can find in the references. The cross section peaks in the forward direction and is proportional to the atomic number Z of the target nuclei (which should be obvious since the cross section depends on the density of electrons!). Rewriting the Klein-Nishina result in terms of the photon energy and scattering angle, we can obtain the differential Compton cross-section as a function of the recoil electron energy (see Leo). The result, shown below for some typical gamma energies, shows that the spectrum of scattered electrons is flat at low energies, and then rises to a peak at the maximum energy transfer at $\theta=\pi$. This feature is called the "Compton edge".

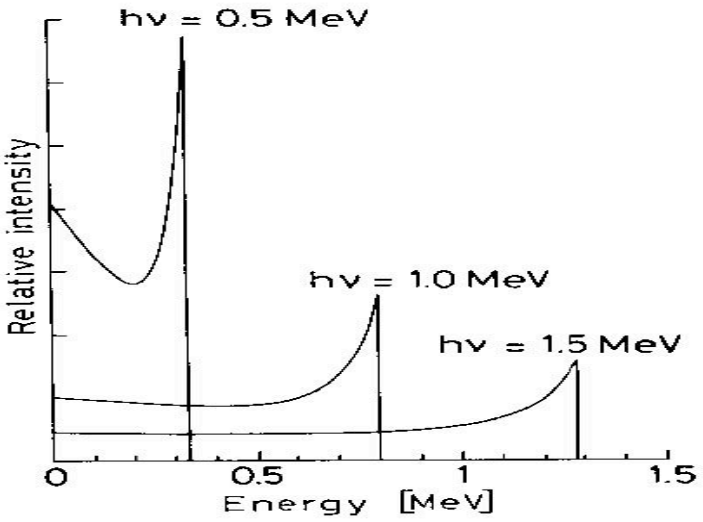

Figure 2 The relative cross section vs. energy for Compton recoil electrons for 3 gamma energies.

iii) In pair production, a photon with energy greater than $2m_ec^2$ converts into an electron-positron pair. This cannot happen in free space, as a single massless photon turning into two massive particles violates conservation of energy and momentum. However, in matter, a nearby nucleus can participate in the recoil, and the pair production process becomes dominant as the photon energy becomes greater than a few MeV.

b) The Interaction of Charged Particles with Matter

Thus every gamma ray ultimately interacts with matter in a way that transfers energy to electrons, and detection of gamma rays then becomes the problem of detecting of MeV electrons. When a high-energy charged particle passes through bulk matter, it loses energy mainly by a succession of inelastic atomic collisions, leaving behind a trail of ionized atoms. The amount of ionized charge can be measured in many ways, and this is the primary means for the detection of particles. There is a rich experimental and theoretical body of work about this phenomenon, and it all follows the original treatment of Niels Bohr**,** who wrote down the rate of energy loss as a function of distance, dE/dx. For further discussion of the *specific energy loss*, dE/dx, see Melissinos, Sec 5.2.2 or Knoll Chap 2, Sec. I, or the Alpha-Ray Spectroscopy write-up from this course.

4. Experimental Detection of Gamma Rays

The detection of gamma rays relies on transfer of their energy to electrons and measurement of the ionization created as the high-energy electrons move through matter. We now review how this can be done with a scintillator, photomultiplier, and associated electronics.

a) Scintillators

One method for the detection of ionizing radiation is based on materials that convert the ionization energy into visible light, or scintillators. These are as common as "old fashion" TV's, where the image is the result of an electron beam striking "phosphors" on the inside face of the CRT. For particle detection, and particularly detection with energy measurement, the scintillators of choice are certain inorganic crystals doped with small amounts of "activators" in a strategy vaguely reminiscent of the use of dopants in semiconductors. In this laboratory we use NaI(Th), sodium-iodide doped with thallium.

In a pure crystal electron-hole pairs are created as the ionization promotes electrons from the valence to the conduction band. Decay of the electrons back to the valence band is inefficient. The activators create sites in the crystal with energy levels in the forbidden region, close to the conduction band. Electron holes in the valence band drift to the activators and ionize them. The free electrons find the ionized sites and drop in, creating excited activator states. If these decay quickly to visible photons ($t < 500$ ns) the result is called *fluorescence*; this is the most useful component of the scintillation. Other metastable states require addition perturbations, say via thermal energy, in order to de-excite, and lead to slower release of light, called *phosphorescence*. In other cases, the excited activator states decay without radiation, and the energy of the ionization is said to be *quenched*. The number of ionization electron-hole pairs that result in a scintillation photon is called the efficiency of the scintillator. To be useful, the frequency of the scintillation light should be in a regime where the scintillator is transparent (!), and photomultipliers are sensitive. A full description of the theory of inorganic scintillators

can be found in Knoll, Chap 8, or Gilmore and Hemingway, Chapter 9.

It is desirable to have a scintillator that produces a large number of photons for a given gamma energy, because the ideal energy resolution is determined by statistical fluctuations in the number of photons produced in the scintillator. NaI(Th) is commonly used because of its high Z which gives a large cross section for photon interactions. It has a large light yield, and it is inexpensive to grow in large ingots, which makes possible large arrays for applications such as medical x-ray detection. It is hydroscopic (being a salt), so the crystals have to be contained in cans, as you can see in the setups.

The benchmark performance specs for NaI(Th) are $5x10^4$ ion pairs per MeV of incident particle, and a scintillation efficiency of approximately 12%, yielding $4x10^4$ photons per MeV incident.

The large light yield leads to good energy resolution, but the time constant for the signal in inorganic scintillators is longish, ~200 ns. In high rate, or fast timing applications, an alternative family of plastic scintillators is used. In these materials, excitation and decay of molecular states happens with atomic time scales, uncomplicated by transport effects, and the scintillation pulse widths are of order nanoseconds, with fractional nanosecond resolution on the rise time. However, the light output is lower so the energy resolution is poor compared to the inorganics.

b) Photomultipliers

The photomultiplier (PMT) is a tube device that functions as a one-channel image intensifier. Light falls on a photocathode, and electrons are emitted via the photoelectric effect. Some simple electrostatic optics accelerates these electrons and directs them to the first in a series of surfaces, called *dynodes*, chosen from materials with *good secondary electron emission*. The dynodes are arranged mechanically so that adjacent dynodes are within millimeters of each other, and a single high voltage power input is directed down a resistor chain that maintains a potential difference of 50 to 100 V between each pair of dynodes (Fig. 3).

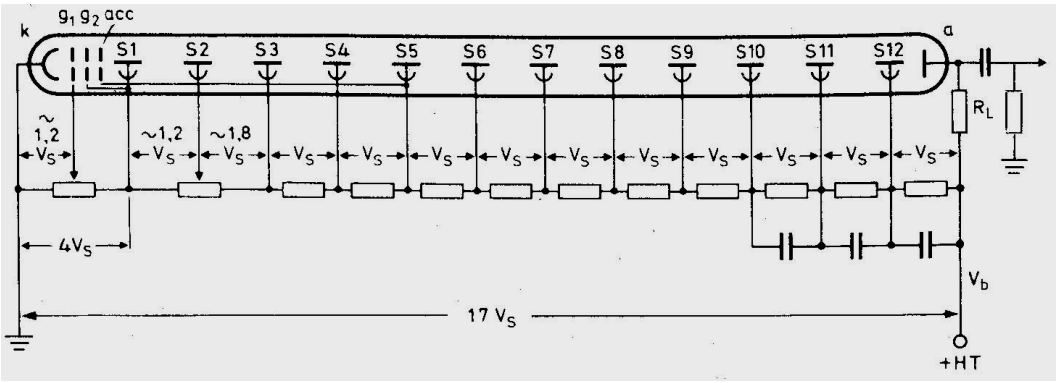

Figure 3 Typical PMT resistor chain in a grounded-cathode system.

In this arrangement, the photoelectrons from the cathode (k) create a shower of electrons off the first dynode(S1), and then a chain-reaction of electron emission flows down the tube, amplifying the size of the electron bunch at each dynode. Finally the large pulse of electrons is collected at the *anode (a)*. Amplifications $\sim 10^6$ are typical, so if 1000 electrons leave the cathode, the final charge pulse is $\sim 10^{-10}$ coulombs), well within the input sensitivity of decent charge integrating

amplifiers.

PMTs come in a variety of sizes and designs for a variety of applications. Recent developments include large light collecting inputs for use in detecting the Cerenkov radiation of solar and astrophysical neutrinos in huge underground water tanks, and also multi-channel tubes for processing position-sensitive signals from bundles of scintillating fibers. The main tube we use in our experiment (in the silver housing) is a standard design from RCA. The supply voltage is arranged as in Fig. 3, the cathode is at ground and the anode is at positive high voltage, which means the signal from the anode must be coupled out through a big blocking capacitor. Other tubes in the lab, including a few demonstration models near the gamma bench, use a grounded anode scheme, so the cathode is at a negative high voltage.

When connecting to HV supplies, check that you know what you need, and what the supply produces and don't screw up! If in doubt, disconnect the high-voltage cable from the phototube base, set the HV to a low voltage, and carefully check the high voltage with a handheld DVM right at the high-voltage connector.

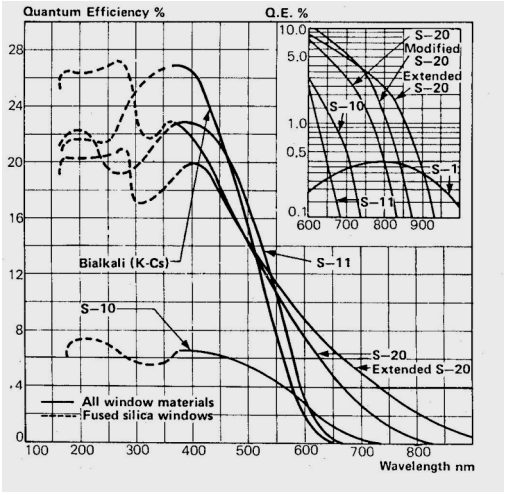

Figure 4 – Quantum efficiency *vs.* wavelength of typical photocathodes

The PMT gain is fixed by the dynode design and the applied high voltage. Small changes in HV lead to significant effects in gain, so good HV regulation is important. With the gain fixed, the tube output depends entirely on the number of electrons at the first step, and one of the key performance issues for PMTs is the number of electrons produced per photon; this ratio is called the *quantum efficiency*. Fig. 4 shows the q.e. for bialkali cathode materials. Notice that the q.e. varies with frequency. The NaI(Th) scintillation peaks at 415 nm, so it's a good match here, but in general there is always the design problem of matching cathodes to scintillators. One expects good cathode materials to have q.e.'s greater than or equal to 20% at the frequencies of interest.

c. Electronics

At this point in the signal chain, for a given gamma interaction we have at the PMT anode a small pulse with a charge proportional to the energy deposited in the scintillator. If there is more than a single monochromatic energy to measure, then we want to convert the charge signal to a voltage signal, digitize the voltage pulse heights, and plot a histogram of the number of occurrences of each pulse height. Knowing the conversion from pulse height into energy will then turn this histogram into a plot of the *energy spectrum* produced by a given source of gamma rays.

You can find more detail about the electronics in Knoll, or particularly in Gilmore and Hemingway, Chapter 4. Briefly, the issues in our setup are as follows. The conversion of the PMT anode charge to a voltage signal is done in a charge-integrating preamplifier contained in the phototube base. This signal is sent to a linear amplifier with so-called RC-CR pulse shaping in which the signal is differentiated to remove baseline shifts and then integrated to remove high frequency noise. Some of the meanings of this will become obvious when you look at the real signals below. The time-constant of the RC-CR circuit is called the "shaping time" and it sets the ability of the apparatus to resolve pulses close together in time. The overall amplification amplifies small energy differences. Other intrinsic contributions to the resolution are due to the scintillator and PMT, as will be discussed below.

Finally, the amplifier output is sent to an analog-to-digital converter (ADC) in the small black box. The ADC output of is sent over the serial bus to the computer, which runs software with the plotting, histogram, and analysis package. It's a pulse-height-analysis: PHA. In the pre-computer days, the histogram function was done in hardware with a special purpose instrument like a big oscilloscope, which could record data in many channels (remarkable at the time), and hence was called a Multi Channel Analyzer. The jargon MCA has stuck, and that's why our device is called "Pocket MCA".

5. Gamma Ray Spectroscopy: Experimental Procedure

You should augment the following practical discussion with insights from the references, particularly Gilmore and Hemingway, which is a great hands-on guidebook.

There are two tubes connected to two power supplies in the "NIM crate". Each tube is optically coupled to a large NaI(Th) crystal in a sealed can. The old tube allows you to look at a raw photomultiplier signal with the scope; the new tube is used for the quantitative measurements. You will use a standard set of radioactive sources, including the gamma emitters ^{60}Co and ^{137}Cs.

a. The Signal Chain

The apparatus should not be a "black box". Examine the signal each step of the way to make sure you understand the signal train.

i) The PMT signal

The old tube has a simple base that makes the anode signal available for examination. Disconnect the HV supply, open the Bud Box, and take a look at the resistor chain that provides the dynode voltage. It's nothing fancy! Close it up and connect the HV to the "TC951" supply. Set the HV to **NEGATIVE 1.5 kV**, pausing for a few seconds at each turn of the knob (the tube is happiest to charge up to the final HV "smoothly", rather than in one big step).

Make sure all sources are far away. Connect the anode to the oscilloscope input. You are looking for a small signal so don't use a 50-ohm termination on the cable. Trigger the scope in "normal" mode on the channel you are using, and set a negative threshold starting at 10 mV or so. The PMT pulses are small negative-going pulses with sharp rise and exponential decay times ~2 μsec. The size of the pulse if determined by the light output of the scintillator, the efficiency of the optical coupling of the scintillator light to the PMT, and the PMT gain. The length of the pulse is almost entirely due to the time constants of the NaI scintillator. Place the Cs source close to the scintilla-

tor. You should see a large increase in the pulse frequency and amplitude. You can use the scope threshold to get an idea of how many pulses are coming in at the larger negative amplitudes. Sketch the pulses and include in your report. This is all we do with the old tube. Turn off the HV when you are done!

ii) The Pre-Amplifier Pulse

The newer looking tube has a nice shiny monolithic construction with a preamplifier integrated into the tube base. Put the sources far away. Use the Ortec 478 HV supply and set the HV to **POSITIVE 1.1 kV,** pausing a few seconds at each turn of the knob, as before. Make sure the multiconductor power cable is hooked up between the preamp and the back of the 485 amplifier. Connect the preamp output to the scope using a 50 ohm termination, and trigger on positive signals. This is an inverting preamp, you should see positive pulses with a long integration time. Why do you think the integration time is so long?

First, connect the pulser to the TEST input of the preamp. Set the pulser to give a negative output. Observe the preamp output on the scope as you vary the pulser amplitude.

Turn off the pulser and place the Cs source right against the scintillator housing. Observe the pulses from the preamp. Adjust scope so that you can see how the pulses pile on top of each other as new signals arrive before the old ones have decayed. This is called *pile-up*. If we blindly digitized the peak pulse heights, we would incur a large uncontrollably random offset error due to the DC *baseline shift*. That's why the next stage, the amplifier, starts by differentiating the signal, effectively applying a high pass filter which cuts out the DC baseline offset, and registers the peaks. Leave the source in place as you now continue to move down the signal chain and set things up for viewing the spectrum.

iii) The Pulse Shaping Amplifier

Connect the pre-amp to the ORTEC 485 amplifier and connect the output of the amplifier to the scope using a 50 ohm termination on the cable. Take care that you have the amplifier set up properly to accept positive signals, and select unipolar output. Trigger the scope on positive signals, and adjust the amplifier gain so that the signal range is between 0 and 10V. The signal should be round at the top. If it's flat, you are amplifying beyond the maximum output of the amplifier; this is called *clipping*. Due to the pulse shaping in the amplifier, the width of the pulse is now divorced from the scintillator time constants and is a function of the shaping time of the amplifier. The shorter the shaping, the better the time resolution, but the worse the energy resolution.

iv) The ADC and Pulse-Height-Analyzer

Plug the amplifier output into the cable going to the Pocket MCA. Use a "tee" on the amplifier output so you can observe the signal to the MCA on the scope. The MCA is on if the red indicator light is lit. Log onto the PC. Find the folder "MCA8000 WIN32" and run the application PMCA. You should get a standard Windows application screen with a large space for the histogram and, on the right, a column for display of counting statistics. When you start up, you will be asked whether to open an old data file or connect to an MCA. Chose connect. You may get a stale spectrum from the last measurement. On the banner, go to MCA, then "delete data", which clears the spectrum, and "reset time", which clears the counting statistics. Then do "start acquisi-

tion", and you should see the Cs-137 spectrum begin to build up (details below). Once you have understood how to basically make this work, you should take some time to understand the further use of the program to analyze the data. Learn how to define a "Region of Interest" (ROI), and get the centroid, width, and area of a peak. Learn how to input a calibration, and change the scale from channels to MeV. Learn how to modify your least-count resolution by changing the number of channels. Learn how to look up the energies of gamma peaks in online libraries, which will be very useful for understanding all the contributions to your spectra.

b. The Cs-137 Spectrum

Cs-137 is a standard calibration source with a single gamma line. As shown in Fig. 5 below, the nuclear decays starts with β emission, 8% of the time directly to the ground state, and the rest of the time to a short-lived intermediate state that decays by emission of a 0.662 MeV γ. The β's are stopped in the casing of the scintillator, but the γ's are penetrating. A typical Cs-137 spectrum is shown in Fig. 6 below.

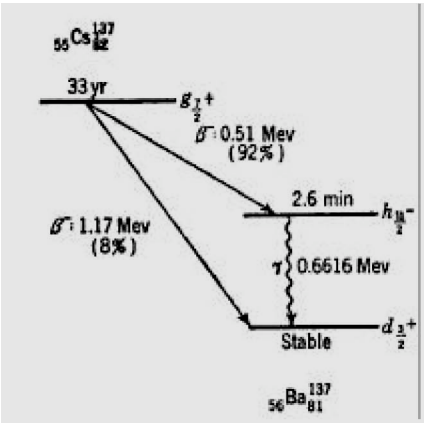

Figure 5 Cs-137 decay scheme

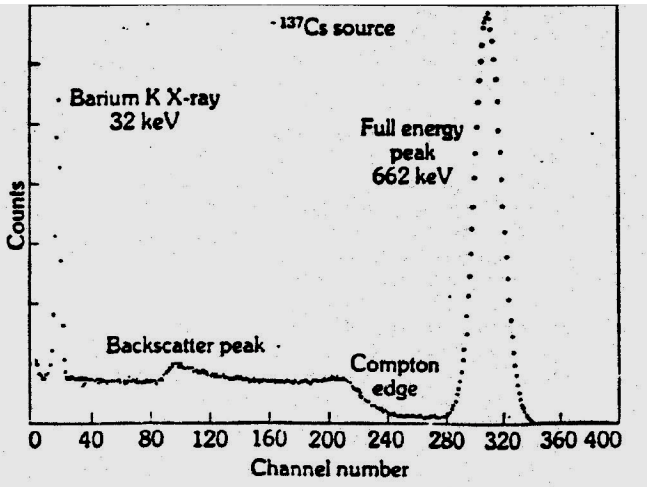

Figure 6 The Cs-137 gamma spectrum

It is best to use more channels than shown in Fig. 6, at least 1024. This is set by the "ADC Gain" in the MCA setup. You should adjust your amplifier gain so that the spectrum fills out the *dynamic range*. You should be able to see the barium X-ray at the low end. (What is the source of this?) Use the known barium energy and the full energy peak to calibrate the scale into MeV/count, including an estimate of the uncertainty. Examine the other structures, such as the backscatter peak and the Compton edge. Do these occur at the energies you would expect? Add some lead nearby to increase the backscatter rate. Besides the increase in the size of the backscatter peak, can you also identify a lead X-ray? Use the peak-finding software to estimate the widths of the peak.

General Notes:

Usually it is best to put the sources right on the center of the scintillator to maximize rates and to get the best resolution.

It isn't always obvious which is the "front side" of the sources. To check which side is the front, you can measure the rate with either side facing the scintillator. The side that gives the

higher rate is the front side.

Some sources are "old" (in half lives) and their activity is low. You may need to take rather long runs with the weaker sources to get good "statistics".

For all sources, record the date and original activity. Then calculate the expected activities "today" and compare it with the measured activities (counts/sec).

Print out spectra for all the sources studied, and label all notable features.

c. The Co-60 Spectrum

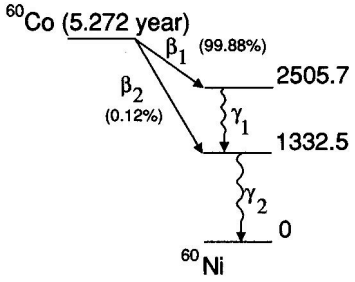

Figure 7 – Co-60 decay scheme

Co-60 gives a nice 2-γ cascade after beta decay. Record the spectrum. See if you can propagate your Cs137 calibration through, and measure the Co-60 gamma energies. Identify all structures and label them on your printout. Is there one Compton edge or two? Use the peak-finding software to estimate the widths of the peaks. Compare the widths of the Co-60 gamma peaks to each other, and to the width of the Cs-137 peak. Read up about the contributions to resolution. Understand how the width is related to number of counts, and therefore should scale approximately as the square root of …what? Can you confirm the expected dependence?

d. Na-22 Spectrum

Sodium–22 is similar to Cesium 137; there is a beta transition followed by a single electromagnetic transition which emits a 1.277 MeV gamma ray. However, unlike cesium, the beta ray is this case is a *positron*, the antiparticle of the electron. This positron will typically annihilate with an electron in the source or the cladding, through the "two-photon annihilation" process $e^+ + e^- \rightarrow \gamma + \gamma$ yielding two back-to-back gamma rays with $E_\gamma = m_e c^2$ = 511 KeV. The Na-22 spectrum should show two gamma lines, one from the nuclear decay, and one from positron annihilation. Note that in the annihilation line, besides measuring the rest mass of the electron, you are seeing with your own eyes (and the apparatus of gamma ray spectroscopy) the conversion of matter into energy, and the laboratory manifestation of the most famous formula in physics,

$$E = mc^2$$

d. Unknown

Ask the instructor for an unknown and identify it. [Hint: It is a mixture with 2 or more components.]

5. Questions

(1) What is the source of the barium X-ray on the low end of the Cs-137 spectrum?

(2) Label all the prominent features on your spectra. Do the Compton edges and backscatter peaks occur at the energies you would expect?

(3) Ideally the fractional width of the peaks in the gamma spectra would be determined by the statistical fluctuations in the number of photons the gamma produces in the scintillator, *i.e.*, $\Delta E / E = \Delta N / N = 1 / \sqrt{N} \propto 1 / \sqrt{E}$ where N is the number of visible photons produced in the scintillator and detected by the photomultiplier. (See Sect. 4 a,b.) Estimate N for the Cs-137 peak in NaI scintillator, and compare your measured width with that expected.

(4) Make a table of the energies of all the peaks you've observed, and compare the energy determined from the Cs-137 calibration with the expected energy. Also list the width of each peak. Plot the fractional width $\Delta E/E$ *vs.* $1/\sqrt{E}$ to see if the expected linear $1/\sqrt{E}$ behavior is observed. (See Question 3.)

(5) What is the unknown source? Explain how you identified it.

(6) For radionuclides with more than one gamma peak, the relative strength of the peaks can change significantly with time after the source is prepared. Explain.

(7) Explain briefly what the "pocket MCA" does.

6. References

Gilmore and Hemingway, Practical Gamma-Ray Spectrometry
Knoll, Radiation Detection and Measurement
Leo, Techniques for Nuclear and Particle Detection
Melissinos, Experiments in Modern Physics