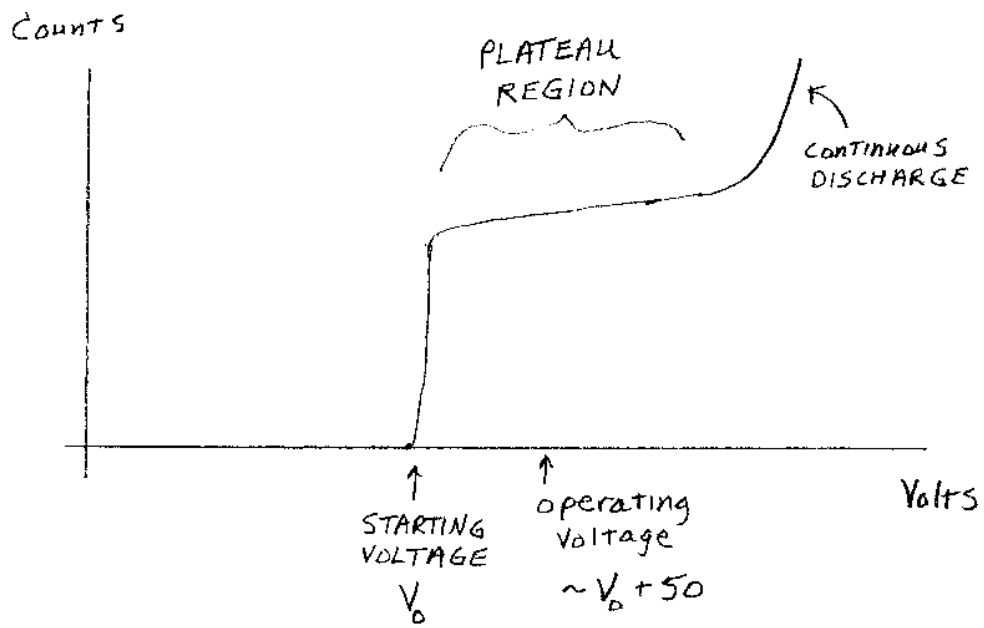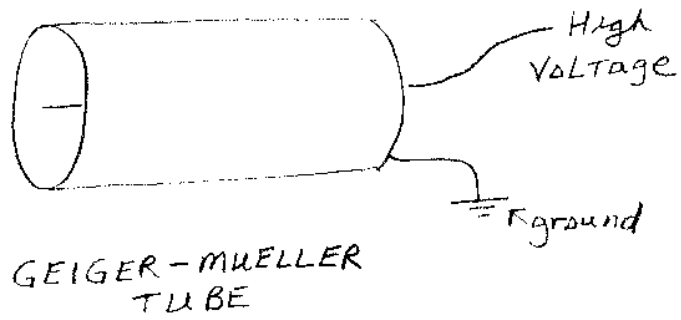# Introduction to Geiger Counters

A Geiger counter (Geiger-Muller tube) is a device used for the detection and measurement of all types of radiation: alpha, beta and gamma radiation. Basically it consists of a pair of electrodes surrounded by a gas. The electrodes have a high voltage across them. The gas used is usually Helium or Argon. When radiation enters the tube it can ionize the gas. The ions (and electrons) are attracted to the electrodes and an electric current is produced. A scaler counts the current pulses, and one obtains a "count" whenever radiation ionizes the gas.

The apparatus consists of two parts, the tube and the (counter + power supply). The Geiger-Mueller tube is usually cylindrical, with a wire down the center. The (counter + power supply) have voltage controls and timer options. A high voltage is established across the cylinder and the wire as shown on the page of figures.

When ionizing radiation such as an alpha, beta or gamma particle enters the tube, it can ionize some of the gas molecules in the tube. From these ionized atoms, an electron is knocked out of the atom, and the remaining atom is positively charged. The high voltage in the tube produces an electric field inside the tube. The electrons that were knocked out of the atom are attracted to the positive electrode, and the positively charged ions are attracted to the negative electrode. This produces a pulse of current in the wires connecting the electrodes, and this pulse is counted. After the pulse is counted, the charged ions become neutralized, and the Geiger counter is ready to record another pulse. In order for the Geiger counter tube to restore itself quickly to its original state after radiation has entered, a gas is added to the tube.

For proper use of the Geiger counter, one must have the appropriate voltage across the electrodes. If the voltage is too low, the electric field in the tube is too weak to cause a current pulse. If the voltage is too high, the tube will undergo continuous discharge, and the tube can be damaged. Usually the manufacture recommends the correct voltage to use for the tube. Larger tubes require larger voltages to produce the necessary electric fields inside the tube. In class we will do an experiment to determine the proper operating voltage. First we will place a radioactive isotope in from of the Geiger-Mueller tube. Then, we will slowly vary the voltage across the tube and measure the counting rate. On the figures page is a graph of what we might expect to see when the voltage is increased across the tube.

For low voltages, no counts are recorded. This is because the electric field is too weak for even one pulse to be recorded. As the voltage is increased, eventually one obtains a counting rate. The voltage at which the G-M tube just begins to count is called the starting potential. The counting rate quickly rises as the voltage is increased. For our equipment, the rise is so fast, that the graph looks like a "step"

High
Voltage

ground

GEIGER - MUELLER
TUBE

Counts

PLATEAU
REGION

continuous
DISCHARGE

Volts

STARTING
VOLTAGE
V_0

operating
Voltage
$\sim V_0 + 50$

potential. After the quick rise, the counting rate levels off. This range of voltages is termed the "plateau" region. Eventually, the voltage becomes too high and we have continuous discharge. The threshold voltage is the voltage where the plateau region begins. Proper operation is when the voltage is in the plateau region of the curve. For best operation, the voltage should be selected fairly close to the threshold voltage, and within the first 1/4 of the way into the plateau region. A rule we follow with the G-M tubes in our lab is the following: for the larger tubes to set the operating voltage about 75 Volts above the starting potential; for the smaller tubes to set the operating voltage about 50 volts above the starting potential.

In the plateau region the graph of counting rate vs. voltage is in general not completely flat. The plateau is not a perfect plateau. In fact, the slope of the curve in the plateau region is a measure of the quality of the G-M tube. For a good G-M tube, the plateau region should rise at a rate less than 10 percent per 100 volts. That is, for a change of 100 volts, (Δcounting rate)/(average counting rate) should be less than 0.1. An excellent tube could have the plateau slope as low as 3 percent per 100 volts.

Efficiency of the Geiger-counter:

The efficiency of a detector is given by the ratio of the (number of particles of radiation detected)/(number of particles of radiation emitted):

$$\varepsilon \equiv \frac{number\ of\ particles\ of\ radiation\ detected}{number\ of\ particles\ of\ radiation\ emitted} \tag{1}$$

This definition for the efficiency of a detector is also used for our other detectors. In class we will measure the efficiency of our Geiger counter system and find that it is quite small. The reason that the efficiency is small for a G-M tube is that a gas is used to absorb the energy. A gas is not very dense, so most of the radiation passes right through the tube. Unless alpha particles are very energetic, they will be absorbed in the cylinder that encloses the gas and never even make it into the G-M tube. If beta particles enter the tube they have the best chance to cause ionization. Gamma particles themselves have a very small chance of ionizing the gas in the tube. Gamma particles are detected when they scatter an electron in the metal cylinder around the gas into the tube. So although the Geiger counter can detect all three types of radiation, it is most efficient for beta particles and not very efficient for gamma particles. Our scintillation detectors will prove to be much more efficient for detecting specific radiation.

Some of the advantages of using a Geiger Counter are:

a)They are relatively inexpensive
b)They are durable and easily portable
c)They can detect all types of radiation

Some of the disadvantages of using a Geiger Counter are:

a)They cannot differentiate which type of radiation is being detected.
b)They cannot be used to determine the exact energy of the detected radiation
c)They have a very low efficiency

Resolving time (Dead time)

After a count has been recorded, it takes the G-M tube a certain amount of time to reset itself to be ready to record the next count. The resolving time or "dead time", T, of a detector is the time it takes for the detector to "reset" itself. Since the detector is "not operating" while it is being reset, the measured activity is not the true activity of the sample. If the counting rate is high, then the effect of dead time is very important. We will first discuss how to correct for dead time, and then discuss how one can measure what it is.

Correcting for the Resolving time:
We define the following variables:
T = the resolving time or dead time of the detector
t_r = the real time that the detector is operating. This is the actual time that the detector is on. It is our counting time. tr does not depend on the dead time of the detector, but on how long we actually record counts.
t_l = the live time that the detector is operating. This is the time that the detector is able to record counts. t_l depends on the dead time of the detector.
C = the total number of counts that we record.
n = the measured counting rate, $n = C/t_r$
N = the true counting rate, $N = C/t_l$

Note that the ratio n/N is equal to:

$$\frac{n}{N} = \frac{C/t_r}{C/t_i} = \frac{t_l}{t_r} \tag{2}$$

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This means that the fraction of the counts that we record is the ratio of the "live time" to the "real time". This ratio is the fraction of the time that the detector is able to record counts. The key relationship we need is between the real time, live time, and dead time. To a good approximation, the live time is equal to the real time minus C times the dead time T:

$$t_l = t_r - CT \tag{3}$$

This is true since CT is the total time that the detector is unable to record counts during the counting time t_r. We can solve for N in terms of n and T by combining the two equations above. First divide the second equation by t_r:

$$\frac{t_l}{t_r} = 1 - \frac{CT}{t_r} = 1 - nT \tag{4}$$

From the first equation, we see that the left side is equal to n/N:

$$\frac{n}{N} = 1 - nT \tag{5}$$

Solving for N, we obtain the equation:

$$N = \frac{n}{1 - nT} \tag{6}$$

This is the equation we need to determine the true counting rate from the measured one. Notice that N is always larger than n. Also note that the product nT is the key parameter in determining by how much the true counting rate increases from the measured counting rate. For small values of nT, the product nT (unitless) is the fractional increase that N is of n. For values of $nT < 0.01$ dead time is not important, and are less than a 1% effect. Dead time changes the measured value for the counting rate by 5% when $nT = 0.05$. The product nT is small when either the counting rate n is small, or the dead time T is small.

Measuring the Resolving Time

We can get an estimate of the resolving time of our detector by performing the following measurement. First we determine the counting rate with one source alone, call this counting rate n_1. Then we add a second source next to the first one and determine the counting rate with both sources together. Call this counting rate n_{12}. Finally, we take away source 1 and measure the counting rate with source 2 alone. We call this counting rate n_2.

You might think that the measured counting times n_{12} should equal n_1 plus n_2. If there were no dead time this would be true. However, with dead time, n_{12} is less than the sum of $n_1 + n_2$. This is because with both sources present the detector is "dead" more often than when the sources are being counted alone. The true counting times do add up:

$$N_{12} = N_1 + N_2 \tag{7}$$

since these are the counting rates corrected for dead time. Substituting the expressions for the measured counting times into the above equation gives:

$$\frac{n_{12}}{1 - n_{12}T} = \frac{n_1}{1 - n_1T} + \frac{n_2}{1 - n_2T} \tag{8}$$

An approximate solution to these equations is given by

$$T \approx \frac{n_1 + n_2 - n_{12}}{2n_1 n_2} \tag{9}$$

In our laboratory we will measure n_1, n_2, and n_{12} and used the formula above to get an approximate value for the dead time of the Geiger counter. It is difficult to get a precise value for T. one needs to be very careful that the positions of source 1 and 2 with respect to the detector alone is the same as the positions of these sources when they are measured together. Also, since n_{12} is not much smaller than $n_1 + n_2$, one needs to measure all three quantities very accurately. For this one needs many counts, since the relative statistical error equals . For sufficient accuracy one needs to use an active source for a long time. The values that we usually obtain in our experiments range from 100 to 500μsec. The dead time of the G-M tube is also available from the manufacturer, and are between 100 and 300μsec. As the G-M tube is used, the dead time can increase.

Gamma Scintillation Detectors

Gamma particles are best detected with crystal scintillation detectors. The two main type of crystals used are sodium iodide (NaI) and Germanium (Ge). A nice thing about gamma detectors is that they can measure the energy of the gamma particle. To understand how the gamma detectors work, we need to understand how the gamma particle interacts with matter. Although the gamma particle is produced in the nucleus, when it travels through matter, it mainly interacts with electrons

orbiting the nucleus. Two different types of interaction with the electrons can occur: photo-absorption and Compton scattering. We begin by discussing these two types of gamma interactions, then we discuss the operation of the gamma detector. Photo-absorption:

Photo-absorption

In photo-absorption, the gamma is absorbed by the electron. The interaction with an electron at rest is shown graphically on the figures page. The gamma particle (photon) enters from the left with a distinct momentum and energy, and the electron is at rest. After the interaction, and gamma particle has been "absorbed" by the electron which travels off to the right. Since energy and momentum are conserved in the interaction the electron gains the energy and momentum of the gamma photon.
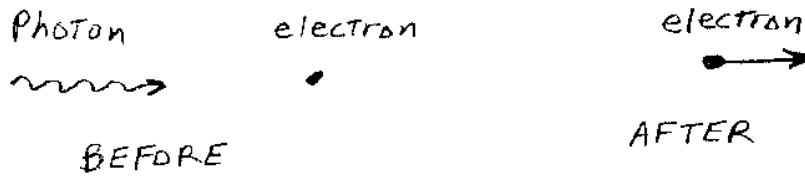
Compton Scattering

In Compton scattering, the gamma scatters off the electron. The interaction with an electron at rest is shown graphically on the figures page. The gamma particle (photon) enters from the left and the electron is at rest. In this case, the gamma is not absorbed, but scatters off the electron. The electron has gained some energy, and the gamma photon has lost some. The scattered gamma photon can interact with other electrons in the material.

When a photon approaches an electron, one cannot predict exactly will happen. There is a certain probability that photo-absorption will happen, a probability that Compton scattering will occur, and a probability that no interaction will take place at all. The angle that the photon scatters is also probabilistic. Using the principles of quantum mechanics, one can calculate the probabilities for each of these possibilities. As with radioactive decay, probability enters in the physics of the interaction. The probability of each process depends on the energy of the gamma. For photo-absorption the probability decreases rapidly with the energy of the gamma. For higher energies, the probability for Compton scattering is much larger than for photo-absorption.
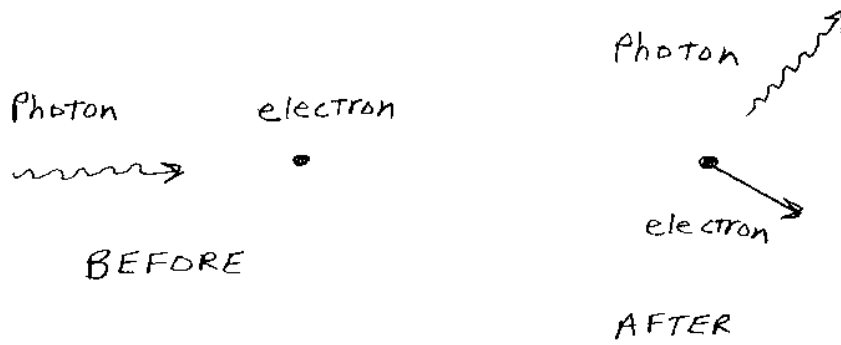
<div align="center">

The NaI Multi-Channel Analyzer (MCA)

</div>

The MCA system is used to detect only gamma and X-ray radiation. However, it detects the radiation well, and the MCA can also determine the energy of gamma and X-ray particles. The MCA system consists of 3 main parts: the detector itself, the amplifier/power-supply, and a computer. The detector has two parts: a scintillation crystal (sodium iodide) and a photo-multiplier tube. The computer stores and

PHOTO-ABSORPTION

Photon   electron   electron

~~~~→   •   •→

BEFORE   AFTER

COMPTON SCATTERING

                                        Photon   ⤴

Photon   electron

~~~~→   •   •
                                            ↘
                                        electron

BEFORE   AFTER

8

displays the data. For proper operation, you will need to set the high voltage of the power supply and the amplifier gain correctly.
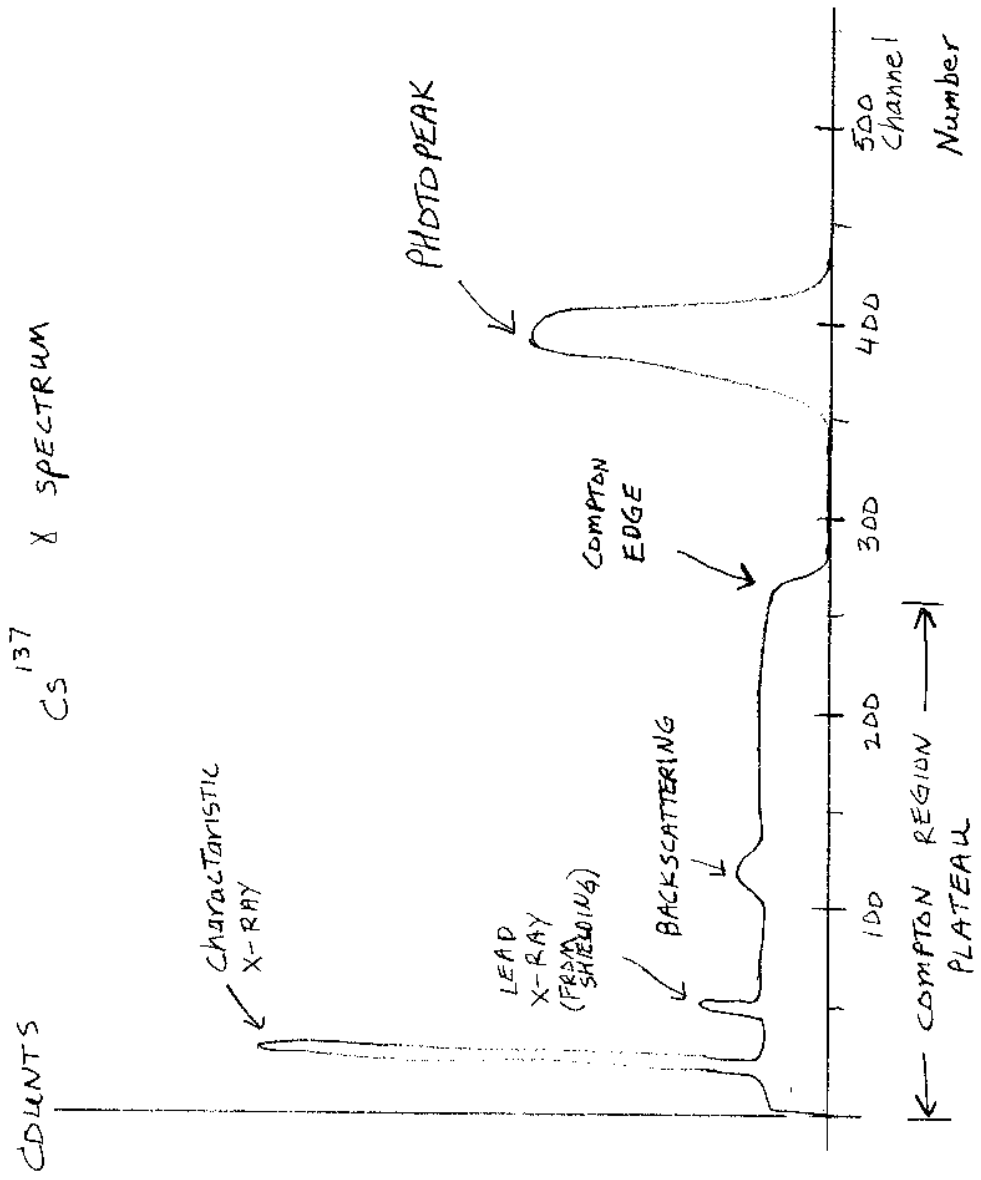
The computer displays the data graphically. The horizontal axis corresponds to the channel number. On the vertical axis, the number of counts for the channel is plotted. For example, in the figure on the figures page, there are around 1200 counts in channel number 390. Channel 200 has around 250 counts, and for channels greater than 420 there are very few counts. We have different types of MCA systems in our lab. Some will have a total of 1024 channels, some 2048 channels, and one a total of 8096 channels. In the figure below, there are a total of 1024 channels.

A nice property of the detector is that the channel number is to a very good approximation proportional to the energy of the gamma particle. That is, counts that register in channel 400 have twice the energy as those that register in channel 200. The scaling of the horizontal axis, i.e. the energy per channel number, depends on the amplifier gain and the voltage on the photo-multiplier tube. We will adjust the amplifier gain to best suit the needs of our experiment. The voltage for the photo-multiplier tube is determined by the manufacture of the detector.

To interpret our data properly and identify the desired photopeaks, we need to understand all the features of the gamma spectrum. We will discuss these features via a standard example: the spectrum of Cs^{137}, which is shown on the page with figures. When a gamma particle interacts with the detector a number of different outcomes can result. The gamma can be photo-absorbed by an electron in the NaI crystal, the gamma can Compton scatter off an electron in the crystal, or the gamma can scatter off an electron outside the crystal and then enter the NaI crystal. Each of these possibilities gives a particular feature to the spectrum. We take each case one at a time:

1.Photo-absorption in the NaI crystal

This is the ideal case, the gamma is photo-absorbed by an electron in the NaI crystal. The electron in the crystal then acquires all the energy of the gamma particle. This energetic electron "bounces" around in the crystal transferring its energy to other electrons. Due to the properties of the crystal, the energy goes into producing electron-hole pairs. When the electrons fall back into the "holes" in the crystal, a low energy photon (visible light) is emitted. The essential role of the crystal is to convert one high energy photon (gamma particle) into a large number of low energy photons (visible light). The visible light is then detected and measured. One can think of the crystal as "making change" in a bank. Suppose you had a $ 1000 bill, and wanted to buy a candy bar. The bill is too big for the store to accept. So you go to the bank and get change: 1000 one dollar bills. Now the store can accept your money. The

Cs^{137} γ SPECTRUM

COUNTS

Characteristic X-RAY

LEAD X-RAY (FROM SHIELDING)

BACKSCATTERING

COMPTON EDGE

PHOTO PEAK

COMPTON REGION PLATEAU

100   200   300   400   500   Channel Number

crystal changes one high energy photon into many low energy photons. We can count the number of low energy photons with a photomultiplier tube. The nice thing about the crystal is that the number of low energy photons (of visible light) is proportional to the energy of the gamma particle.

The low energy (visible) photons enter the photo-multiplier tube at one end. The net effect is that a current pulse is produced. The nice thing about the photomultiplier tube is that the current pulse it produces is proportional to the number of visible photons that enter the tube. The photomultiplier tube requires a high voltage. The value of the voltage is given by the manufacture, and ranges from 550 to 1000 volts for our photomultiplier tubes. Before you turn on the MCA system, be sure that the high voltage is set properly. Once set, we will not change it during the experiment(s).

The current pulse from the photomultiplier tube enters an amplifier, which amplifies the current. Finally, this amplified current is input into a "card" in the computer. The "card" contains a multi-channel analyzer (MCA). The multi-channel analyzer "bins" the pulse according to its strength. Pulses with larger current get "binned" in a larger channel number. Changing the amplifier gain changes the scale on the horizontal axis.

Although there are many steps to the detector system, the end result is that the channel number that gets "binned" is proportional to the energy deposited in the crystal. The binned channel is proportional to the current pulse which is proportional to the number of visible photons which is proportional to the energy of the gamma. This approximate proportionality is what makes the crystal an accurate measuring device.

We have described the ideal case: the gamma is photo-absorbed by an electron in the crystal. This senario would result in a sharp spike at a channel number corresponding to the energy of the gamma. However, thermal effects in the NaI crystal broaden the sharp spike into a "bell-shaped" Gaussian peak. For the Cs^{137} example in the figure above, the peak caused by photo-absorption is at channel number 390. We refer to this peak as the photopeak. The channel number of the photopeak is proportional to the energy of the gamma particle. If we measure a different isotope which emits a gamma at a different energy, the photopeak will be shifted. The position of the photopeak will also change if we change the amplifier gain. For experiments where calibration is important, we keep the amplifier gain set to a particular value which is useful for all the experiments.

2. The gamma particle Compton scatters off an electron in the crystal

A common situation is when the gamma particle scatters off an electron in the crystal. After scattering, the gamma can leave the crystal. In this case, only part of

the gamma's energy is deposited in the NaI crystal. There will be a count recorded at a channel number less than the channel number of the photopeak. The actual amount of energy that the electron in the crystal obtains depends on the angle of scattering. This means that Compton scattering results in counts in a range of channel numbers. In our Cs137 example in the figure, one can see a flat plateau between 0 and 270. The plateau is due to Compton scattering and is called the Compton plateau or Compton region.

If the gamma particle just glances off an electron in the crystal, then the electron will obtain very little energy. The count will be recorded in a low channel number. The electron will receive the most energy when the gamma scatters backwards. In this case, a count is recorded in a higher channel number, channel number 270 in our example. This particular feature, the end of the plateau is referred to as the Compton edge. Using kinematics one can calculate this energy to be:

$$E_{Compton\ Edge} = \frac{2E_\gamma}{E_\gamma + m_e c^2} \tag{10}$$

where $m_e c^2$, the mass energy of the electron, is 511 KeV. For scattering angles between 0 and 180 degrees, counts are recorded between 0 and the Compton edge. One nice thing about Compton scattering is that the Compton edge is at an energy well enough below the photopeak energy so as to leave the photopeak easy to observe and measure.

3. The gamma scatters off an electron outside the crystal (backscattering)

The gamma particle can Compton scatter off an electron outside the crystal, and then enter the crystal. This feature in the spectrum is referred to as "backscattering", and produces a bump in the spectrum. In our Cs^{137} example, the backscattering "bump" is at channel number 120. The backscattering bump is fairly easy to identify for the following reason. Most of the gamma's that backscatter into the crystal do so at large scattering angles. This means that the energy of the backscatter bump plus the energy of the Compton edge equals the energy of the photopeak:

$$E_{photopeak} = E_{backscattering\ bump} + E_{Compton\ edge}$$

In our example, we have $390 = 120 + 270$.

4. Characteristic X-rays

Characteristic X-rays can be produced by the radioactive isotope. As discussed in Chapter 2, characteristic X-rays can be produced is the isotope undergoes isomeric transition or electron capture. If the nucleus decays via electron capture or electron

conversion, a hole in an inner shell is produced. When an orbiting electron fills the hole, an x-ray is emitted. In the spectra, X-rays may be seen at low channel number. In our Cs^{137} example, the large peak at channel number 30 is a characteristic X-ray from Barium. The energy of the X-ray will depend on the isotope present, not every spectrum will have these characteristic X-rays present.

There is another bump in the spectra of Cs^{137} at around channel number 50. This peak is produced by characteristic X-rays from lead. The lead is in the shielding around the detector. When a gamma from the source knocks out an inner electron in the lead shielding, X-rays can be emitted when inner hole is filled. This peak will always be present when lead shielding is used. If we took the spectrum without the lead shielding, the peak would disappear.

We have described the main features of the gamma spectrum for a single photopeak. If an isotope emits more than one gamma, then each gamma will produce a photopeak, a Compton region, backscattering bump, and maybe characteristic X-rays. Although these patterns will overlap with multiple gamma production, the photopeaks are usually clear enough to distinguish.

High Resolution Germanium Detectors

We also have a high resolution Ge detector in our laboratory. The photopeaks for these detectors are very clear and narrow. One does not need to worry about the Compton region or backscattering peaks.

Liquid Scintillation Detector

The liquid scintillation detector is the detector often used by biologists. The detector is a liquid, or "fluor", and the sample is placed in the liquid. The fluor contains a substance that fluoresces when a charged particle is slowed down (or absorbed) by it. The fluorescence that it emitted is in the visible light region. Photo-multiplier tubes are placed around the liquid to detect this emitted light. The detector is designed to detect mainly (or only) beta particles.

Basically, the detector works as follows: When a beta particle is emitted, it enters the fluid and excites the "fluor" as it slows down. The fluor then de-excites and emits photons. The photons are detected by a photo-multiplier tube, which sends a current pulse to an amplifier. The amplified current pulse is then binned via a multi-channel analyzer similar to the gamma spectrometer. The continuous energy spectrum is recorded by the detector.

Most liquid scintillation detectors do not print out or display the whole spectrum as is done with the gamma detectors in the lab. For liquid scintillation detectors, the

user usually sets a counting window: the initial and ending channels. The detector prints out and/or displays the sum of all the counts between the initial and final channels. These channels are often refered to as the lower and upper channels. In order to set an appropriate window, the user must know the energy range of the beta that is emitted and the energy/(channel number) for the detector.

The energy of the emitted electron in beta decay is not mono-energetic, the electron shares its energy with the neutrino. Hence, the beta spectrum does not have a distinct peak, but rather a continuous spectrum. Thus, the liquid scintillation detector is not useful in identifing the isotopes in a sample, but rather in counting the amount of a single known isotope in the sample. The detector is mainly used in radioisotope tracing experiments. The liquid scintillation detector has nice features for biologists:

1. Biological samples are often in liquid form, or can be placed in liquids.

2. Hydrogen and carbon are common elements in biological samples, and can be tagged using ^3H (tritium) and ^{14}C. These two isotopes are beta emitters.

3. The liquid scintillation detector is very efficient since the sample is placed in the detecting material.

In the next chapter we will discuss the calibration and methods of analysis of the liquid scintillation detector.