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 in the next figure.

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. Photo-absorption cannot occur with a "free" (or unbound) electron. In order to conserve relativistic energy and momentum, there must be a third object involved in the process. Thus, photo-absorption in the crystal occurs with a "bound" electron, and the nucleus that the electron is bound to also gains a small amount of momentum.

Compton Scattering

In Compton scattering, the gamma scatters off the electron. The interaction with an electron at rest is shown graphically in the figure. 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

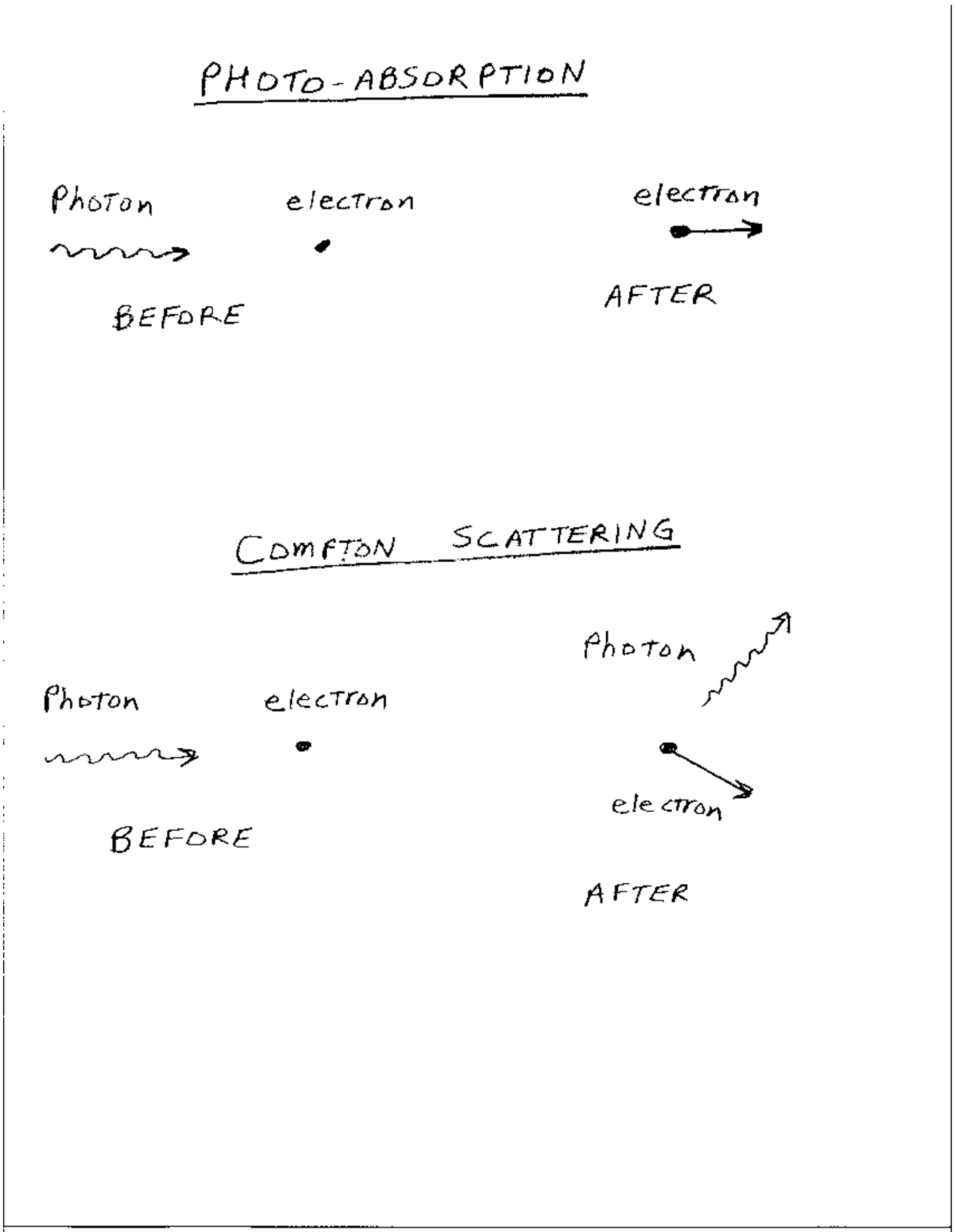


PHOTO-ABSORPTION
Photon
electron
electron
BEFORE
AFTER
COMPTON SCATTERING
Photon
Photon
electron
electron
BEFORE
AFTER

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.

The NaI Multi-Channel Analyzer (MCA)

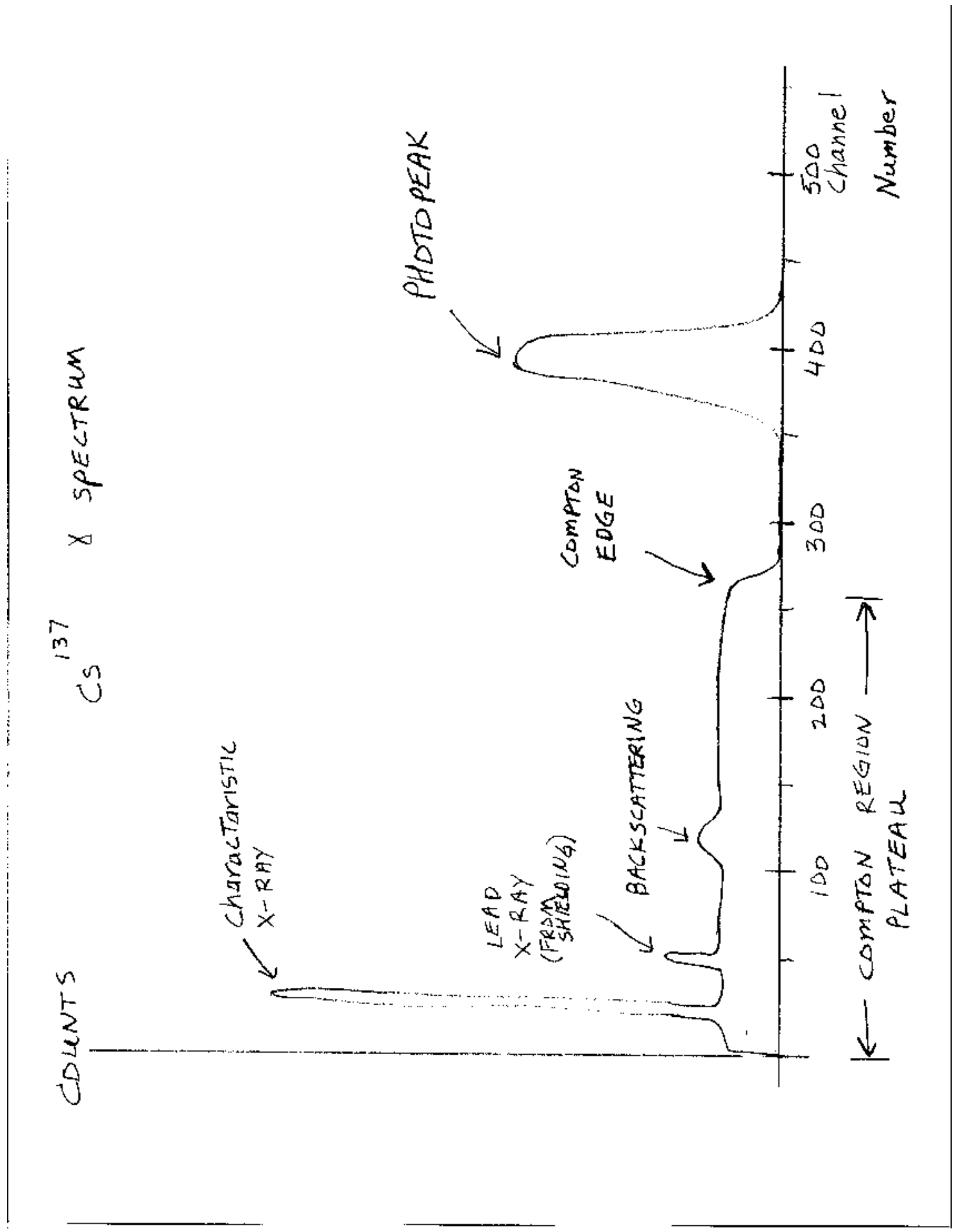
The MCA system is used to detect only gamma and X-ray radiation. However, it detects the radiation well, and the MCA can also determine the energy of gamma and X-ray particles. The MCA system consists of 3 main parts: the detector itself, the amplifier/power-supply, and a computer. The detector has two parts: a scintillation crystal (sodium iodide) and a photo-multiplier tube. The computer stores and 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 is the channel number, and the vertical axis is the counts for the various channels. For example, in the figure below, 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 Cs137 as shown in the figure.

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:


COUNTS
Cs 137 γ SPECTRUM
Characteristic X-RAY
LEAD X-RAY (FROM SHIELDING)
BACKSCATTERING
COMPTON EDGE
PHOTOPEAK
100
200
300
400
500
Channel Number
COMPTON REGION PLATEAU

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 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. <u>The gamma particle Compton scatters off an electron in the crystal</u>

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:

$$E_{Compton\ Edge} = \frac{2E_\gamma}{E_\gamma + m_e c^2} \tag{1}$$

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. <u>The gamma scatters off an electron outside the crystal (backscattering)</u>

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.