DRAFT: Measuring the Compton Effect using Gamma Rays

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last edit: 22 Nov 2004

Abstract

Arthur Compton showed in 1923 that light carries energy and momentum and is subject to the same laws of conservation of momentum and energy as massive particles are. These results helped convince people that light has particle-like properties as well as the heretofore familiar wave-like ones. You will perform an experiment similar to the one Compton did except you will use gamma rays rather than X-rays and scatter the photons off aluminum instead of carbon. You will measure the energy of the scattered photons as a function of their scattering angle and verify that the scattered photon's energy agrees with what it should be if the photon behaves as a discrete particle of definite momentum and energy, and elastically scatters off an electron of a target atom.

Contents

1 Preface to Users

I wrote this lab manual at the request of Dr. Thomas Coan. Under his supervision, I designed, built, and tested this experiment. I am writing this because I want you to enjoy and get as much out of this experiment as I did creating it. I have also included some background information on the Compton effect, the inner workings of the equipment with which you will be working, as well as radiation safety. If you have questions about how the lab is supposed to function, I am available through email contact at casey_deen@excite.com (no, I won't do your homework for you). Note to students: This lab has been vetted and edited by me (TEC) to ensure physics accuracy.

2 Useful Numbers

The following constants and numbers are useful in the execution and write-up of this lab.

- $\hbar c = 197\,\text{MeV-fm}$
- $1\text{ fm} = 10^{-15}\,\text{m}$ (a "fermi")
- $1\,\text{Å} = 1 \times 10^{-10}\,\text{m}$ (an "angstrom")
- Electron mass $= m_e c^2 = 0.511\,\text{MeV}$
- Planck's constant $h = 6.626 \times 10^{-34}\,\text{J-s}$
- $\text{c} = 3.00 \times 10^{8}\,\text{m/s}$
- Lorentz factor $\gamma = \frac{1}{\sqrt{(1-(\frac{v}{c})^2)}}$
- Energy of ^{137}Cs gamma ray $= 0.662$ MeV
- Γ for ^{137}Cs $= 3.3\ [\frac{R-cm^2}{hr-mCi}]$
- w_R for γ rays $= 1$
- Density of lead $= 11.34\ \text{g}/cm^3$
- (μ/ρ) for Pb, γ-0.600 MeV $= 0.1248\ cm^2/\text{g}$

3 Introduction

The Compton effect was discovered by Arthur Compton in 1923 [Semat 1972] when he noticed that the energy of scattered x-rays depended upon their scattering angle in the same way they would if you considered the X-ray as discrete particles of definite momentum and energy colliding elastically with electrons of the target material. This simple result demonstrates the particle nature of light

when interacting with matter. At high enough energies, photons behave more as small billiard balls than a wave when interacting with atomic and subatomic particles.

In Compton's experiment, X-rays were first scattered off a block of carbon and then had their wavelength measured by the combination of a calcite crystal and a ionization chamber using the Bragg refraction technique. The combination of the calcite crystal and ionization chamber is better known as a Bragg spectrometer (Figure 2) and is itself the basis of a dedicated PHYS 4211 experiment.

You will scatter high energy photons ($E_\gamma = 662\,\text{keV}$) from a radioactive source off an aluminum target and measure the energy of the scattered photons using not a Bragg spectrometer but a more convenient combination of a Na(Tl) crystal and a "photomultiplier tube."

4 Equipment/Materials Used

- Canberra 35+ Multichannel Analyzer
- Photo-Multiplier Tube with NaI(Ti) Scintillation crystal and Charge Sensitive Pre-amplifier attached
- Spectroscopy Amplifier (Ortec 2010)
- High Voltage power supply capable of +1000 V
- Low Voltage power supply capable of -24 V
- Lead Bricks
- 100 μCi Cesium-137 source

5 Compton Scattering Theory

5.1 Angular Energy Dependence

Compton scattering can be understood by examining a simple elastic collision between two particles (Figure 1). The only trick is, one of the particles is a photon, while the other particle is a "massive" (i.e., having mass) particle. Assuming that the conservation of energy and momentum hold in this process, we have an ordinary two dimensional collision problem. Since the easiest reference frame in which to analyze collision problems is the center of mass frame, let us go there:

Since there is only one massive particle (the electron) the center of mass frame is the frame where the electron is stationary. To make things easy, let us assume that the photon is incident from the left moving toward the right. After the collision, the Compton-shifted photon continues on with some new trajectory

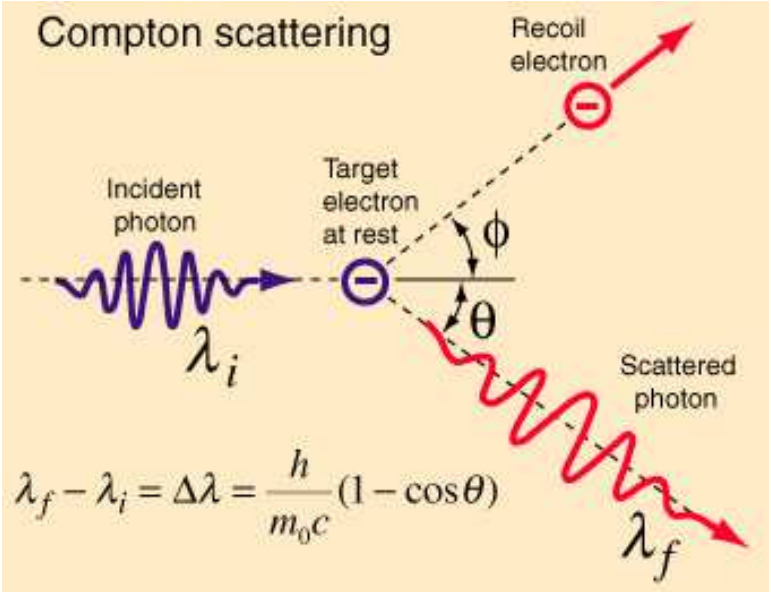

Figure 1: The Compton Effect. A photon incident from the left collides elastically with an electron at rest, imparting some of its energy (and momentum) to it. The scattered photon's energy and wavelength are correlated with its scattering angle. Figure taken from [Nave 2002]

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offset from its original course by angle theta, while the electron recoils with some recoil velocity $\vec{V_r}$ at a trajectory offset by angle ϕ.

From the conservation of energy

$$h\nu + mc^2 = h\nu' + \gamma mc^2 \tag{1}$$

where ν is the frequency of the incident light and ν' is the frequency of the scattered light.

From the conservation of relativistic momentum,
in the x direction:

$$\frac{h\nu}{c} = \frac{h\nu'}{c}\cos\theta + \gamma m|\vec{V_r}|\cos\phi; \tag{2}$$

and in the y direction:

$$0 = -\frac{h\nu'}{c}\sin\theta + \gamma m|\vec{V_r}|\sin\phi; \tag{3}$$

Combining these three equations, the dependence of the energy of the scattered photon on the scattering angle is [Semat 1972].

$$E' = \frac{E}{(1 + \alpha(1 - \cos\theta))} \tag{4}$$

where

α = Energy of photon / Rest energy of the electron

and

θ = photon scattering angle

Since the energy of light depends on its wavelength, equation (4) can be rearranged to yield an expression for the change in wavelength $\Delta\lambda$:

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{5}$$

where $\frac{h}{m_e c}$ is the *Compton wavelength* of an electron and is equal to approximately 0.0242 A. For our radioactive ^{137}Cs source, which emits 662 KeV gamma rays, $\alpha = 1.2$.

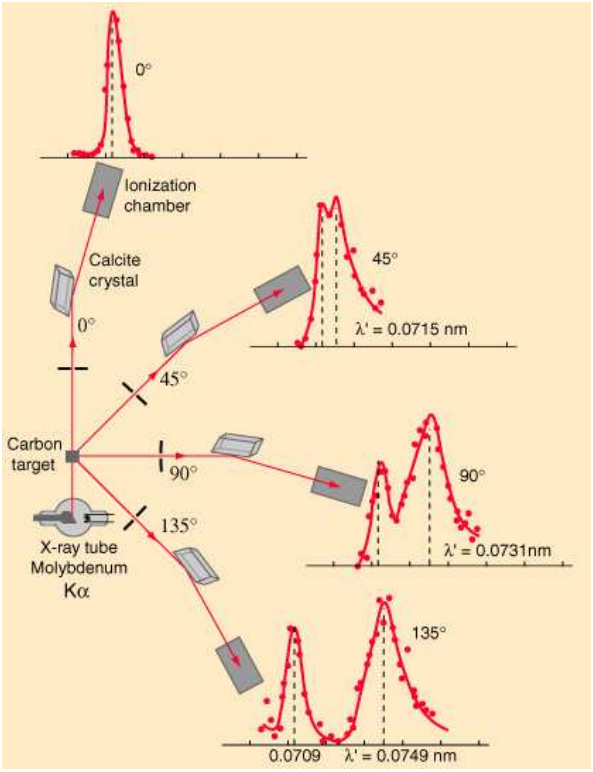

Figure 2: Compton's experimental setup. The crystal and the ionization counter act as a Bragg Spectrometer. You will use a combination of a NaI(Tl) crystal and a photomultiplier tube as your photon detector. Figure taken from [Nave 2002]

5.2 Differential Cross Section

The Klein-Nishina formula was an early success of Quantum Electrodynamics and predicts the differential Compton cross section to be:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\frac{1}{(1+\gamma(1-\cos\theta))^2}(1+\cos^2\theta+\frac{\gamma^2(1-\cos\theta)^2}{1+\gamma(1-\cos\theta)}) \tag{6}$$

The differential cross section describes the effective cross section of an electron as seen by a gamma ray photon as a function of the scattering angle of the photon. The cross section, while having units of area, is not a measure of the actual physical size of an electron. It is more accurately the likelihood of a given reaction to occur. Think of the differential cross section as the average fraction of the particles in a beam scattered into the solid angle $d\Omega$ per unit time per unit flux. As seen in equation (6), the cross section varies with the energy of the incident photon, as well as the angle at which it scatters.

As seen in figure 3, scattering is fairly isotropic at low energies relative to the rest energy of an electron (0.511 MeV). At energies comparable to and above the electron rest energy, photons are preferentially scattered in the forward direction. In other words, photons are more likely to strike a 'glancing blow' rather than a back-scatter.

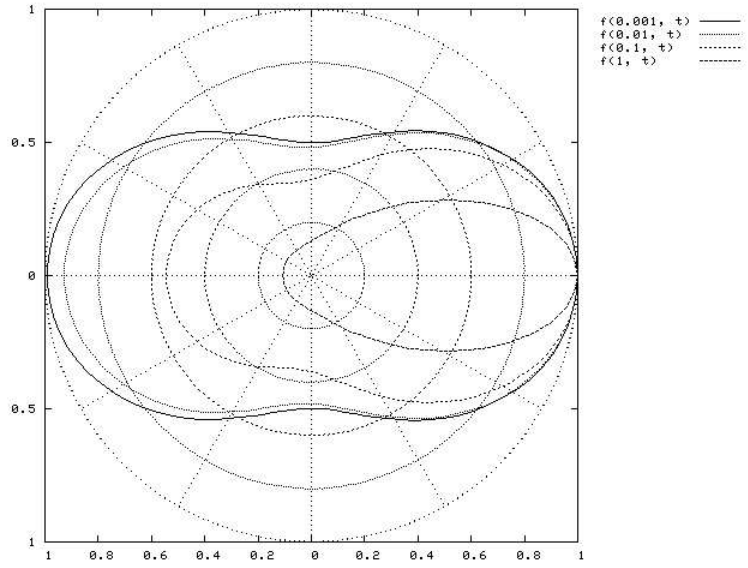

Figure 3: Polar Plot of the Klein-Nishina Formula ($f(Energy, \theta)$)at varying energies (in keV). Photons incident from left. Distance from origin is proportional to scattering cross section at that angle.

$d\Omega$ refers to the differential solid angle. A solid angle is measured in units of steradians, and can be represented by a surface area on a sphere. Given a

unit sphere, the total surface area is 4π. Dividing the sphere in two, the area of a hemisphere is 2π, implying that the hemisphere subtends an angle of 2π steradians. In spherical coordinates

$$\Omega = \int \int \sin\theta d\theta d\phi \text{[Wolfram 2004]}$$

In the case of Compton scattering, since the Klein-Nishina formula does not depend upon the azimuthal angle ϕ, we can integrate it out, turning $\int d\phi$ into 2π. You may find this useful in determining uncertainty for your detector arrangement.

6 Electronics used in this lab

Now we will discuss some of the electronics you will be using to measure the Compton Effect, as well as the procedure for calibrating these instruments.

6.1 Description of the Devices

6.1.1 Scintillation Crystal - NaI(Tl)

Contained in the aluminum hull in front of the PMT is a scintillation crystal which emits light when struck by charged radiation (e^-, α). The charged particle recoils through the crystal, losing energy by ionizing and exciting molecules and atoms along its path. These ionizations and excitations begin to decay and the rate of decay is governed by a dying exponential with a time constant τ, which is known as the decay constant. When the excitations decay back to the ground state, they release energy in the form of a photon. While the resonances for most crystals are fairly wide, most have a peak wavelength, and most photons emitted are close to this wavelength. The crystal is transparent to this wavelength of light, and allows the photon to travel to the edge of the crystal and into the PMT.

In order to be detected by the scintillation crystal, photons (i.e. x and γ rays) must produce a charged particle, or else the photon will simply pass through the crystal undetected. This occurs when the photon interacts with an electron via the photoelectric, Compton, or pair-production effect. The photoelectric effect occurs when a photon absorbs all of a photon's energy and is ejected from its atomic or molecular orbit. Electrons produces by Compton scattering are imparted with a partial amount of the photon's energy, allowing the Compton-shifted photon to continue through the crystal. Pair production occurs at energies above 1.022 MeV and occurs when a photon comes in close proximity with an atomic nucleus. The positron and electron are imparted with equal amounts of the excess energy of the photon after creation of two 0.511 MeV particles. At photon energies below 1.022 MeV, pair production is not possible.

NaI(Tl) crystals are particularly sensitive to gamma rays due to the large atomic number of Iodine, which provides many electrons to bleed off the energy

of the gamma rays. It is important to chose a scintillator which has a non-negligible photoelectric cross section at the gamma ray energy in question. If the total cross section is not large enough, most photons will pass through the scintillator undetected. Likewise, if the photoelectric cross section is dominated by the Compton effect, most of the electrons scattered in the scintillation crystal will be Compton recoil electrons. Depending on the scattering angle of the photon, the recoil electrons will have some fraction of the energy contained in the photon, which tends to produce a "smearing" of the distribution of photon energy, called a "Compton Edge". Photoelectrons, which contain ALL of the energy carried by the photon, do not suffer this smearing effect and produce a well-formed gaussian distribution of photoelectron energy.

The crystal is doped with Thallium to increase its sensitivity and provide impurities to aid electron/hole mobility within the crystal. NaI(Tl) has a relatively long decay constant of 230 ns, during which the majority of atoms/ions transition back to the ground state, emitting a 413 nm wavelength photon. The crystal is extremely hygroscopic, meaning that it reacts with water and moisture in the air. Any cracks or leaks in the aluminum hull or seal will degrade crystal quality and performance.

Detector resolution is usually given in terms of the energy full width at half-maximum (FWHM) of the peak. Resolution is defined as $\frac{FWHM}{E}$ where E is the energy of the peak. The resolution of NaI(Tl) detectors is nominally 8%.

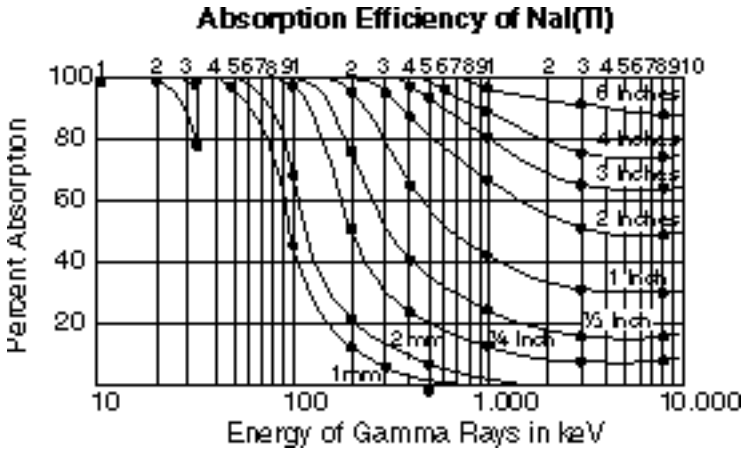

Figure 4: Efficiency of NaI(Tl) detector crystals with respect to crystal thickness and photon energy. Our crystal is approximately 3 inches thick, and our photon energy is approximately 0.662 MeV. Source: [Canberra 2004]

As shown in Figure 4, our 3 thick circular slab of NaI(Tl) is quite effective at absorbing gamma rays. A beam of 662 keV gamma rays will emerge 85% less intense from our detector.

6.1.2 Photo-Multiplier Tube (PMT)

The Photo-Multiplier Tube (PMT) attaches to the face of the scintillation crystal via an optical coupling, which consists of a fine layer of optical grease and some tape. The PMT operates on the principle of the photoelectric effect. Photons incident on the window of the PMT fall on a photocathode made out of semiconductor material. Semiconductors are prefered to metal for PMTs due to their large *escape depth*, or thickness of material through which a photoelectron can escape. This is due to the lack of conduction-band electrons in semiconductors, allowing the photoelectrons to retain most of their kinetic energy until they reach the surface.

Electrons are ejected due to the photoelectric effect, overcoming the work function of the particular semiconductor used for the plate, and drift toward the second dynode. The second plate is at -100 volts with respect to a third dynode, so when the photo-electrons strike the second dynode, they eject even more electrons which drift toward the third dynode. Usually there are 10 to 14 dynodes (or stages) in a PMT, each stage increasing the number of electrons by a factor of 5 or 6. Gains of 10^7 are common, making even single photons detectable. While single photons are in theory detectable, PMTs are not perfect devices. In fact, only about 30% of the photons incident on the photocathode get converted into a measureable signal.

6.1.3 Charge Sensitive Preamplifier

Attached to the end of the Photo-Multiplier Tube (PMT) is a charge sensitive preamplifier. The preamplifier accepts a signal in the form of a pulse of charge from the PMT and produces an amplified voltage signal at the output ready for further processing.

6.1.4 Spectroscopy Amplifier

The spectroscopy amplifier is a device which accepts small voltage spikes (figure 5) from the PMT preamplifier, and amplifies and shapes the pulses to be well defined and Gaussian (figure 6). The pulse height is proportional to the original amplitude of the voltage spike. The shape and size of the output pulses can be controlled with the switches and knobs on the front of the spectroscopy amplifier.

Rise time is the time it takes for the pulse to rise from 10% of its maximum value to 90%. Fall time is defined as the opposite, the time it takes for the pulse to fall from 90% of its maximum value to 10%. For an optimal signal-to-noise ratio, spectroscopy amps usually match the time constants of the differentiating and integrating filters and only list one time constant on the front panel as a shaping constant. In general, the smaller the shaping constant produces the shorter and more compact pulse. Longer shaping constants produce wider (longer) pulses, but provide a better signal-to-noise ratio.

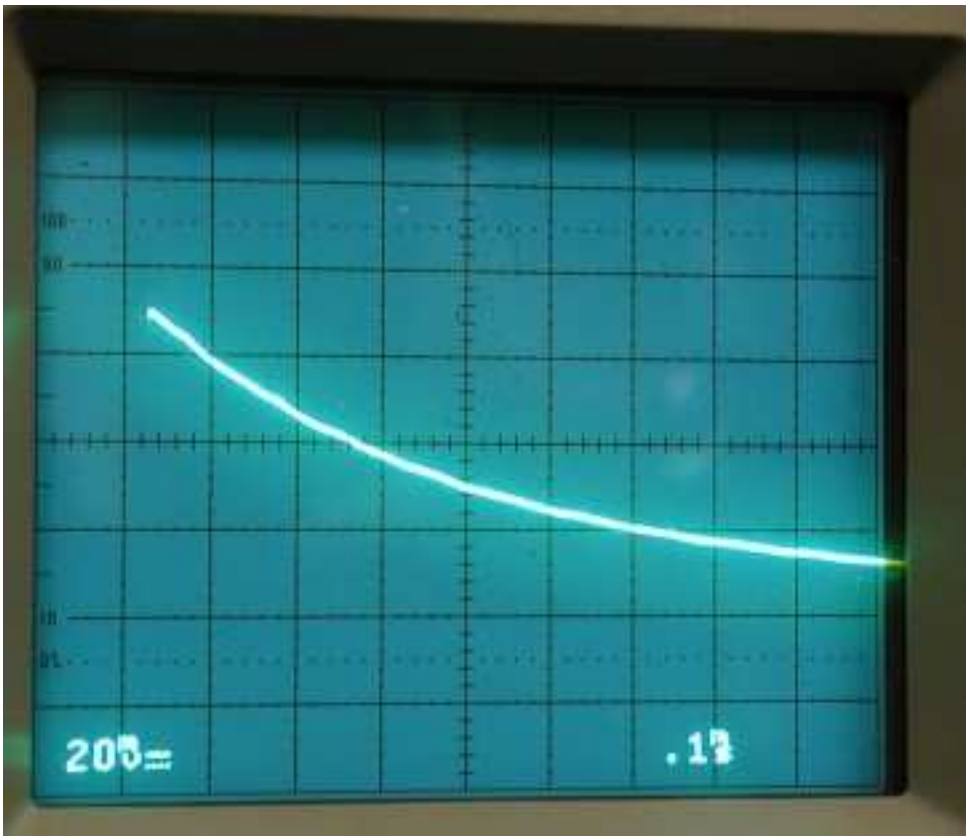

Figure 5: Voltage spike from the preamplifier. Note the dying exponential shape, as well as the time scale. Source: Author

Pile-ups and Undershoots

In an idea situation, a shaping circuit would not be necessary. The amplifier would simply see a single voltage spike from the preamp, amplify it to the MCA, and return to an idle state, waiting for the next voltage spike to arrive. Since the processes studied by the spectroscopy amplifier are inherently random, this is hardly ever the case, except at very low counting rates. As seen in figure 1, the tail on the voltage spike stretches for several tens of microseconds. If there were no shaping circuit, one pulse might ride on the tail of another, and may appear as though it is larger than it actually is. This phenomenon is known as a Pile-up. Pile-ups are avoided by either restricting the counting rate so that it is statistically unlikely for a Pile-up to occur, or to shorten the tail of the pulse so that collisions are not as likely to occur. In order to preserve their usefulness at high counting rates, spectroscopy amplifiers shape the pulse so that the tail is significantly shortened.

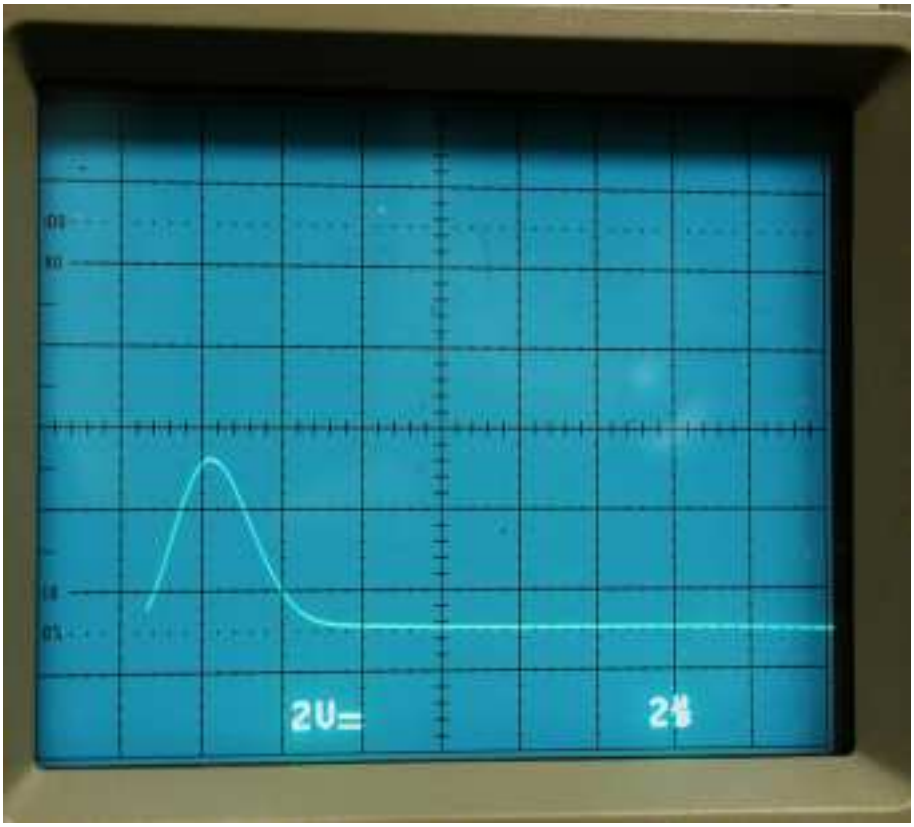

Figure 6: Voltage spike after shaping by the spectroscopy amplifier circuits. Note that it is approximately gaussian. Source: Author

One artifact of the shaping circuit, however, is the presence of an undershoot, as seen in figure 7. This will produce an amplitude defect in following signals. The Pole-Zero cancellation circuit is used to correct this undershoot, and consists of a variable resistor in parallel with the CR differentiator. The Pole-Zero cancellation circuit is controlled by a screw-potentiometer on the front panel of the spectroscopy amplifier. While looking at the output of the amplifier on an oscilloscope, use a small screwdriver to adjust the potentiometer until the undershoot is eliminated. This step is vital, as amplitudes can drift if the undershoot is not properly eliminated.

6.1.5 MultiChannel Analyzer (MCA)

The Multi-Channel Analyzer is a device which accepts inputs ranging from 0 to 10.0 Volts and creates a histogram, each consecutive channel representing an increasing range of voltage. This particular model MCA is a Canberra Series

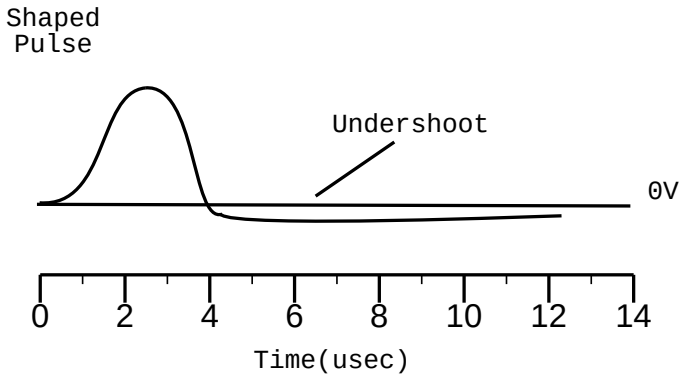

Figure 7: Diagram of an undershoot defect. If not corrected, undershoot can make subsequent pulses appear smaller than they actually are. Source: Author

35+ with 4096 channels. Roughly speaking, this corresponds to a voltage resolution of 2.4 mV per channel, assuming the MCA is linear. The MCA examines the output of the spectroscopy amplifier. When active, the MCA counts pulses, categorizing them by their respective pulse heights. As more pulses arrive which fall into a particular bin, more counts for that particular channel are reflected on the CRT of the device. This device is quite linear, with a correlation function (which relates pulse voltage to channel number) of:

$$Voltage(x) = 46.1mV + 2.35mV/channel * x$$

where x is the channel number, with a χ^2 value of 0.00012. (For more information, see Compton Scattering Log Book pg. 44)

6.2 Genesis of a Count on the MCA

Now that we have discussed all the electronics used to turn a photon of a particular energy into a count on the MCA, let us trace the path of the signal. The gamma ray enters the aluminum housing and penetrates the NaI(Tl) crystal. It is then photo-electrically absorbed by one of the electrons orbiting an Iodine atom, which ejects it from the atom. On its way through the crystal, the photoelectron ionizes and excites the crystal structure. After a decay time of 230 nanoseconds, the ionizations and excitations decay back to the ground state, releasing green photons. The number of photons generated is proportional to the energy of the photoelectron, which is linearly related to the energy of the gamma ray.

The photons enter the window of the PhotoMultiplier tube and strike the photocathode. The photoelectrons generated here are ejected from the surface of the semiconductor, and make their way toward the positive potential of the first dynode. After striking the first stage, more electrons are ejected from the first stage, and follow the voltage difference to the second dynode, which is

at a positive potential relative to the first stage. This multiplicative process continues down the stages of the photomultiplier, until a small but measurable pulse of charge is seen at the output of the PMT. The size of the spike is linearly related to the number of photons which were incident on the photocathode, and hence linearly related to the energy of the gamma ray.

The preamplifier amplifies the weak charge signal from the PMT and converts it into a voltage signal through the use of an Op(erational) Amp(lifier) and sends the signal through a BNC cable to the Spectroscopy Amplifier.

The spectroscopy amplifier, using a series of a differentiating filter, op amp, and integrating filter, shapes and amplifies the voltage spike to a well-defined gaussian pulse, the amplitude of which is linearly related to the amplitude of the voltage spike. The gain on the amplifier is set so that the majority of "interesting" pulses will have amplitudes between 0 and 10 V.

The output of the spectroscopy amplifier is then fed into the MCA. The MCA examines the pulse and sorts it according to pulse height. The MCA finally registers a count in the channel number into which the pulse height fell. This channel, or bin number, is linearly related to the amplitude of the pulse height, which is linearly related to the energy of the γ-ray photon incident on the crystal.

6.3 Connecting the Electronics

6.3.1 Scintillation Crystal/PMT/Preamp

The Bicron detector is a combined apparatus of the NaI(Tl) scintillation crystal, photo multiplier tube, and PA-14 preamplifer is lashed to a detector holder made out of PVC, plywood, two handles, and two delrin pegs (Figure 8).

Figure 8: PMT Connections. HV +1000V via an SHV cable, DC -24V via a BNC cable, output (S)ignal to spectroscopy amp via a BNC cable. Source: Author

The HV connector on the left of the preamp provides the necessary high voltage for the PMT and is connected via a SHV cable to a high voltage supply capable of producing at least +1000 V. The DC connector supplies a negative voltage via a BNC cable connected to a low voltage power supply. The output signal is carried from the preamp to the spectroscopy amplifier via a BNC cable connected to the S connector. The schematics for the preamp can be found in the preamp.pdf file in the /compton/whitesheets/ directory

6.3.2 Spectroscopy Amplifier

The Model 2010 Canberra Spectroscopy Amplifier has an input and two outputs. The input is connected directly from the output of the Preamp, while the unipolar output is fed into the ADC IN of the MCA. The Spectroscopy Amplifier is powered by NIM bin connections. The defaults for this setup are shown below (Figure 9).

```
Restorer: ASYM, MED
Threshold: VAR
Input Polarity: POS
Unipolar Output: POS polarity
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See the calibration section to see how to adjust the gain, shaping, and pole zero.

6.3.3 Low Voltage Power Supply

The low voltage power supply provides power for the preamplifier connected to the PMT. It provides the bias voltage for the preamplifier to draw off of to create the pulses it receives from the PMT. Be sure that the inside conductor of the cable is -24 volts relative to the outside sheath.

Figure 9: Spectroscopy Amplifier with default settings used for the Compton scattering experiment. Source: Author

6.3.4 High Voltage Power Supply

The High Voltage Power Supply should be capable of providing a voltage of approximately +1000 V. Be sure to connect the HV power supply to the preamp using a SHV cable.

6.4 Calibration of the Electronics

1. Connect the input of the 2010 Spectroscopy Amplifier to a pulse generator. Set the Gain on the Amplifier to an intermediate setting.

2. Tee the input and the output of the AMP into an oscilloscope. The other end of the output Tee should go into the ADC IN of the MCA.

3. Turn on the NIM bin and Oscilloscope. Disregard the output of the amplifier for now. Make sure the trace resembles the trace in figure X. You may have to play with the attenuating switches in the pulser. Make sure the polarity is positive. The peak voltage should be less than a volt.

4. Next, disregard the input to the amplifier and lock onto the output. The shaping knob on the amplifier will tell you how fast the shaped pulse will rise/fall to 1/e (62%) of its peak value. You can use this number to adjust the timescale of the oscilloscope. If the pulse is "hitting a rail" or "clipping", you may need to decrease the amplitude of the pulser.

5. Using a small screwdriver, adjust the pole-zero potentiometer until the undershoot is no longer noticable. The trace should look similar to Figure X in the Electronics handout. You may need to adjust the gain or the voltage of the pulser to keep the amplified, shaped pulse from getting "clipped" by the +12 V rail. Try to keep the output voltage below +10 V as that is the upper limit of the MCA.

6. Remove the Pulser from the input of the spectroscopy amp. Connect the output of the spectroscopy amp to the ADC IN EXT connector on the rear of the MCA, and place the ADC IN toggle switch to EXT. Connect the (S)ignal output of the PMT preamp in its place. Dial up +1000 V on the High Voltage power supply, and -24 V on the low voltage power supply. Place small gamma ray sources (1 μCi or less) of several different energies (at least 3) one at a time in front of the scintillation crystal. Turn on the MCA and begin acquiring a spectrum.

   Adjust the amplifier gain and PMT voltage until the peak from ^{137}Cs is roughly in the third quarter of channels. Acquire a spectrum on the MCA for a short while until you see clearly defined peaks for each radioactive source.

7. Record the channel number of each of the peaks, as well as their FWHM. Consulting your favorite nuclear physics reference, record the energy of the gamma rays. Plot channel number (x) versus energy (y) in gnuplot and fit a line to it. You will use this line to extrapolate the energy of the scattered photons from just knowing the channel number of their peak. **IMPORTANT!!!** Once you have calibrated your equipment, you cannont for any reason change any setting. If you can help it, try not to turn off the equipment either.

7 Radiation Safety

In this lab, you will be dealing with a non-negligable amount of γ-ray radiation. Hence, a discussion of radiation safety and biological side effects relative to this experiment is prudent.

7.1 Dosimetric Units

Scientists developed several radiological units in order to describe and predict the effect of irradiation on biologicial tissue. There at least two families of units

commonly used in describing radiation and its effects, the old standard units, and the SI (*Systeme International*) units.

7.1.1 Activity

The SI unit for Activity is the *becquerel* (bq), while the old standard unit is the *Curie* (Ci). Activity is a measure of how radioactively "hot" a source is. 1 becquerel is the amount of material which will produce 1 nuclear decay per second. 1 curie is equivalent to the amount of material which will produce 3.7 X 10^{10} decays per second. Named after Marie Curie, the discoverer of radium, 1 Ci is equivalent to the activity of 1 gram of radium. 1 Ci = 3.7 X 10^{10} [Nave 2002].

7.1.2 Exposure

The unit for exposure is the *Roentgen* (R) and is defined as the quantity of radiation (usually x or γ rays) which produces an ionization of 2.58 X 10^{-4} Coulomb/kg of air at STP. Given an source of isotropic radiation and neglecting attenuation due to air, the *exposure rate* is given by the formula:

$$Rate = \frac{\Gamma A}{d^2} \tag{7}$$

where A is the activity of the source, d is the distance from the source, and Γ is an *exposure rate constant* which is calculated from the characteristics of the source (photon energy, decay scheme, absorption coefficient in air, and the ionization of electrons). For ^{137}Cs, $\Gamma = 3.3$ $[\frac{R-cm^2}{hr-mCi}]$ [Leo 1994]

7.1.3 Absorbed Dose

The SI unit for Absorbed Dose is the Gray (Gy), and the old standard unit is the Rad. Absorbed dose measures the amount of energy actually deposited in biological tissue. 1 gray corresponds to 1 joule of energy deposited in 1 kg of tissue. 1 rad referrs to 0.01 joules of energy being absorbed per kilogram of tissue. In order to determine the biological significance of an absorbed dose, you must consider the "quality factor", or biological effectiveness of the type of radiation in question.

7.1.4 Biologically Effective Dose

Some types of radiation are more damaging to living tissue than others. This makes it necessary to qualify the risk associated with radiation by the type of radiation to which tissue is exposed. For massive particles (α, neutrons) which may ionize many atoms and molecules while losing kinetic energy in tissue, the relative biological effectiveness (RBE) may be as high as 20, so that 1 rad of absorbed dose is equivalent to 20 rems. However, for x and γ rays, the rbe is taken to be 1, since on average if a photon is stopped in tissue, only one ionization is produced. The SI unit for the Biologically Effective Dose is the Sievert (Sv) and it is equal to the absorbed dose in grays multiplied times the

RBE of the type of radiation. The old standard unit is the Rem, and it is equal to the absorbed dose in rad multiplied times the RBE of the type of radiation. 1 Sv = 100 rem [Nave 2002].

7.2 Shielding Considerations

While the radiation levels to which you will be exposed are fairly low, it is still a good idea to limit exposure. One way of limiting exposure is to surround the radioactive material with an adequate layer of shielding material. The best material for shielding depends on the type of radiation to be shielded, but for the gamma rays we will be using in this experiment, lead (Pb) is by far the best choice. It is a high-Z material, meaning that it has numerous electrons to absorb gamma rays, and is also quite dense (Figure 10).

At a photon energy of 0.600 MeV, the mass attenuation coefficient for lead is 0.1248 cm^2/g [NIST 1996]. The mass attenuation coeffcient μ/ρ is defined in the following way: Given a beam of monoenergetic photons with intensity $I_\circ$ incident on a layer of material of mass thickness x and density ρ, the beam will exit from the layer of material with a lower intensity given by:

$$I = I_o e^{-\frac{\mu}{\rho}x} \tag{8}$$

The mass thickness x is defined as the product of the layer thickness t and the density ρ [NIST 1996]. The density of lead is 11.34 g/cm^3. So, to a good approximation, every centimeter of lead between a source (Figure 11)and a detector will attenuate a beam of 662 keV photons by 75%.

So, before we determine how much shielding we need, we must first figure out the target exposure we are willing to tolerate. Idealy, we would like the entire experiment to expose the experimenters to no more than 10 μSv (1 mrem) of radiation. Estimating conservatively to err on the side of caution, we can make the following assumptions:

- The entire experiment will require the student being in close proximity to the experiment a total of 10 hours. When the experiment is simply running and collecting data, the student need not be present, and should remove him/herself from the area.
- The student will remain an average of 50 cm away from the source. Most often, the student will be further away than this, but there are times when it is necessary to be closer.
- Since the radioactive element will be on the ground level, the student is safely out of the path from at least half of the photons. In fact, from a distance of 50 cm, a student with body surface area 0.45 m^2 only should take up approximately 1.8 steradians out of a possible 4π of solid angle. This means a meagar 14% of isotropically radiated photons will have the possibility of interacting with an experimenter at this distance.

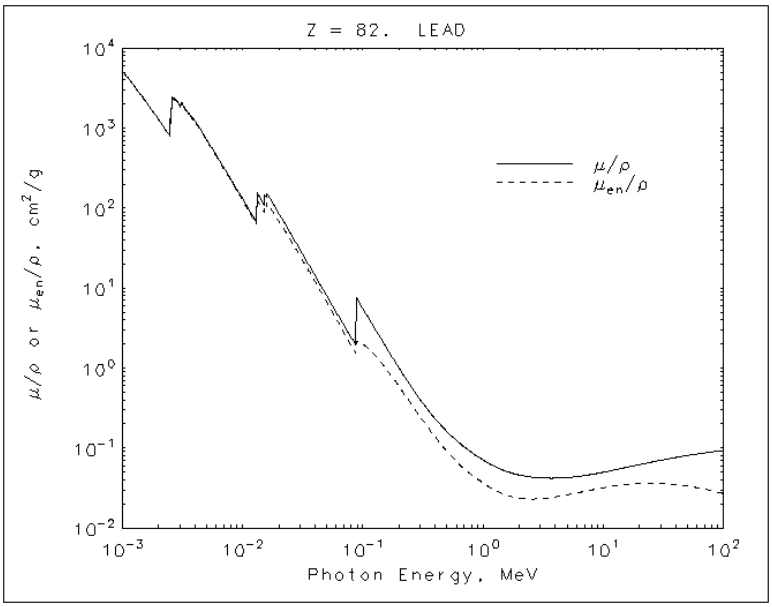

Figure 10: Total photon mass attenuation coefficient versus photon energy for Lead. For 0.662 MeV photons, $\mu/\rho = 0.1236$ g/cm^2. Source: [[NIST 1996]]

- Since the Compton scattering effect for electrons is quite small for photons at this energy, especially for backscatters, the number of photons which scatter off the aluminum target and strike the experimenter will be negligable. We assume that the experimenter stays behind the and lead sheilding, and does not venture into the unshielded areas of the room.

Human tissue absorbs approximately 9.3 mJ per Roentgen of γ ray radiation. First, let us calculate the exposure with no shielding. The Activity of the source is 100 μCi, the exposure rate constant is 3.3 $[\frac{R-cm^2}{hr-mCi}]$, and the experimenter is at an average distance of 50 cm, the exposure rate is: $\frac{3.3*0.1mCi}{(50cm)^2} = 132$ μR/hr. The dosage rate is the exposure rate multiplied by the absorption of human tissue. The dosage is: 9.3 X 10^{-3} * 132 μR = 1.23 μGy/hr. Since the experiment will take 10 hours to complete, the total dosage is approximately 12.3 μGy. Since ^{137}Cs emits gamma rays, the relative biological effectiveness (or *radiation weighting factor,* w_R) is 1, meaning that the effective dose is 0.012 mSv = 1.2 mrem, which is roughly equivalent to a 6 hour subsonic airplane flight at 8000 m. This is a fairly small dose of radiation, a factor of 10 weaker than a chest x-ray.

We are already close to our target of 10 μSv, so any shielding we add will be "icing on the cake." We can make the shields as thick as we want, but there are a few things to consider:

- You will never be able to block 100% of the radiation. You can get really

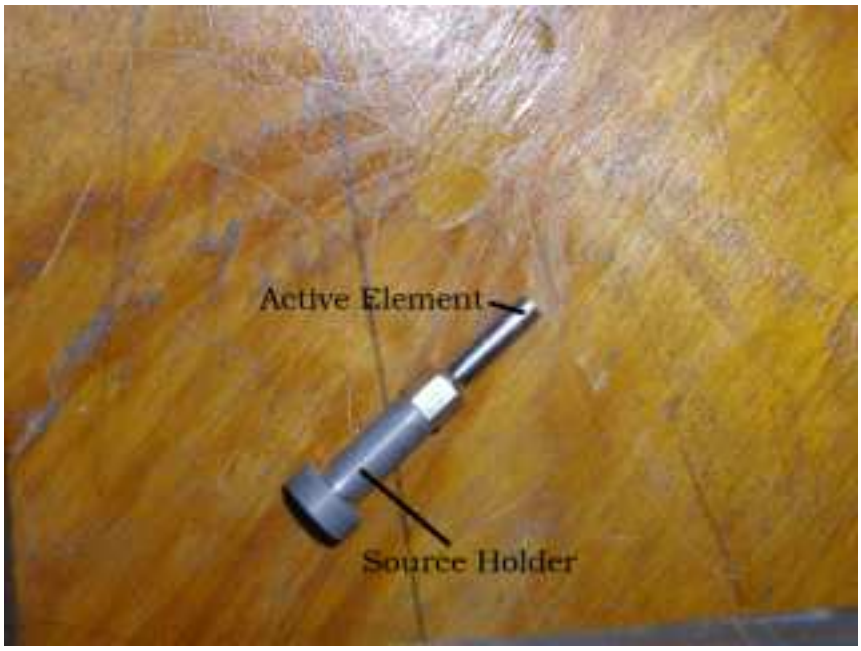

Figure 11: ^{137}Cs source screwed into source holder. This is then inserted into the collimator brick. Source: Author

really really close, but given the statistical nature of the universe, once in a while, a photon will sneak through.

- Lead is HEAVY. If you do not believe this, pick up a brick and drop it on your foot. You do not want to be sweating too much while moving 40 bricks around just to take another set of data.
- Lead is poisonous. If you do not believe this.... wait... nevermind. While you are protecting yourself from the dangers of radiation, you are also exposing yourself to the dangers of lead poisoning.

With this in mind, we can look at equation (8) and figure out the optimal thickness of lead to use in sheilding for our experiment. Plugging and chugging, we find that 5cm of lead (coincidentally the thickness of our bricks) corresponds to roughly a ten-thousand fold attenuation in beam intensity. This in turn drops the exposure rate, dosage rate, and total dose to nanoscopic levels. The estimated dosage rate with 5 cm of lead sheilding is 1 nSv/hr (0.10 μrem), well below background natural radiation levels, which are on the order of 300 nSv/hr (30 μrem/hr).

7.3 General Radiation Safety

Some things to keep in mind when dealing with radiation:

- The intensity of isotropic ratiation falls off as $\frac{1}{r^2}$. If you go twice as far away, you are only receiving a fourth of the radiation. Keep your distance and only approach the source if necessary
- No eating or drinking in the lab! If radiation somehow finds its way into your system, it can be much more damaging that if it is outside. You should not have to worry about the radiation rubbing off anywhere since it is contained in the source holder, but you need to be careful of the lead dust from the bricks, which can be just as harmful. Be sure to wash your hands throuroghly after handling either the lead bricks, the radioactive source, or anything that could possibly have lead dust on it.
- Always have the Geiger counter on when working with radiation. If nothing else, the constant beeps will remind you that you are working with radiation. You can also use it to leak-check your sheilding.
- Do not irrationally fear radiation. Respect it, but do not let it scare you away. Most of it is going right through you, and you get almost 300 millirem per year from natural sources (cosmic rays from outer space, elements in the soil, and the majority coming from radon in the atmosphere). Unless you live in a lead-brick house, you cannot escape it. Even if you do, your body contains certain radioactive isotopes (Carbon dating relies on this)
- Always shield your self as much as possible from the source. This means placing a lead brick in front of the collimator when working with the detector on the other side of the board.

7.4 Suggestions for Shielding Configurations

- In order to reduce the amount of radiation to which you will be exposed, the ^{137}Cs source will be housed in a collimater, which is simply a lead brick with a hole drilled through it. The source holder fits inside the holder, allowing the active element to slightly protrude from one side of the brick. This side will sit facing the arcing aluminum target, while the other side will face the experimenter (Figure 13).
- For adequate protection from the gamma rays coming through the less-dense aluminum and steel holder, another lead brick should be placed immediately behind the collimater brick (Figure 12).
- To prevent the Compton scattered photons from being washed out by the direct photons from the source, place two bricks lengthwise between the source and the detector. You will need to reposition these bricks each time you move the detector to a different angle (Figure 14).
- Figure 12 shows a sample configuration for the sheilding. Try to make yours look similar. If you are unsure about the effectiveness of a configuration, use the geiger counter to check for radiation "leaks."

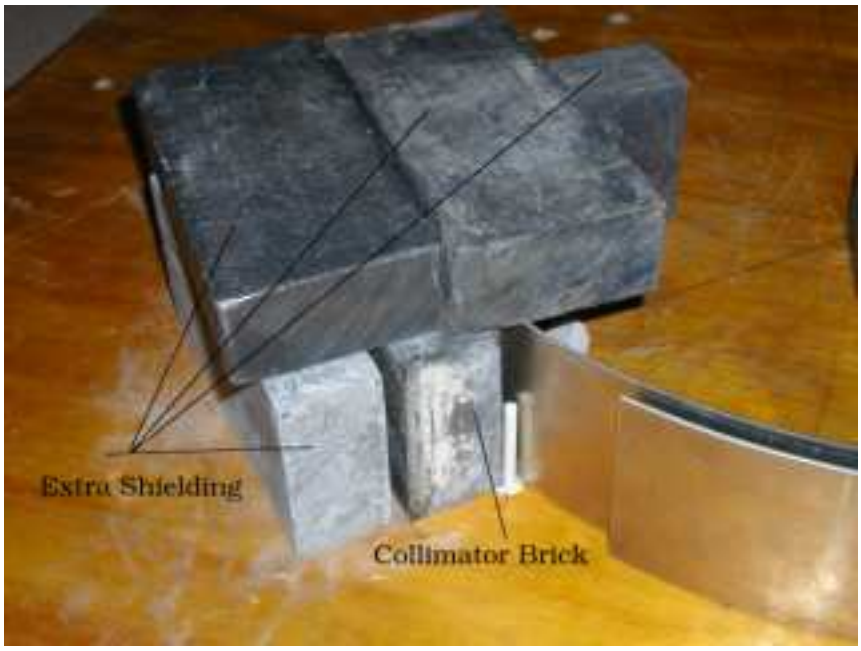

Figure 12: Shielding configuration. The source is held by the collimator brick in the middle of the lead bricks. Source: Author

8 Running the experiment

8.1 Theory of Operation

We are use a scattering design developed by Lorbach and improved by Cornell ([Cornell 1984]) which presents a much larger effective target area than a traditional point-like target without introducing excess uncertainty. The design is a platter with a circle inscribed on it (Figure 14). Extending radially from the center of the circle are lines spaced at 15 degree increments subtending a total angle of 270 degrees. Spaced at a distance of 30 cm from the centerpoint are a series of delrin washers recessed into the platter. The washers straddle an arc over which the aluminum targets are placed. The targets are $4\,\text{in} \times \frac{1}{8}\,\text{in}$ aluminum alloy bands which are curved with radius 30 cm. The bands subtend angles of 135°, 90°, and 30°. To hold the targets in place, delrin pegs are inserted into the delrin washers and traps the target in place (Figure 14). The bands can be interchanged to create the largest possible target as the angle α between the source and detector varries.

Beyond the washers which hold the targets, there are two more rings of holes. Each set of two holes is positioned on a radial line, and is intended to receive the mating delrin pegs from the bottom of the detector holder to hold it in place at the specified angle (Figure 15).

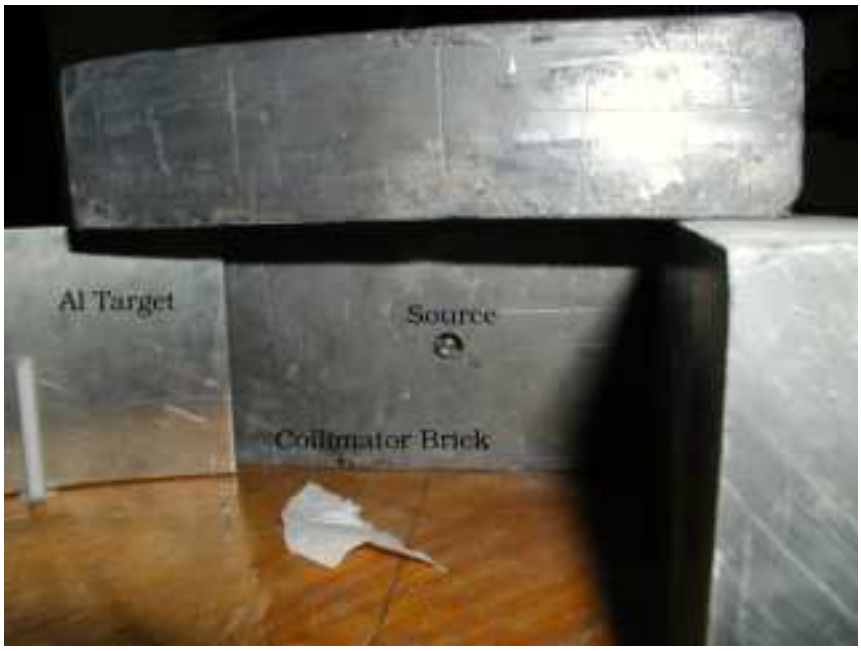

Figure 13: View of source from opposite side of lead shielding. Source: Author

At one end of the arc of holes is marked the footprint of the lead brick collimator. It should be centered orthogonally on a line from the center of the circle, tangent to the circle at the middle of the brick. The hole for the source should be as close to the circumference of the circle as possible.

The radial lines will allow you to determine the angle α between the detector and source. α will always contain the aluminum target. When a photon from the source scatters anywhere off the circular aluminum target and is then detected by the detector, no matter where on the target it scattered, the scattering angle (θ) of the photon will be constant and related to the angle α. You will derive this relation in lab question 5.

8.2 Preparation

Before removing the ^{137}Cs source from its lead-lined container, it is best to prepare all electronics and mechanical parts so there is a minimum of reconfiguration once the source is in the collimator. Here are some suggestions:

- Place the wooden platter on the ground with the handles facing up. The arrow on the board, which points in the direction of the unshielded radiation, should face a direction in which there will not be heavy human traffic. Remember, gamma radiation can easily penetrate walls, so think about what is behind the walls, (i.e. hallways and stairwells). If you are

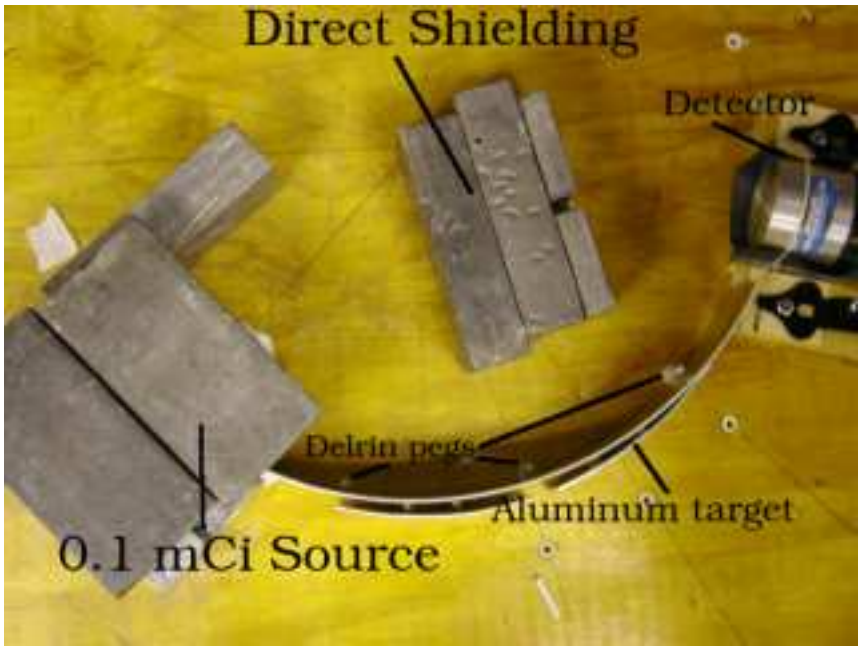

Figure 14: Birds eye view of the experiment set up. The source is contained in the collimator brick so that it is located on the circumference of the circle. The angle between the source and the detector is $\alpha = 120°$. Source: Author

doing this in lab 1, I suggest aiming the arrow out to the parking lot behind the building.

- If you only have 1 set of curved aluminum bands (4 pieces in a set) you probably will not have a large enough count rate to examine any angles larger than $\alpha = 180°$. If you have two sets of curved aluminum bands, you can attempt to gather larger angles. Whenever you have extra targets (i.e. the delrin holders are full) you can increase the counting rate by setting the extra targets directly behind the outer ring of delrin pegs. This effectively doubles the target area. Be sure to keep the extra targets close to the original circle, as a significant deviation will allow photons scattered at different angles to reach the detector, introducing error in your measurments.

- Be sure that the BNC and SHV cables attached to the rear of the PMT are long enough to reach from the electronics cart to the opposite side of the platter.

- It is best to start off at small scattering angles, where the differential cross section, and hence the counting rate is comparitively large. You will be able to see the gaussian peak of the Compton shifted photons readily

Figure 15: Alignment of the detector housing. In order for the pegs to fit in the placement holes, the hatch marks on both sides of the detector cradle and the platter must line up. Source: Author

visible. At larger scattering angles, the cross section and hence count rate is much smaller, and requires a much longer time for the peak to become apparent.

8.3 Acquiring Data

1. You will first need to set up the computer as specified in section I of the /compton/canberra(nucleus)/TUTORIAL.TXT file. The computer must be running linux and have the DAMP (Data Acquisition and Management Program) suite of applications installed. (The following instructions are also contained in the TUTORIAL.TXT file) Start DAMP by opening a terminal and typing : `./damp` in the directory /home/user/compton/.

2. Once all electronics are connected, place the detector directly across the circle from the source. Remove the direct shielding bricks and place the source in the collimator. Turn on the power to all electronics. Apply the proper voltages (Section 6.3) to the PMT, and make sure that the spectroscopy amplifier has been propery setup/calibrated (Section 6.4).

To begin collecting a spectrum, follow the data collection directions in the file MCA.txt. Collect data for enough time so that a clear energy peak is visible on the display of the MCA, recording the amount of time necessary to take the spectrum, as well as the size and number of aluminum targets used. Extract data from the MCA to the computer using the instructions contained in TUTORIAL.TXT. A good idea is to title each spectrum by the angle α at which it was collected.

3. Slide the direct shielding bricks in front of the collimator brick, and move the detector to a new location. Depending on where you move it, you will need to either add or take out aluminum target bands and target holder pegs. Be careful not to stretch the cables connected to the PMT. If they are too short, replace them with longer cables.

4. Slide the direct shielding bricks back in between the PMT and the source. You will need to position them differently for each location of the detector (Section 7.4).

5. Repeat steps 2-4 for a number of different scattering angles. Larger scattering angles will require more time for the peak to become apparent.

6. Once you have collected data on all angles you wish to examine, **turn down** and then off the HV on the PMT, and turn off the low voltage power supply for the preamp. Turn off the NIM bin, as well as the MCA.

7. Remove the source from the collimator using tweezers and place it back in its lead container. Either have your instructor return the lead container back to the lead "pig" in room 1 or place it strategically underneath the lead bricks so that you will be shielded from its radiation.

8.4 Analyzing the Data

1. Plot and Fit the data using the plot and fit routines in DAMP. For more detailed instructions, consult the TUTORIAL.TXT file. Print the log file (./data/fitted/xxxxx.log) for each spectrum which contains the parameters for the fit. The fit is a gaussian distribution superimposed on a linear base. The most important number is the mean (μ) which gives the location (channel number) of the middle of the peak.

2. Applying the calibration you calculated in section 6.4, convert the channel numbers of the peaks to photon energy. Now, you can create the famous 'Compton Plot' which plots wavelength (λ) as a function of $(1 - \cos\theta)$, where theta is the scattering angle. Note: the scattering angle is NOT α! Look at Lab Question 5 for a hint. You can use any plotting program you chose, but gnuplot is recommended for ease of use and flexibility. A tutorial for gnuplot can be found in the /gnuplot directory.

Sample data, plots, and fit logs can be found in the directory ./sampledata/. To view the plots which are in postscript (.ps) format, type: `ggv test.ps` where test is the name of the file you wish to view

9 Lab Questions

1. Derive the steps between equations 4 and 5.

2. For γ-rays from ^{137}Cs through NaI(Tl) what is the major scattering cross section? Compare the relative cross sections of the photoelectric, Compton, and pair-production effects. Why is NaI(Tl) considered a good γ-ray detector?

3. Semiconductors are used as photocathodes in PMTs because of the lack of numerous conduction band electrons. Why does this allow photoelectrons to maintain much of their kinetic energy?

4. What is the wavelength shift for 0.662 MeV γ rays scattered off an aluminum atom at 90°? Compare to the wavelength shift of a photon scattered off a free electron. Will you have difficulty distinguishing between the two?

5. Derive the relation between the angle between the detector and the source α and the scattering angle θ.

6. Compare the approximate relative cross sections of an electron at different angles with respect to that of the smallest angle by comparing the number of photons/sec registered by the detector. In determining the relative cross section, be sure to incorporate the target size, distance from the target to the detector, counting time, and of course, number of counts. Organize your results in a table. Do you results agree with theory?

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