Flux Studies: Muons & Gamma Rays

By:
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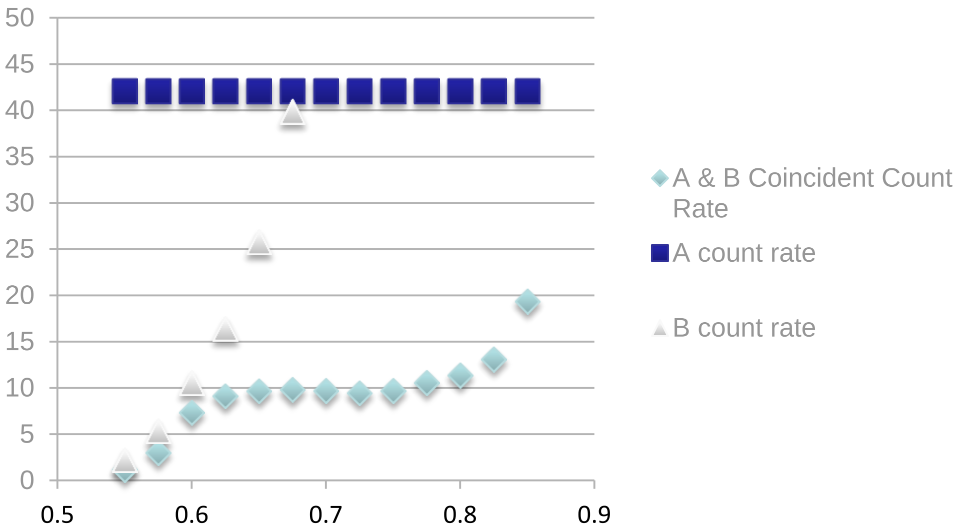
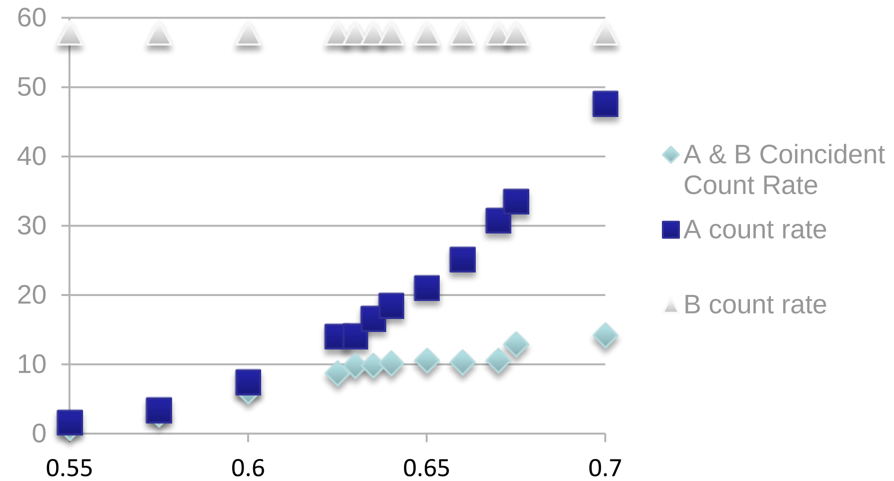
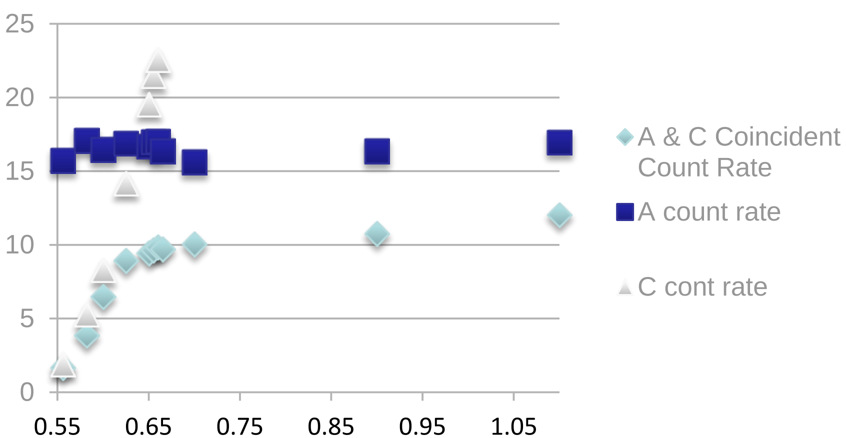
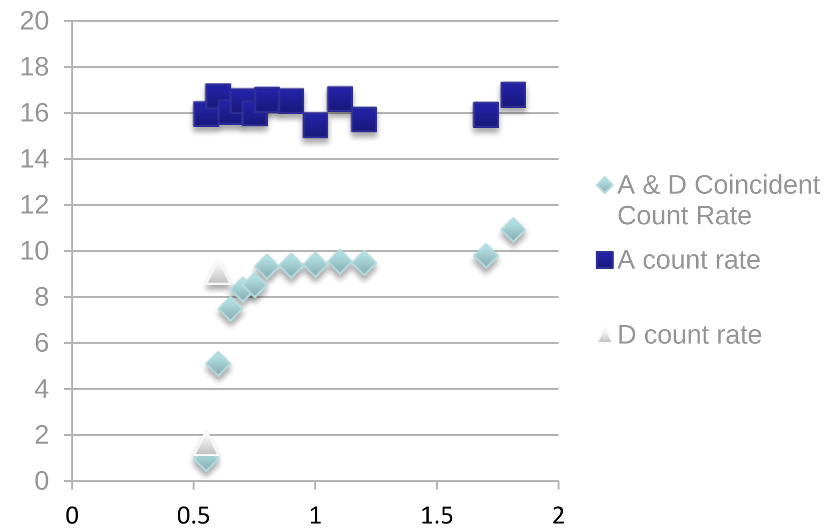
Calibration Graphs









Part I: Muons

Investigative Question

- What effect will increasing the height of shielding have on the flux of charged particles in the vertical direction?

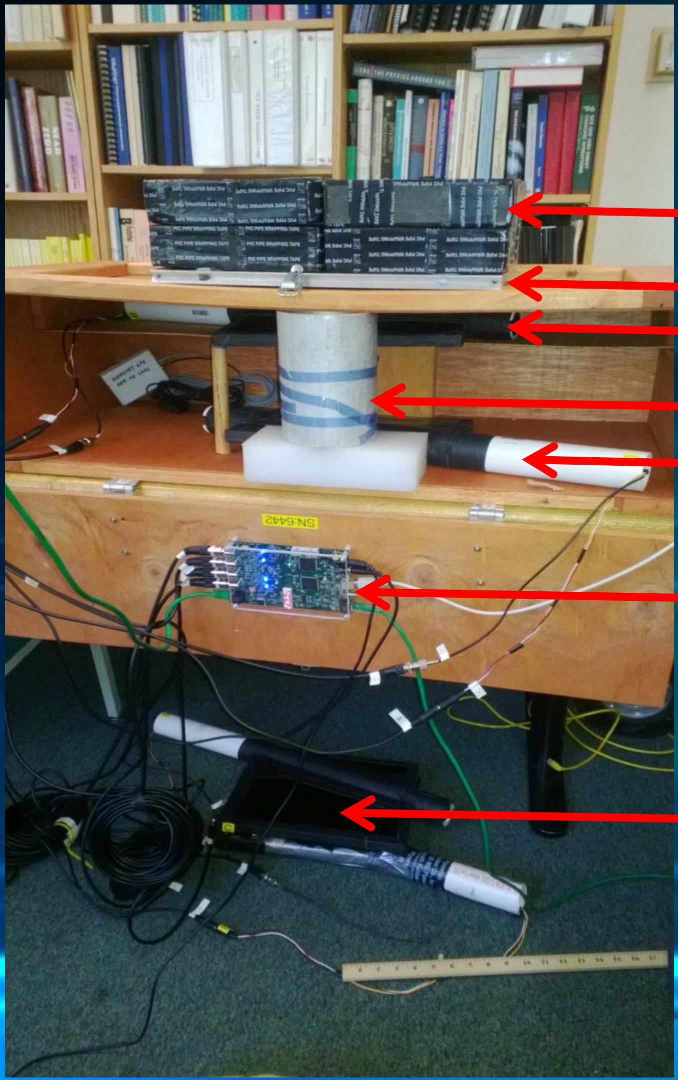
Hypothesis

- If the height of shielding is increased, the flux will decrease in a non linear fashion, because the energy distribution of the charged particles is not uniform.

Materials

- Wooden Box
- Table
- 4 Scintillators
- Scrap Metal Reinforcements
- 24 Lead Bricks
- 2 Pieces of Aluminum

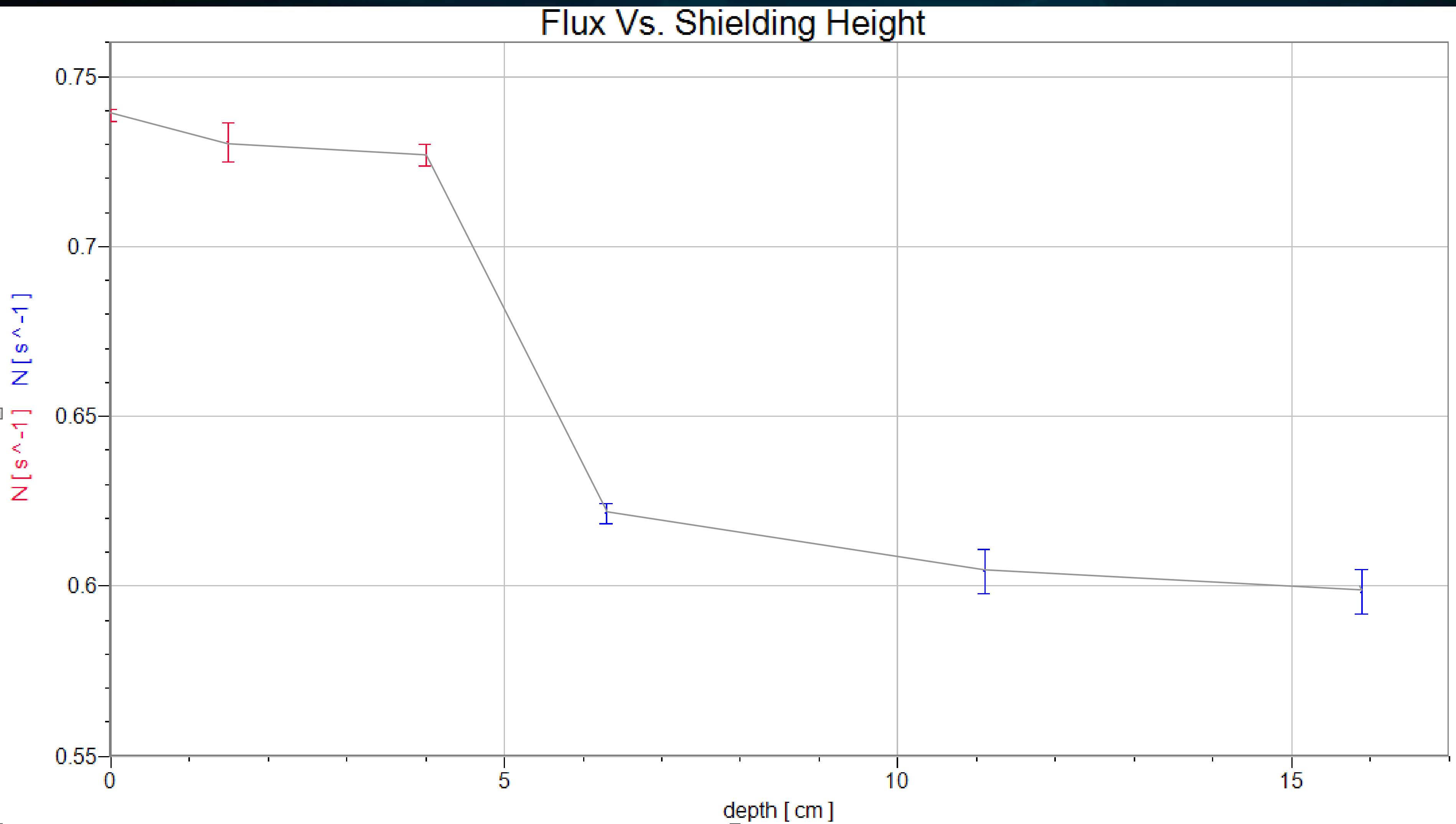
Experimental Setup

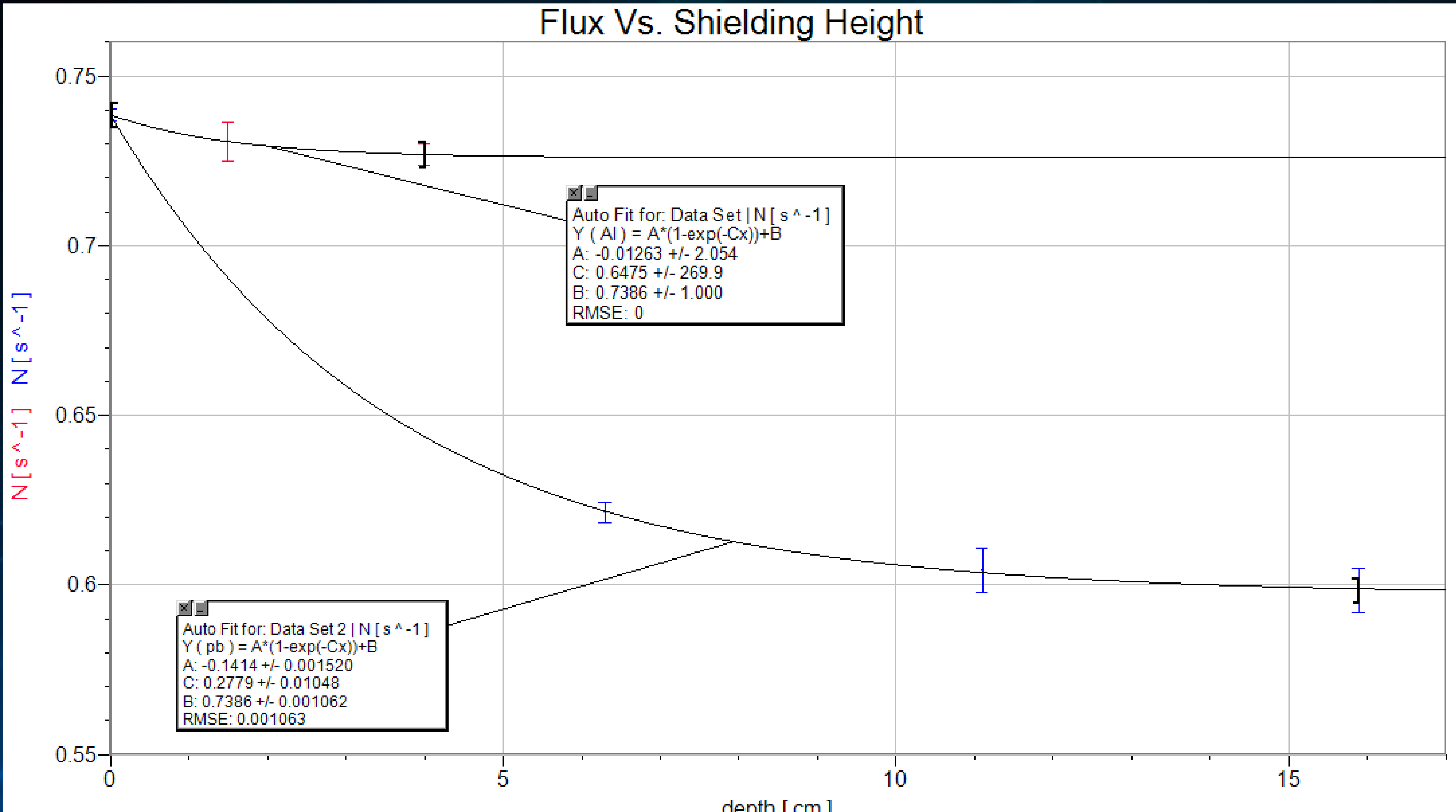


Lead
Aluminum Plate
Scintillator
Scrap Metal Reinforcement
Scintillator
DAQ Board
2 Scintillators

Procedure

1. Obtain materials and set up as shown in the experimental diagram (previous slide) but do not place any lead.
2. Connect the DAQ board to a computer, set all 4 detectors do coincidence settings, clear the count, and run a trial. To have reasonable error bars, be sure to run trials for 5 hours or more.
3. Repeat step 2 for 1 layer of aluminum, and 2 layers of aluminum. Then add 1, 2, and 3 layers of lead on top of the layers of aluminum, and repeat step 2 for each level of shielding.

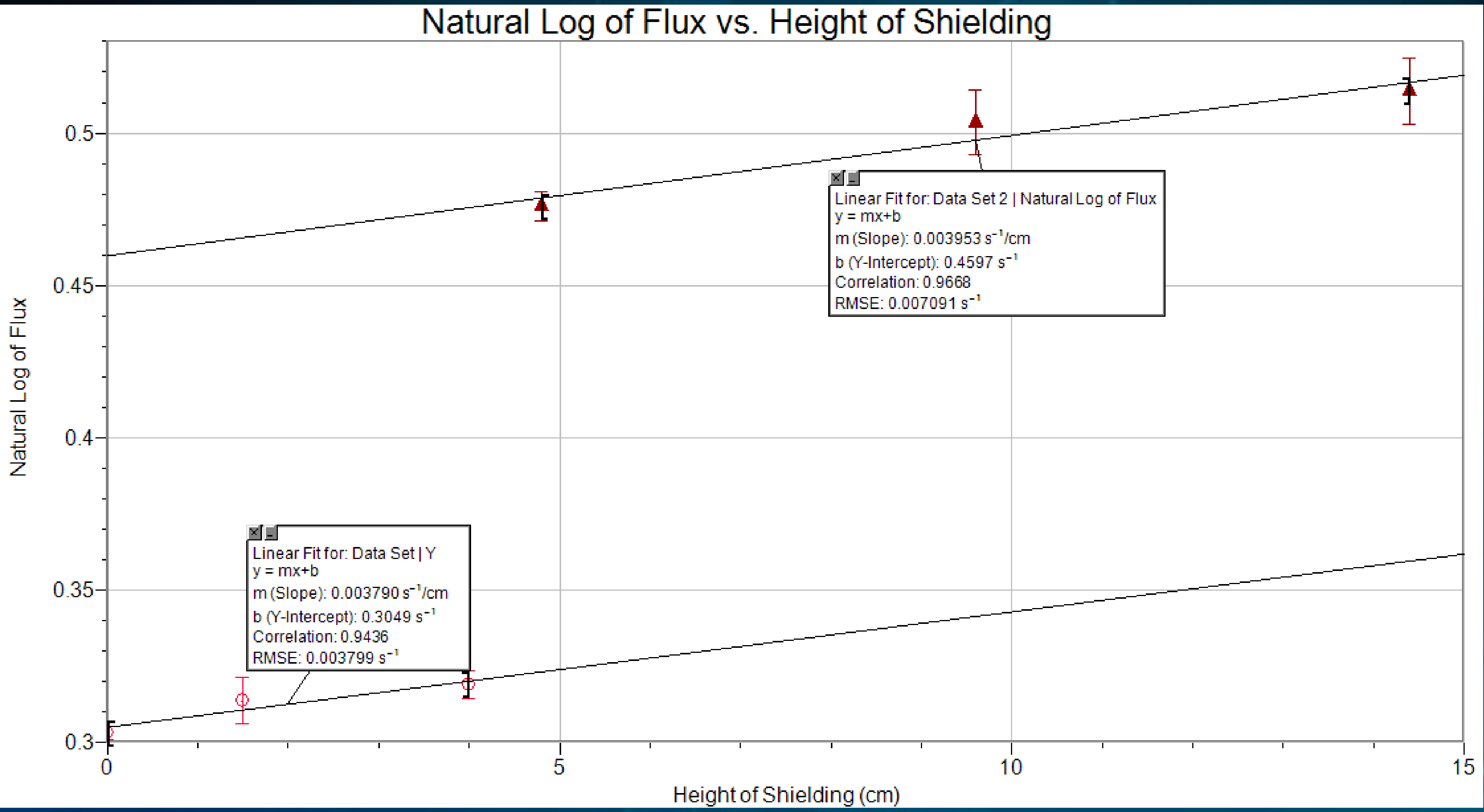

Flux Vs. Shielding Height
0.75
0.7
0.65
0.6
0.55
N [s ^ -1]
N [s ^ -1]
0
5
10
15
depth [cm]



Flux Vs. Shielding Height
Auto Fit for: Data Set | N [s ^ -1]
Y (Al) = A*(1-exp(-Cx))+B
A: -0.01263 +/- 2.054
C: 0.6475 +/- 269.9
B: 0.7386 +/- 1.000
RMSE: 0
Auto Fit for: Data Set 2 | N [s ^ -1]
Y (pb) = A*(1-exp(-Cx))+B
A: -0.1414 +/- 0.001520
C: 0.2779 +/- 0.01048
B: 0.7386 +/- 0.001062
RMSE: 0.001063
N [s ^ -1]
N [s ^ -1]
0.75
0.7
0.65
0.6
0.55
0
5
10
15
depth [cm]

Analysis

- The graph of flux vs. shielding height shows an inverse exponential relationship.



Natural Log of Flux vs. Height of Shielding
Natural Log of Flux
Height of Shielding (cm)
0.3
0.35
0.4
0.45
0.5
0
5
10
15
Linear Fit for: Data Set 2 | Natural Log of Flux
y = mx+b
m (Slope): 0.003953 s-1/cm
b (Y-Intercept): 0.4597 s-1
Correlation: 0.9668
RMSE: 0.007091 s-1
Linear Fit for: Data Set | Y
y = mx+b
m (Slope): 0.003790 s-1/cm
b (Y-Intercept): 0.3049 s-1
Correlation: 0.9436
RMSE: 0.003799 s-1

Analysis

<u>Particle Population Decay Equation:</u>

$$N = N_0 e^{-\alpha x}$$

Aluminum:

$$N = .73858 \pm .00133 e^{-.00379 \pm 00133 x}$$

$$\alpha = .003179 \pm .00133$$

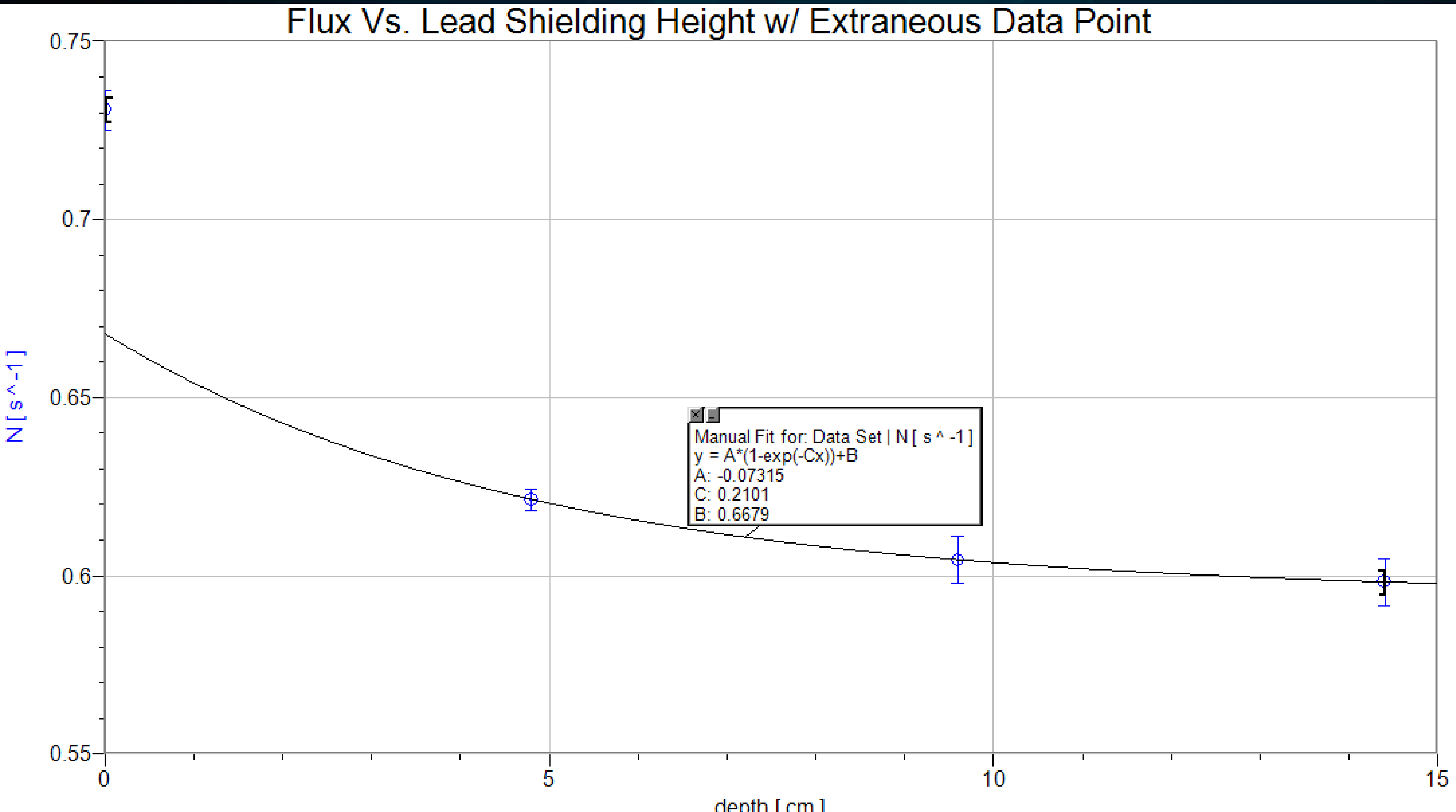
α = attenuation coefficient of aluminum

Lead:

$$N = .631473 \pm .0068 e^{-.003953 \pm .001045 x}$$

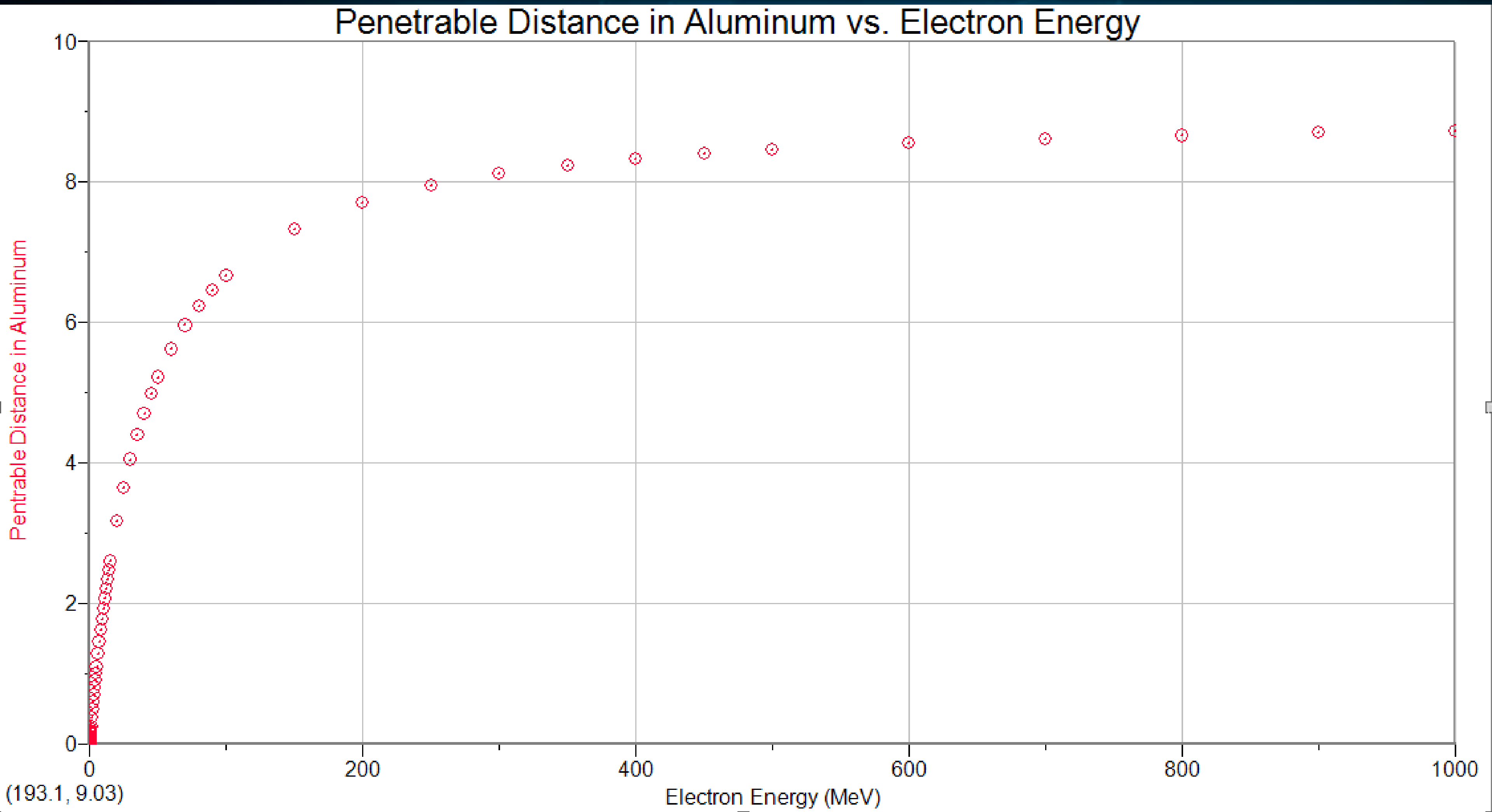
$$\alpha = .003953 \pm .001045$$

α = attenuation coefficient of lead

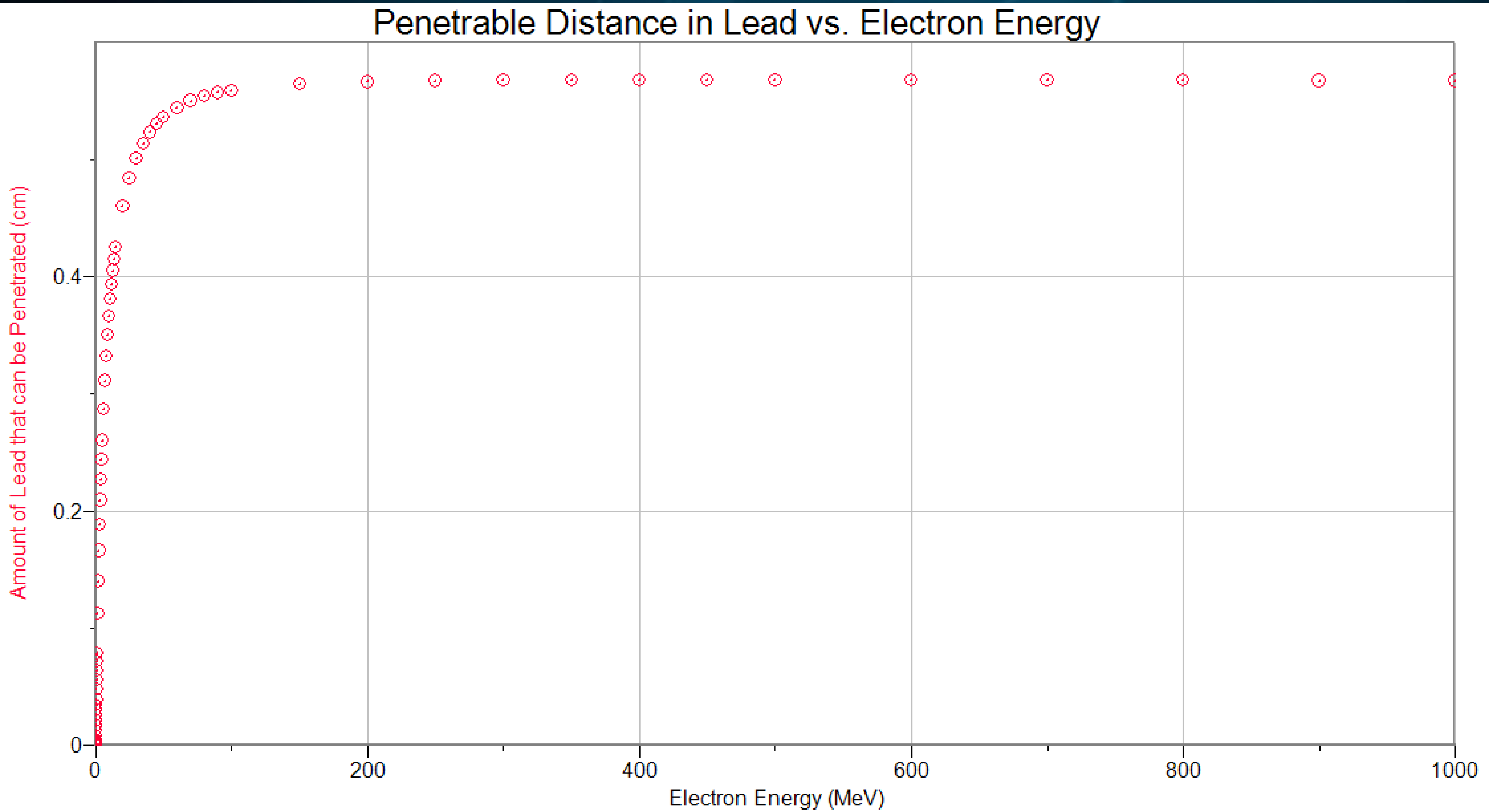

Flux Vs. Lead Shielding Height w/ Extraneous Data Point
0.75
0.7
0.65
0.6
0.55
N [s ^ -1]
0
5
10
15
depth [cm]
Manual Fit for: Data Set | N [s ^ -1]
y = A*(1-exp(-Cx))+B
A: -0.07315
C: 0.2101
B: 0.6679

Differentiating Particles

The initial flux (x=0) predicted by this equation is lower than the measured initial flux. Another way of saying this is that the first layer of shielding stopped a greater number of particles than would be predicted by the trend followed by subsequent layers of shielding. This implies the existence of a type of particle that was “seen”, or shielded, by only the first layer and therefore did not make it to the other layers of shielding. This particle would have to be at a lower energy than muons (the main constituent of cosmic showers) in order to be stopped by the first layer of shielding. Because both types of particles are traveling at similar relativistic speeds, lesser energy implies a lesser mass. The only fundamental lepton with a lower mass than the muon is the electron; therefore, this “new” particle seen only in the first layer of shielding must be the electron. We now know that cosmic showers consist of electrons and muons. We predict that there are also Tau particles; however, extremely extensive shielding is required to uncover that portion of the showers.



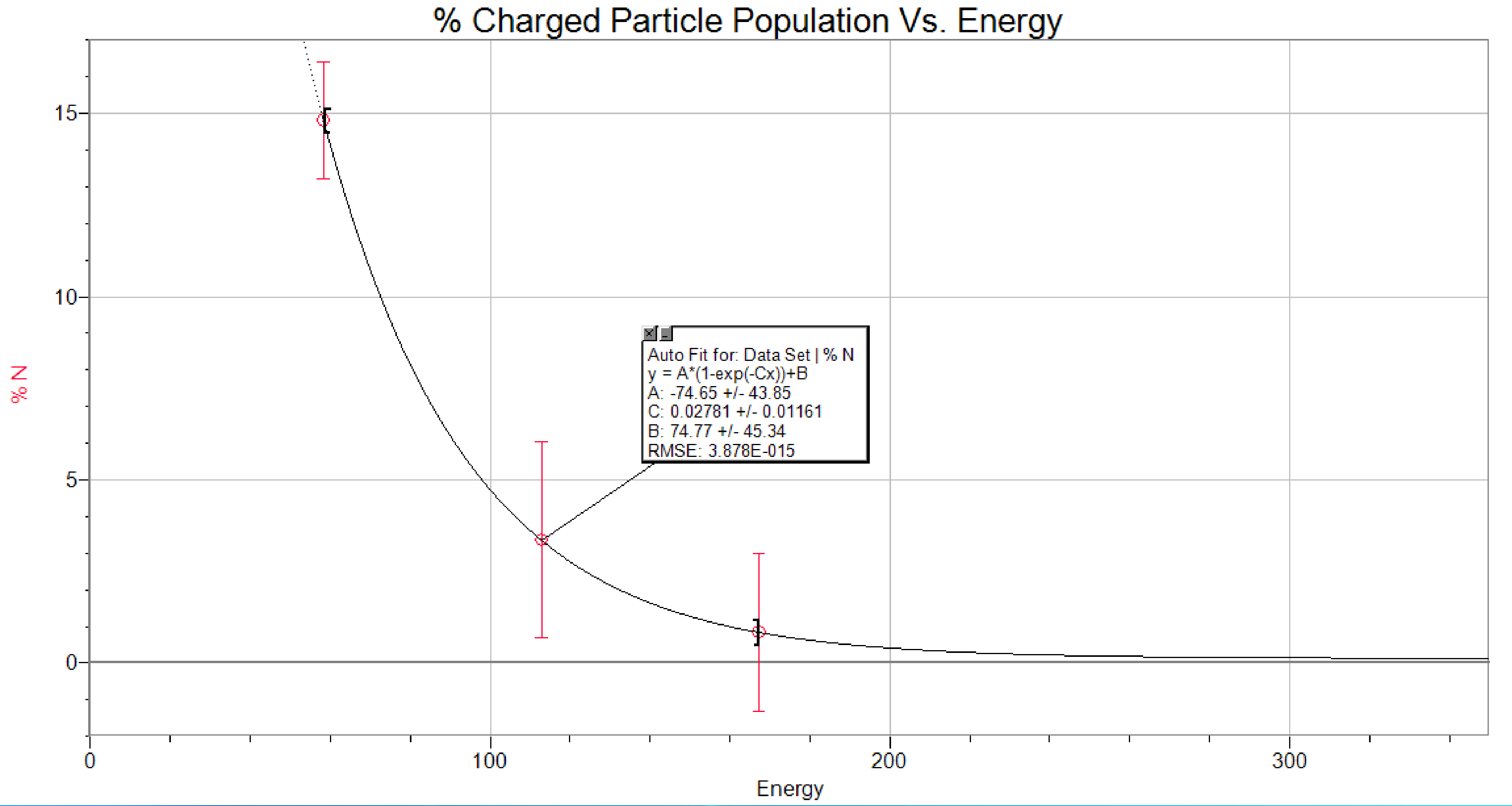
Penetrable Distance in Aluminum vs. Electron Energy
Pentrable Distance in Aluminum
Electron Energy (MeV)
0
2
4
6
8
10
200
400
600
800
1000
(193.1, 9.03)

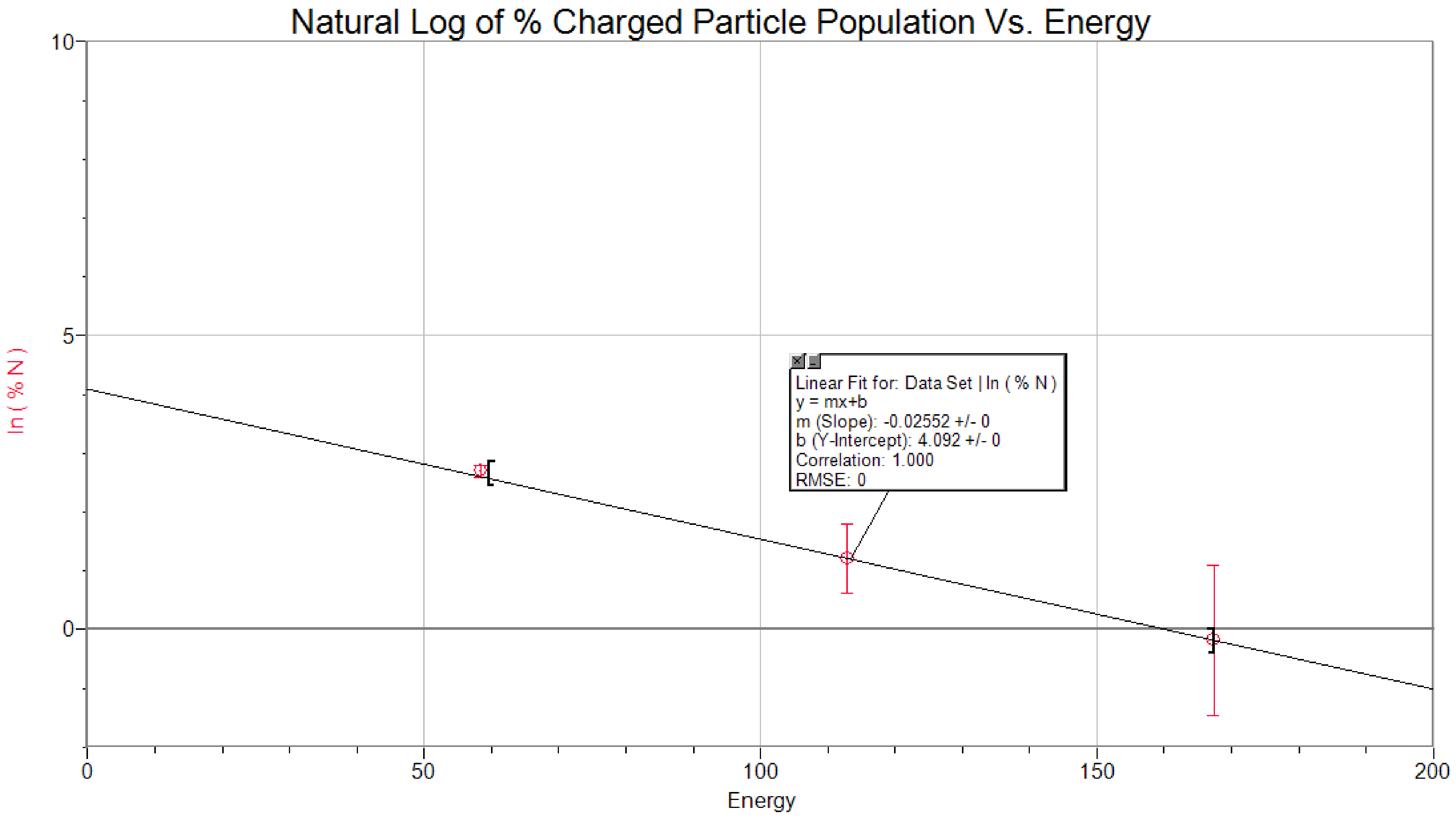

Penetrable Distance in Lead vs. Electron Energy
Amount of Lead that can be Penetrated (cm)
0
0.2
0.4
0
200
400
600
800
1000
Electron Energy (MeV)

$$\%N = \%N_0 e^{-kx}$$

$$\%N = 1.4e^{-.02552x}$$

%N = percent of charged particles with energy x
K = decay rate constant




Natural Log of % Charged Particle Population Vs. Energy
Linear Fit for: Data Set | ln (% N)
y = mx+b
m (Slope): -0.02552 +/- 0
b (Y-Intercept): 4.092 +/- 0
Correlation: 1.000
RMSE: 0
ln (% N)
Energy
10
5
0
0
50
100
150
200

Analysis

- Lower energy particles lose energy at a faster rate than higher energy particles. This is true because lower energy particles have a shorter relativistic lifetime than higher energy particles; furthermore, higher energy particles are moving at a slightly higher relativistic velocity, meaning they can travel through greater distances during their lifetime (before decaying).

$$E' = \gamma mc^2 - mc^2$$

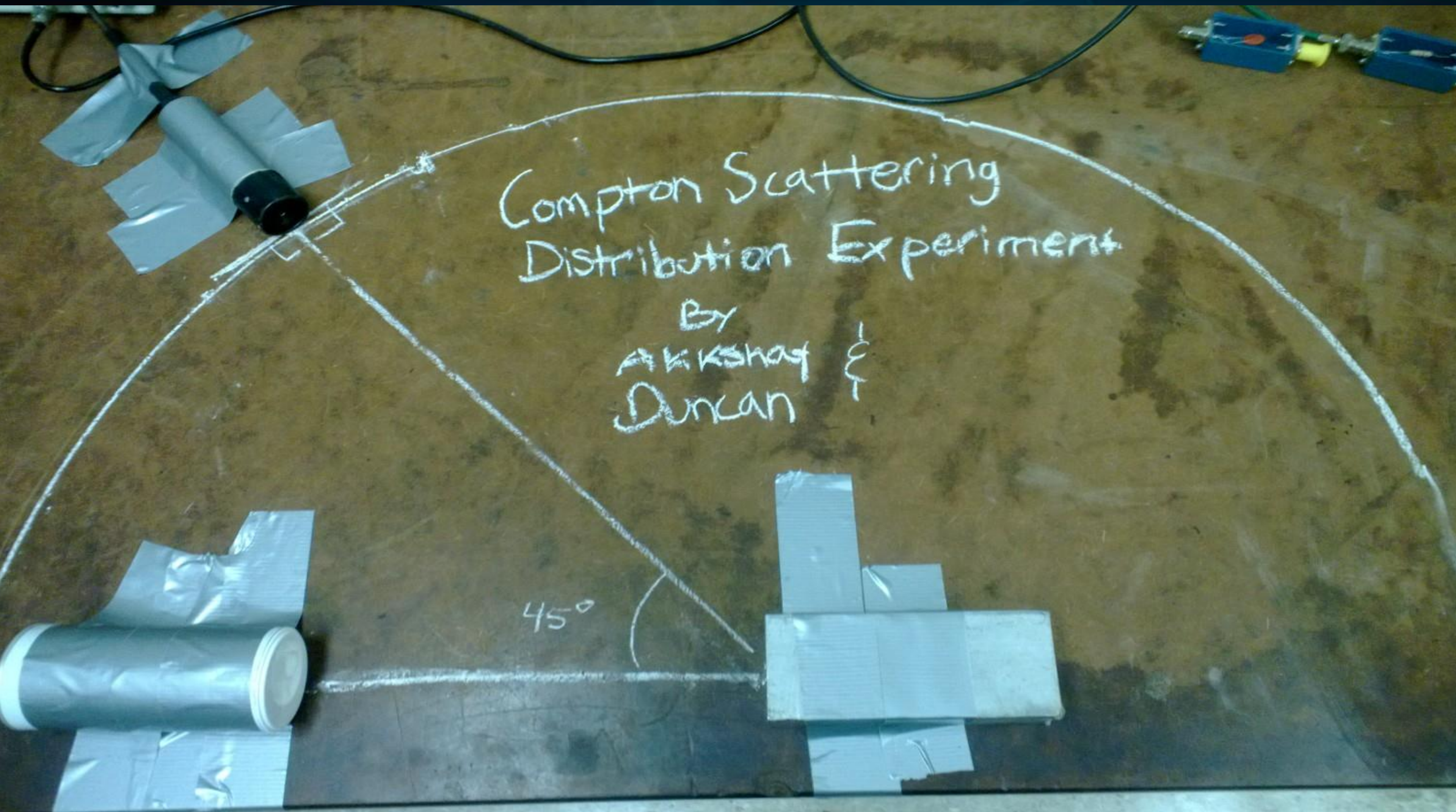
$$v' = c\sqrt{1 - \left(\frac{mc^2}{E + mc^2}\right)^2}$$

$$\Gamma' = \frac{1}{\sqrt{1 - \frac{v'^2}{c^2}}} \times \Gamma$$

Conclusion

Our hypothesis was proven correct. As the height of shielding increases, the flux of charged particles in the vertical direction decreases exponentially because there is a higher relative abundance of lower energy particles compared to higher energy particles.

Part II: Gamma Rays


Compton Scattering
Distribution Experiment
By
Akkshay &
Duncan
45°

Investigative Question

- What effect will changing the scattering angle have on the event rate of Compton Scattering?

Forming a Hypothesis

For our hypothesis, we wanted to predict the angular distribution of Compton Scattering so that we could later compare it to the distribution found by our experimental results.

The Differential Cross-Section

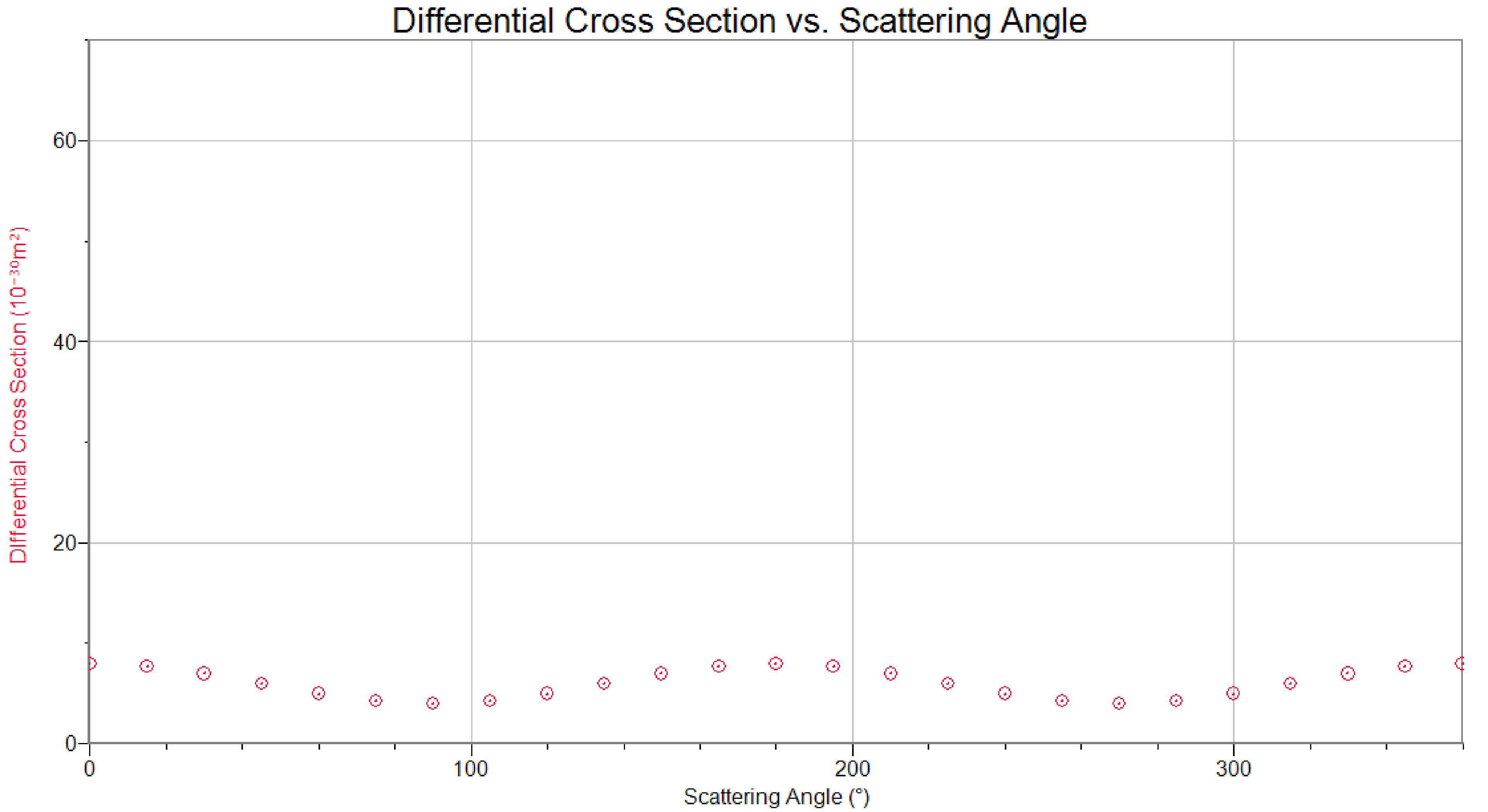
- The differential cross-section is the probability that an event will occur in a given area. For our purposes, we used it as a function of the scattering angle:

$$D(\theta) = \frac{d\sigma}{d\Omega}$$

Klein-Nishina Formula

$$D(\theta) = \frac{d\sigma}{d\Omega} = \frac{\alpha^2 r_c^2 P(E_\gamma,\theta)^2 \left[P(E_\gamma,\theta) + P(E_\gamma,\theta)^{-1} - 1 + cos^2(\theta)\right]}{2}$$

θ is the scattering angle
α is the fine structure constant
m_e is the rest mass of an electron
c is the speed of light
r_c is the reduced Compton wavelength of the emitted electron where $r_c = \frac{\hbar}{m_e c^2}$
ħ is Dirac's Constant where $\hbar = \frac{h}{2\pi}$
$P(E_\gamma, \theta)$ is the ratio of the energy of the photon after and before the interaction where
$P(E_\gamma, \theta) = \frac{1}{1+\left(\frac{E}{m_e c^2}\right)(1-\cos(\theta))}$



Differential Cross Section vs. Scattering Angle
Differential Cross Section ($10^{-30}m^2$)
60
40
20
0
0
100
200
300
Scattering Angle (°)

Predicted Count Rate Distribution

Since the predicted count rate (R) distribution is obtained by multiplying the differential cross section by the overall flux in all directions (scalar for our purposes), it should follow the same shape as the differential cross section distribution. Thus, we can use the differential cross section distribution to form our hypothesis.

$$R(\theta) \propto \varphi \frac{d\sigma}{d\Omega}$$

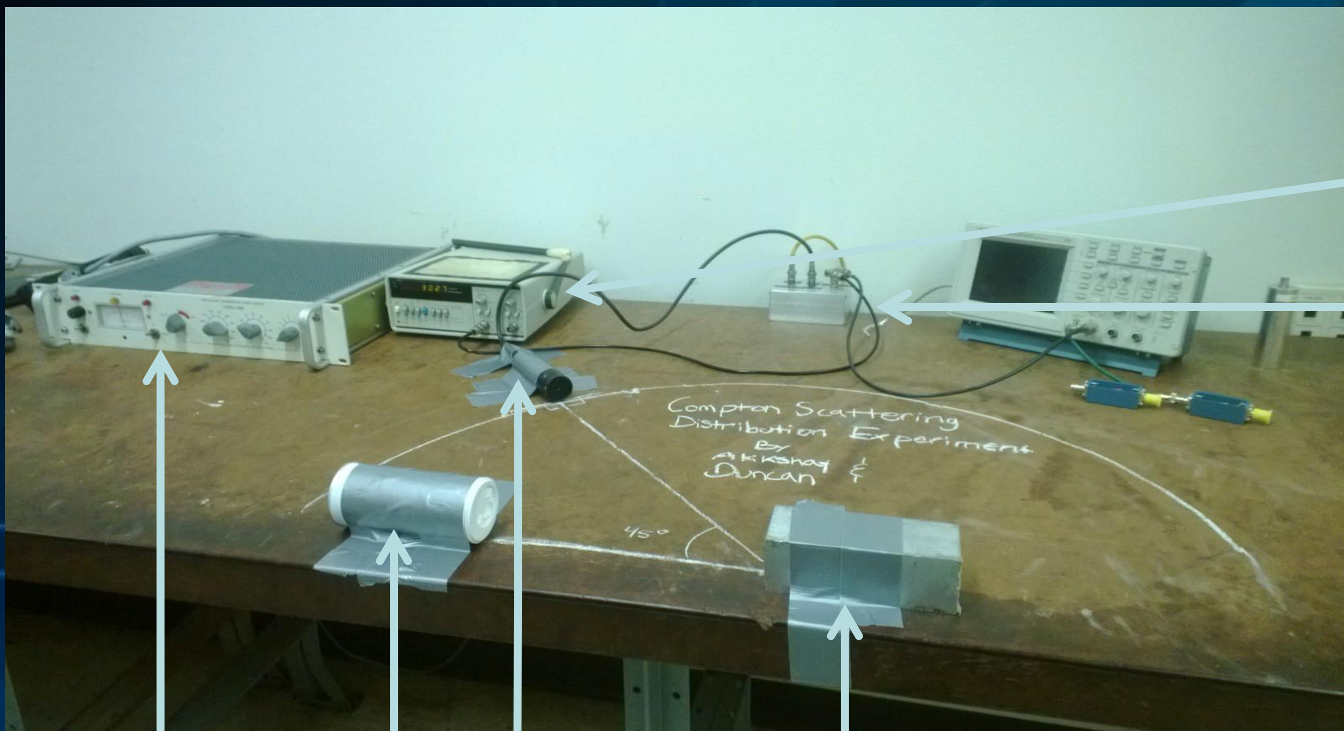
Hypothesis

- If the scattering angle increases, then the count rate will decrease as the angle approaches 90 degrees and increase as the angle approaches 180 degrees because the graph of the differential cross section distribution follows a cosine trend with a local minimum at 90 degrees.

Materials

- Potassium Chloride
- Aluminum Brick
- Geiger-Muller Tube
- High Voltage Calibrated DC Power Source
- Counter High Voltage Power Tube

Experimental Setup



Counter

High Voltage
Power Tube

High Voltage
Calibrated DC Power
Source

Potassium Chloride

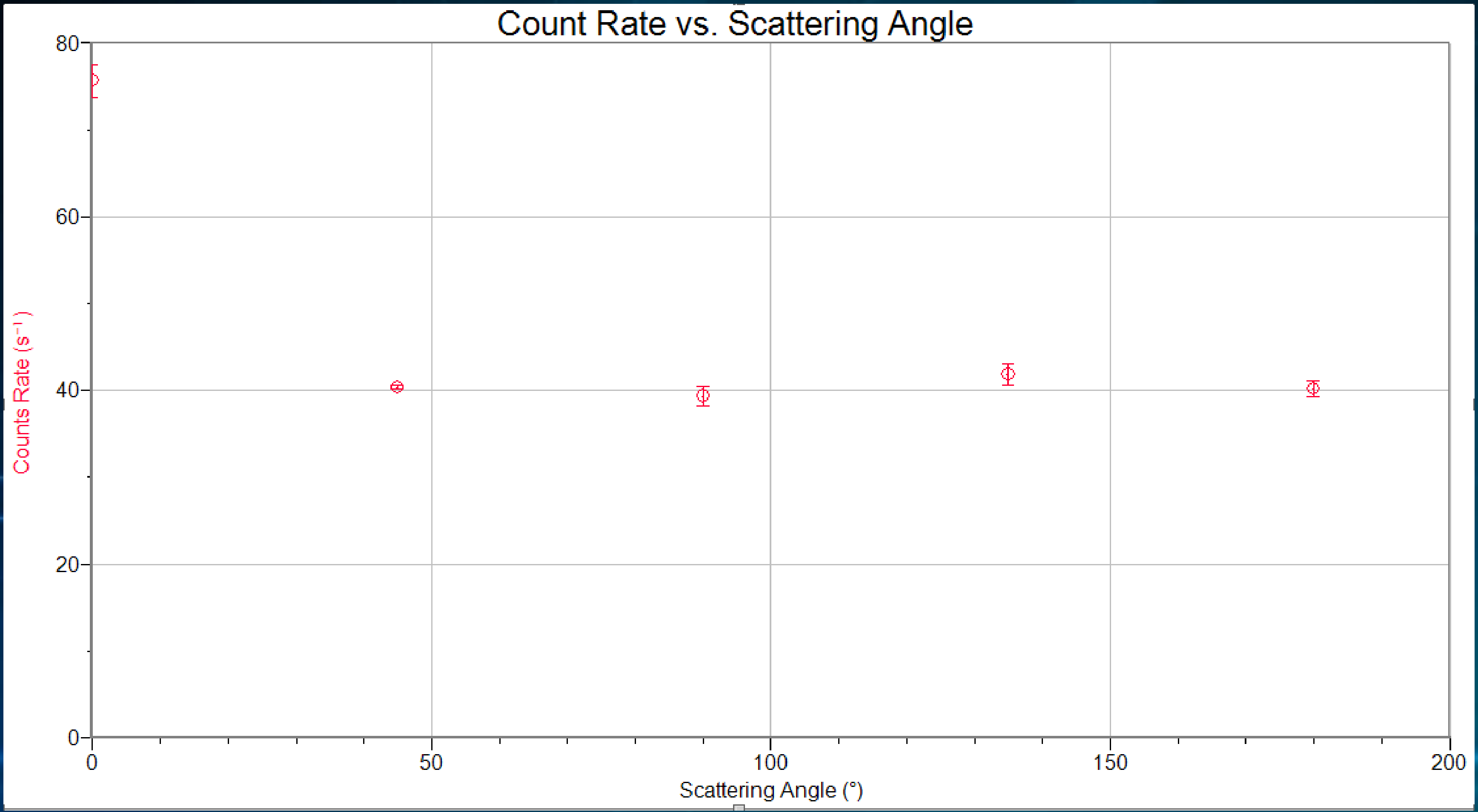
Geiger-Muller Tube

Aluminum Brick

Procedure

1. Set up the gamma ray source, aluminum scatter inducer, and Geiger counter as shown in the experimental setup (previous slide).
2. Connect Geiger-Muller tube to a high voltage power source set around 860 volts as well as an automatic count display.
3. Place the Geiger-Muller tube at an angle theta with respect to the aluminum and conduct a data run, making sure to record total counts detected over the run as well as the length of the run (in seconds).
4. Repeat step 3 for an array of angles from 0 to 180 degrees in intervals of 45 degrees.

Results



Count Rate vs. Scattering Angle
80
60
40
20
0
Counts Rate (s⁻¹)
0
50
100
150
200
Scattering Angle (°)

Analysis

- As the angle increases to 180 degrees, the count rate decreases in a non-linear fashion.
- The points between 45 and 180 degrees (inclusive) fluctuate sinusoidally.

Analysis

- The shape of the distribution does not match the shape of the differential cross section distribution.

But why?! Let’s take a closer look…

Analysis

$$R(\theta) \propto \varphi \frac{d\sigma}{d\Omega}$$

According to the proportionality, the count rate distribution should be some constant times the flux times the differential cross section. Originally, we hypothesized that the count rate distribution would follow the same trend as the differential cross section distribution because we treated the flux as a scalar. We treated the flux as a scalar because the overall flux in all directions should be the same. However, we neglected that the distance between the detector and the potassium chloride increases as our angle increases. Since this distance increases, the flux and distance should share an inverse square relationship.

Analysis

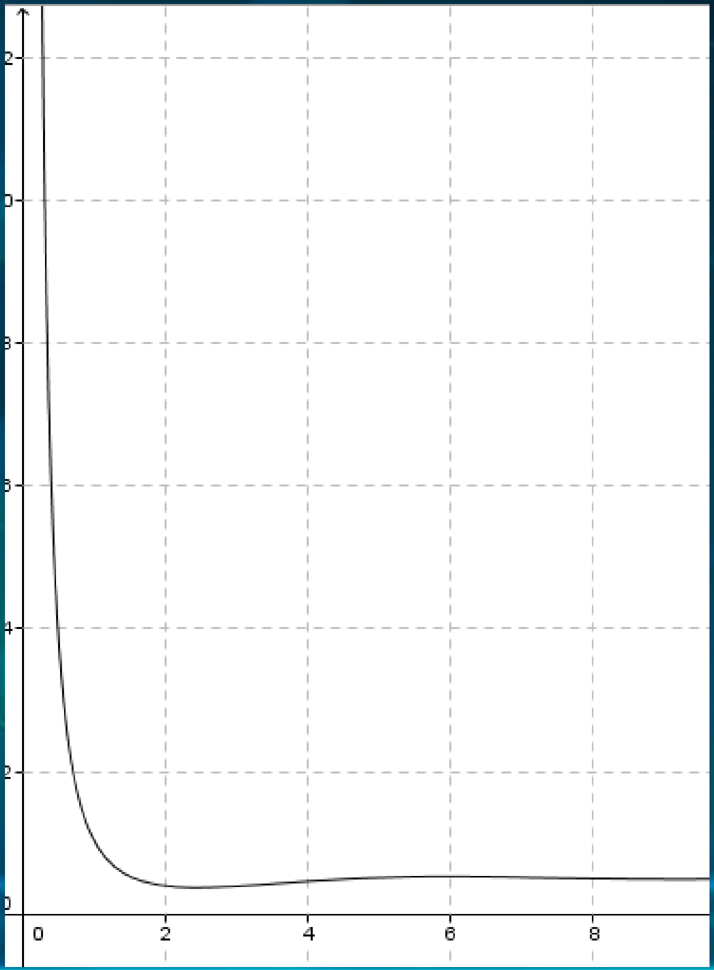
In order to obtain the count rate distribution, we needed to multiply the differential cross section (cosine graph) by the flux (inverse square graph). We can plot

$$\frac{\cos(x)}{x^2}$$

in order to get a better idea of what this looks like.

Analysis

The shape of the graph on the right now matches the shape of the count rate distribution we got from our experimental results.



Conclusion

Our hypothesis, that “If the scattering angle increases, then the count rate will decrease as the angle approaches 90 degrees and increase as the angle approaches 180 degrees” was disproven by our results. The reason was because our hypothesis was based off of a predicted distribution that treated flux as a scalar, when it is actually a variable that fluctuates with distance.

Where do we go from here?

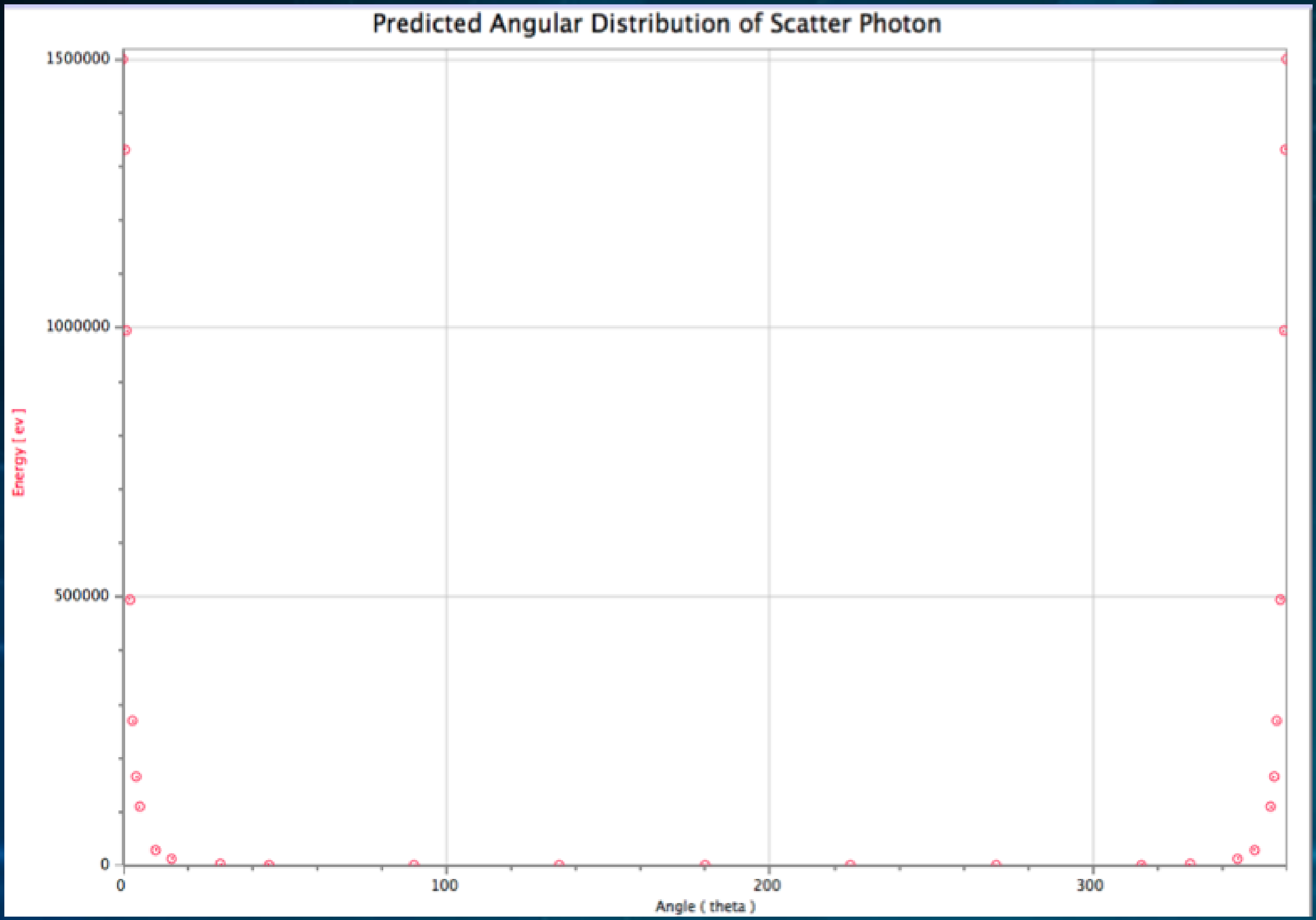
Compton Energy Distribution:

A sodium iodide detector is required to measure the energies of scattered photons/electron from a given deflection angle; however, this detector was unavailable to us. Fortunately, it is possible to calculate energy as a function of the deflection angle theta with the following equation derived from the Compton equation:

$$E_f = hf_f = \frac{m_e c^2 E_i}{E_i(1-\cos\theta) + m_e c^2}$$

$$E_e = \left| \frac{m_e c^2 E_i - E_i(E_i(1-\cos\theta) + m_e c^2)}{E_i(1-\cos\theta) + m_e c^2} \right|$$

Photon Energy Distribution



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