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PHY 460L H001 TEC 224
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Attenuation of Radiation through the absorption of Gamma Rays

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Introduction:

Radiation is a phenomena involving energy emission from subatomic particles as particles and electromagnetic waves. It was first discovered by Wilhelm Conrad Röntgen in 1895, during his experiments with cathode-ray tubes. Further discovers and contributions to the field came from Henri Becquerel, Ernest Rutherford, and both Perrie and Marie Curie in early 20th century. It was discovered that radiation is specific to a given element or its isotope, and occurs naturally in unstable atoms which radiated characteristic energies to form new stable atoms.

The intensity of a source of radionuclide is a measure of the number of nuclei decaying per unit time. This is directly proportional to the number of radionuclide present in the given sample, and thus the radioactivity decreases overtime as the amount of radionuclides decrease. The rate of decay for a radionuclide is generally expressed in terms of its half-life, which is simply the time for a given amount of the radioactivity to decrease to half. Decay processes often leave the sample nuclide in an excited energy state, which results in the nuclide falling directly to the ground state or descending in steps to lower energy states through the emission of energy as gamma radiation.

Gamma rays are photons of a very high-frequency electromagnetic wave. They are emitted in discrete energies corresponding to the energy state transitions a nuclide may undergo when in an excited state. Photons interact with matter in three different ways, through the photoelectric effect, through Compton scattering, and pair production. These processes shall be discussed in the theory section of this lab report. When Gamma rays impact an absorbing material, the radiation is absorbed or scattered. When only half of the incoming radiation passes through the absorber, the thickness of the absorber is called half thickness, denoted by $\mathbf{X_{1/2}}$. If the function of this absorption is plotted and a linear relationship is obtained, one can determine the mass attenuation coefficient for the material.

Lead is a chemical element with Z=82 and is denoted by the symbol Pb. The attenuation of lead and alloys of lead is of scientific interest as it is a cheap and malleable metal. It's high density of 11.34g/cm^3 and relatively high gamma attenuation coefficients allow for thin layers to achieve high attenuation compared to other shielding materials [3]. For the energy level used in our experiment of 662 keV (Cs-137), the mass attenuation coefficient of lead is expected to be 0.1136 g/cm^2.[2]

Theory:

Gamma rays (γ-ray) are photons of energies higher than 100 keV. In the electromagnetic spectrum below, they are shown as photons with a frequency higher than 10^{18} hertz.

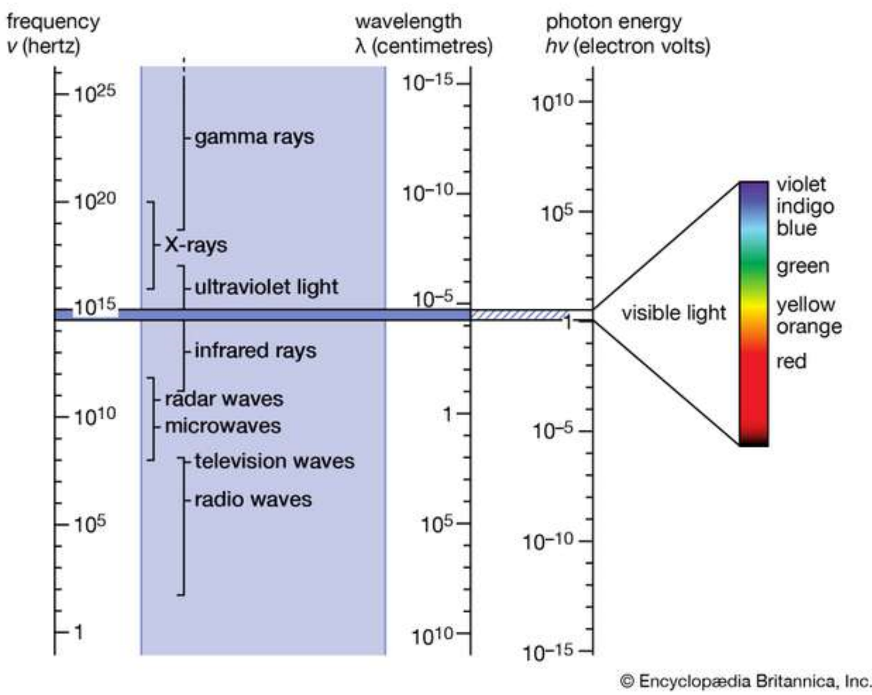

Figure 1: The Electromagnetic Spectrum [1]

Photons interact with matter in three different ways, the photoelectric effect, Compton scattering and pair production. The photoelectric effect is when the incident photon is of a high enough energy to release electrons from atoms and molecules in the absorbing material. The maximum energy of the ejected electron is given by:

$$KE_{max} = E_{\gamma} - \Phi \qquad (1)$$

Where E_{γ} is the energy of the incident photon and Φ is the work function.

The second way is through Compton scattering, in which an interaction occurs between the incident photons and the free electrons. The former transfers some of its energy through an inelastic collision and gains a new energy. The last interaction is pair production, in which a positron and electron collide, they annihilate each other and produce photons.

To investigate the attenuation of gamma rays through a known material, firstly a radiation source of known energy is needed. For this experiment, a Caesium-137 source is used. The Caesium nucleus can decay into a more stable nucleus through two different means as shown in the energy level diagram below.

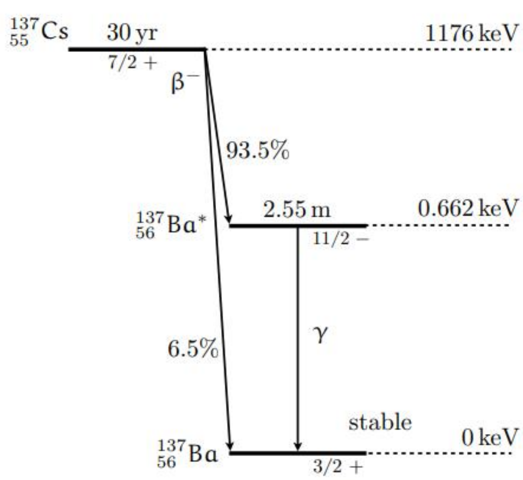

Figure 2: Caesium 137 energy level diagram [6]

The most likely decay is firstly to a meta-stable Ba-137 and then to a stable Ba-137, by emitting 662 keV of energy.

The attenuation of gamma rays itself is exponential in nature and follows the equation;

$$I=I_o e^{-\mu X} \qquad (2)$$

Where I is the intensity of the beam after having passed through X length of material, I_o is the original intensity, μ is the linear attenuation coefficient, and X is the mass thickness. The logarithmic relationship between intensity and thickness, when plotted against each other will give the linear attenuation coefficient as the slope of the natural log of intensity vs thickness as shown in the following **Figure 3.**

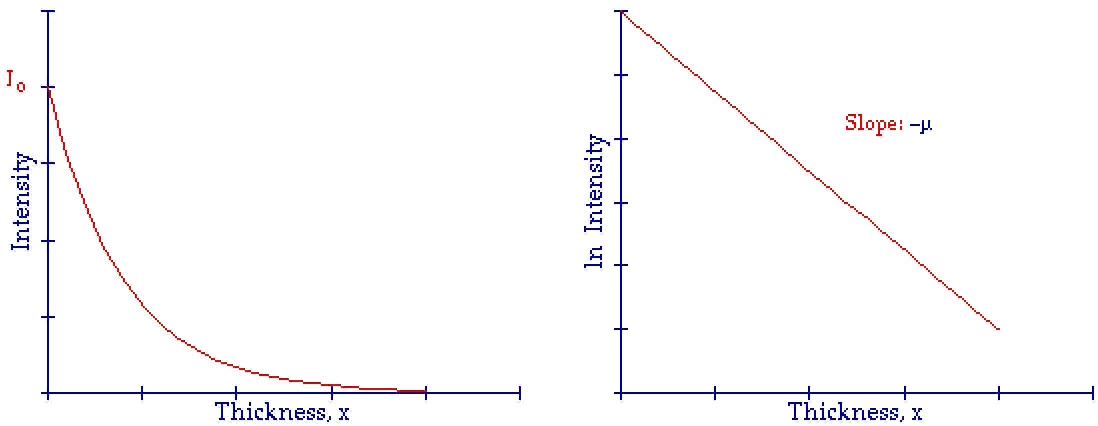

Figure 3: Intensity (I_0 and *ln*(I_0)) vs Thickness (X) plots.[7]

Furthermore, factoring in the fact that the original intensity is cut in half when the gamma rays passes through the $X_{1/2}$ we can rewrite equation *(2)* as;

$$\tfrac{1}{2}\, I=I_o e^{-\mu X_{1/2}} \qquad (3)$$

Then taking the natural log of both sides, and using the rule of exponents we get;

$$\mu = ln(2)/X_{1/2} \qquad (4)$$

Thus we can also determine the value of μ by experimentally by finding $X_{1/2.}$ The mass attenuation coefficient is then the ratio of the linear attenuation coefficient and the materials density.

$$\text{Mass attenuation coefficient} = \mu / \rho \qquad (5)$$

To measure the intensity of radiation, we use a Geiger–Müller counter. The Geiger–Müller counter is an instrument that detects ionizing radiation which includes alpha, beta and gamma radiations.

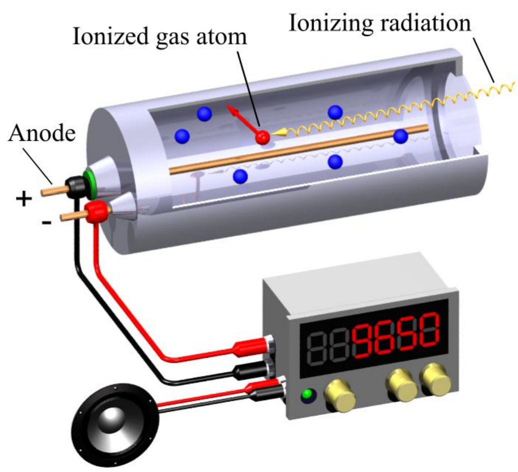

Figure 4: Schematic of a Geiger counter [4]

As shown in the schematic in **Figure 4**, the tube of the GM counter consists of an airtight metallic cylinder closed at both ends and filled with an easily ionized gas, there is a thin conducting wire along the middle that is set to a high positive electric potential. Any incoming radiation that penetrates the tube through the window of the tube ionizes a number of atoms in the gas, which are then attracted to the wire in the middle of the tube. The acceleration caused by the potential difference in the tube further energizes the electron and its collisions with other atoms in the gas creates what's known as an "avalanche", which can be detected as a pulse of current. These pulses can be counted with a radiation counter of fed into an audio device to emit sounds corresponding to the number of counts. For our experiment, we will be using a digital Radiation Counter.

The Geiger–Müller tube's voltage has a characteristic curve as seen in the following **Figure 9.**

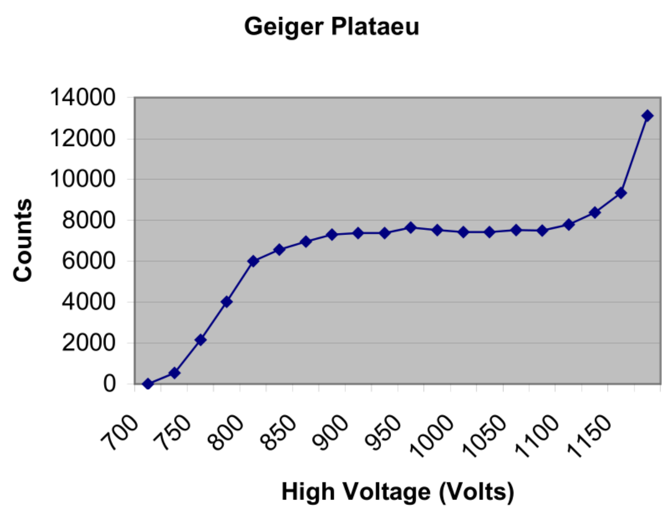

Figure 9: A plateau graph for a Geiger–Müller counter. [5]

Not all Geiger–Müller counters operate with exact characteristics as they can be constructed in various ways. Given this, each Geiger–Müller counter has a different optimal voltage which is important to be determined for optimal performance of the counter.

The Geiger–Müller tube has limited capability of differentiating between two electrons "avalanche" vs one significant one as it takes some time for it to resent after a single detection. This resolving time can be calculated by measuring radiation of sources independently and then simultaneously while not changing the geometric configurations and positions. Once the radiation counts are obtained, the resolving time can be calculated using the following equation

$$T = (r_1+r_2-r_3)/\ (2\ r_1r_2) \qquad (6)$$

Where r_1 is the radiation counts for the first source, r_2 the second source and r_3 both sources combined.

Also, if radiation particles are emitted uniformly in all directions from the source then there is a possibility that the Geiger–Müller counter will be unable to count it. The efficiency of the Geiger–Müller counter must be calculated to get a better idea of how significant this error is.

The radiation counter will thus need to be configured to determine the optimal voltage, resolving time and efficiency before we begin attenuation experiments.

Experiment:

Equipment used:

i) SPECTECH ST360 Counter USM 233386 **Figure 5**

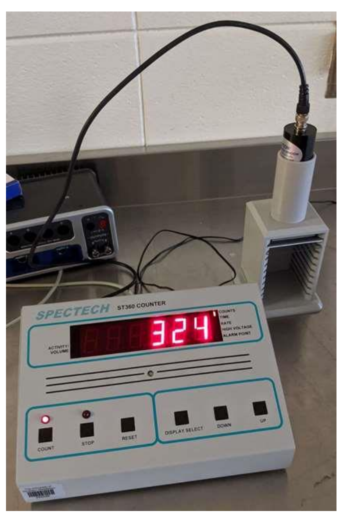

Figure 5

ii) Spectrum Techniques Calibrated Absorber Set Model RAS20 **Figure 6**

Figure 6

a. Lead (0.032-0.25)

iii) Geiger –Mueller Counter **Figure 7**

Figure 7

iv) Radiation Sources **Figure 8**

Figure 8

v) Spectrum Tech ST360 Program

Procedure:

Some key functions of the radiation counter were firstly noted. The most relevant ones were the high voltage functions, preset times, preset number of runs and the step voltage function. It is recommended that one become familiarized with these before starting.

A) Geiger–Müller Plateau

First a radioactive sample was placed directly underneath the Geiger–Müller tube in the first slot and the voltage of tube was gradually increased using “step-up” voltages, which was simply increased applied voltage at 20V in certain pre-defined steps. This was further done for certain intervals of time, in our case 30 seconds. Once the “avalanche” occurred inside the tube, as seen by a significant rise in counts, the number of counts gradually increased. The counting rate eventually stabilized and a plateau was obtained by plotting the voltage against the number of counts. Upon further inspection of the high voltage of the tube, by obtained the voltage through a connected multi-meter rather than the numeric indicator in the radiation counter, some discrepancy was noted as the voltages shown in the counter were not the same as the multi-meter. A graph between the shown voltages in each instrument was then obtained plotted.

B) Background Radiation

To obtain background radiation counts, the Geiger–Müller was operated at the optimal voltage without any radiation sources in the well of the tube. This was done with the same preset-time and number of runs so a more accurate estimation could be obtained.

C) Determine Resolving Time

To determine the resolving time of the Geiger–Müller counter, two sources of radiation are needed. Ideally, two half-circle sources of radiation that can be geometrically aligned inside the well of the tube, along with a half-circle empty source to establish the resolving or dead time of the counter. Due to the unavailability of sources of the specific geometry, a crude means of establishing the resolving time was used. First a measurement for background radiation was done at the optimal voltage as a preset time of 100 seconds. This was followed by a measurement of the Cs-137 source positioned at one end of the source container, mounted on the second shelf of the well for the same counter parameters. The Cs-137 source was then removed, and a Co-60 source was placed on the opposite end of the square source holder. After the Co-60 measurement, both sources were mounted in their previous positions and the radiation emitted by both simultaneously was measured. The dead time was then calculated by using equation *(6)*.

D) Geiger–Müller Counter Efficiency.

To calculate the efficiency of the Geiger–Müller counter, one each of an alpha, beta, and gamma sources were obtained. As per the recommendation of the manual Po-210, Sr-90 and Co-60 were selected. First the background radiation was calculated for the optimal voltage and a present time for 60 seconds. Then the radiation of all the above mentioned sources were measured for the same parameters and recorded. The disintegration rate of the sources was converted from microCuries (µ.Ci) to disintegrations per minute (dpm) using the conversion factor 1 (µ.Ci) = 2.2x106 (dpm) [5]. and tabulated. After adjusting for the background radiation and the resolving time of the Geiger–Müller counter, the counts were compared to disintegration rate and the efficiency rate was calculated.

E) Linear attenuation for Lead (Pb)

a. Procedure One:

Background radiation was measured for 60 seconds at the optimal voltage and recorded, followed by a Cs-137 radiation sample measured on its own by placing it in the second shelf of the Geiger–Müller tube. Then lead slabs of thickness 0.038 inch, 0.064 inch, 0.125 inch, and 0.25 inch were placed in the first shelf of the well for 60 seconds each. These steps were repeated for five times and the counts were averaged. The recorded counts were adjusted for the background radiation, the dead time, and then plotted against the thickness of the slabs. The linear attenuation coefficient was calculated using equation *(4)*. Then the natural log of the counts was plotted against the thickness, and the slope obtained was also recorded as the linear attenuation coefficient.

b. Procedure Two:

Background radiation was measured for 60 seconds at the optimal voltage and recorded, followed by a Cs-137 radiation sample measured on its own by placing it in the fifth shelf of the Geiger–Müller tube. Then lead slabs of thickness 0.038 inch, 0.064 inch, 0.125 inch, and 0.25 inch were placed in the fourth shelf of the well for 60 seconds each. The recorded counts were adjusted for the background radiation, the dead time, and then plotted against the thickness of the slabs. The linear attenuation coefficient was calculated using equation *(4)*. Then the natural log of the counts was plotted against the thickness, and the slope obtained was also recorded as the linear attenuation coefficient.

a. Procedure Two:

Background radiation was measured for 60 seconds at the optimal voltage and recorded, followed by a Cs-137 radiation sample measured on its own by placing it in the fifth shelf of the Geiger–Müller tube. Then lead slab of thickness 0.038 inch was placed in the fourth shelf, followed by the 0.064 inch slab in the 3rd shelf. After the counts were recorded, the 0.125 inch slab was placed in the second shelf and radiation was counted again. After this the 0.25 inch slab was placed in the first shelf of the well and radiation was calculated using similar parameters. The recorded counts were adjusted for the background radiation, the dead time, and then plotted against the varying thickness of the mixture of slabs. The linear attenuation coefficient was calculated using equation *(4)*. Then the natural log of the counts was plotted against the thickness, and the slope obtained was also recorded as the linear attenuation coefficient.

F) Mass attenuation of Lead (Pb)

The linear attenuation coefficient's were used to calculate the mass attenuation coefficient for lead by using equation *(5)* and were then compared to the actual value.

Data:

Data for Geiger–Müller Plateau:

Description	Caesium 137		
Number of Runs	26		
Preset Time	30		
Pause Time	0		
Alarm Level	0		
High Voltage	700		
Step Voltage	20		
Volume	0		
Run	High		Elapsed
Number	Voltage	Counts	Time
1	700	0	30
2	720	0	30
3	740	0	30
4	760	0	30
5	780	0	30
6	800	1170	30
7	820	1232	30
8	840	1310	30
9	860	1298	30
10	880	1411	30
11	900	1453	30
12	920	1463	30
13	940	1516	30
14	960	1539	30
15	980	1637	30
16	1000	1678	30
17	1020	1654	30
18	1040	1628	30
19	1060	1730	30
20	1080	1672	30
21	1100	1801	30
22	1120	1828	30
23	1140	1787	30
24	1160	1793	30
25	1180	1854	30
26	1200	1858	30

Data for Geiger–Müller counter resolving time:

Description	Determine Resolving Time						
Number of Runs	1						
Preset Time	100						
Pause Time	0						
Alarm Level	0						
High Voltage	1200						
Step Voltage	0						
Volume	0						
Run	High		Elapsed	Corrected			
Number	Voltage	Counts	Time	Background	Counts of:		
1	1200	75	60		Background		
2	1200	3169	100	3094.00	Cs		R1
3	1200	2486	100	2411.00	Co		R2
4	1200	5549	100	5474.00	Cs+Co		R3
				Dead Time:	2.07785E-06		
					20.77849932	milliCurie	

Data for Geiger–Müller tube efficiency:

Description	Efficiency Calculations					
Number of Runs	1		K=	2.20E+06		
Preset Time	60		conversion from µ Ci to dpm			
Pause Time	0					
Alarm Level	0		Dead Time=	0.000001		
High Voltage	1200		Background C=	26		
Step Voltage	0					
Volume	0					
Radiation Source:		Activity (µ.Ci)	Converting activity to dpm	Counts adjusted for Dead time	Counts adjusted for background	% efficiency
Co-60	2663	1	2200000.00	2670.110504	2644.110504	0.12
Po-210	4519	0.1	220000.00	4539.514064	4513.514064	2.05
Sr-90	4013	0.1	220000.00	4029.169055	4003.169055	1.82
					Average eff %	1.33

Data for Mass Attenuation Coefficient

Procedure One:

Description	Pb attenuation							
Number of Runs	1							
Preset Time	60							
Pause Time	0							
Alarm Level	0			Dead Time=	0.00002			
High Voltage	1200			Background	24.8			
Step Voltage	0			Counts				
Volume	0			Average=				

Element	Actual thickness (cm)	Mass thickness (mg/cm^2)	Counts	Res. Corr Counts	Bkgd Corr. Counts	LN of counts	Average Counts	Average LN Counts
Cs-137			2300	2410.9	2386.1	7.777		
Cs-137			2311	2423.0	2398.2	7.782		
Cs-137	0.000	0	2261	2368.1	2343.3	7.759	2392.5	7.780
Cs-137			2322	2435.1	2410.3	7.788		
Cs-137			2335	2449.4	2424.6	7.793		
Cs-137			2201	2302.3	2277.5	7.731		
Cs-137			2176	2275.0	2250.2	7.719		
Cs-137	0.097	1031.3	2238	2342.9	2318.1	7.748	2292.2	7.737
Cs-137			2258	2364.8	2340.0	7.758		
Cs-137			2199	2300.2	2275.4	7.730		
Cs-137			1551	1600.7	1575.9	7.363		
Cs-137			1561	1611.3	1586.5	7.369		
Cs-137	0.163	1878.3	1550	1599.6	1574.8	7.362	1594.6	7.374
Cs-137			1560	1610.2	1585.4	7.369		
Cs-137			1621	1675.3	1650.5	7.409		
Cs-137			1610	1663.6	1638.8	7.402		
Cs-137			1598	1650.8	1626.0	7.394		
Cs-137	0.318	3721.8	1627	1681.7	1656.9	7.413	1653.3	7.410
Cs-137			1643	1698.8	1674.0	7.423		
Cs-137			1640	1695.6	1670.8	7.421		
Cs-137			1173	1201.2	1176.4	7.070		
Cs-137			1157	1184.4	1159.6	7.056		
Cs-137	0.635	7413.8	1194	1223.2	1198.4	7.089	1173.5	7.067
Cs-137			1223	1253.7	1228.9	7.114		
Cs-137			1104	1128.9	1104.1	7.007		

Procedure Two:

Description	Pb attenuation				
Number of Runs	1				
Preset Time	60				
Pause Time	0				
Alarm Level	0			Dead Time=	0.00002
High Voltage	1200			Background Counts Average=	26
Step Voltage	0				
Volume	0				
Element	Actual thickness (cm)	Counts	Res. Corr Counts	Bkgd Corr. Counts	LN of counts
Cs-137	0.000	914	931.02	905.02	6.808
Cs-137	0.097	690	699.66	673.66	6.513
Cs-137	0.163	728	738.76	712.76	6.569
Cs-137	0.259	555	561.23	535.23	6.283
Cs-137	0.318	536	541.81	515.81	6.246

Procedure Three:

Description	Pb attenuation				
Number of Runs	1				
Preset Time	60				
Pause Time	0				
Alarm Level	0			Dead Time=	0.00002
High Voltage	1200			Background Counts Average=	26
Step Voltage	0				
Volume	0				
Element	Actual thickness (cm)	Counts	Res. Corr Counts	Bkgd Corr. Counts	LN of counts
Cs-137	0.000	914	931.02	905.02	6.808
Cs-137	0.097	690	699.66	673.66	6.513
Cs-137	0.163	728	738.76	712.76	6.569
Cs-137	0.259	555	561.23	535.23	6.283
Cs-137	0.318	536	541.81	515.81	6.246
Cs-137	0.577	391	394.08	368.08	5.908
Cs-137	0.635	390	393.07	367.07	5.906
Cs-137	1.212	213	213.91	187.91	5.236

Results and Calculations:

The optimal voltage was initially found to be around 900V given the GM plateau, but noticing the difference between the actual output voltage and the shown voltage, 1200V was used as the "high voltage" parameter.

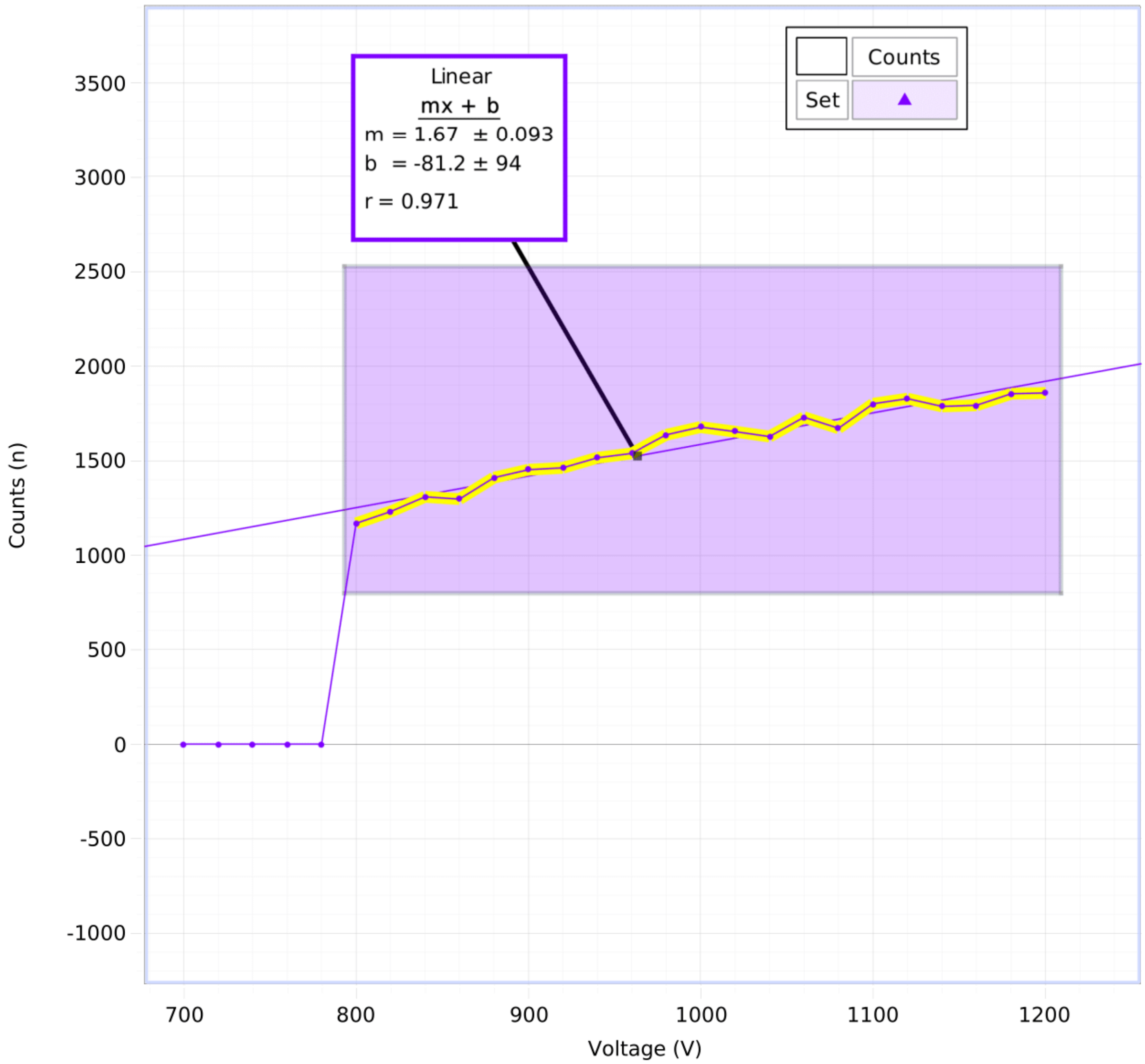

Figure 9: GM Plateau

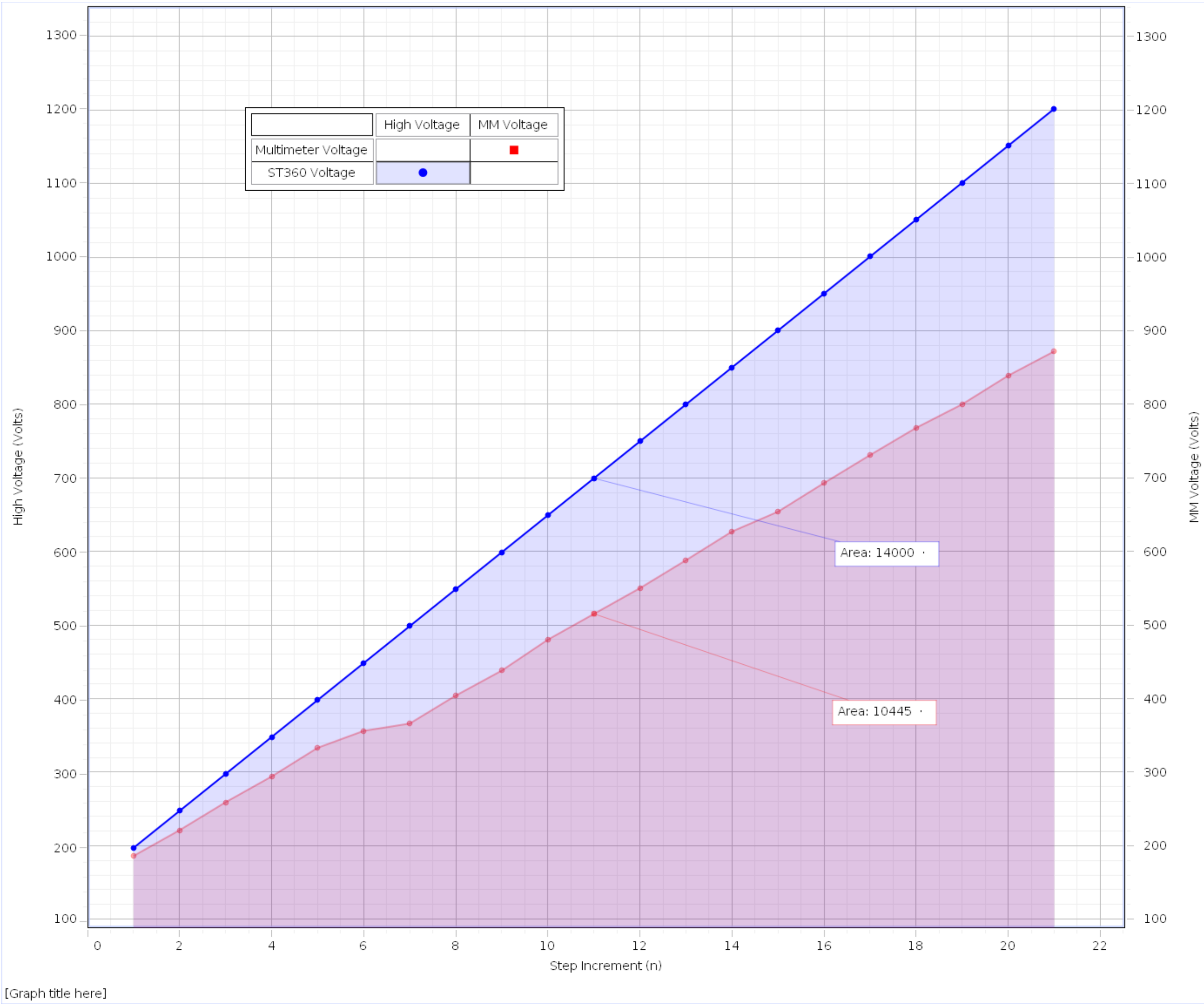

Figure 10: The difference between the display voltage and the multi-meter voltage.

The resolving time was calculated to be approximately 20 µ.s, which even though measured quite crudely, is within the expected resolving time mentioned in the manual for the equipment (1-100 µ.s) [5].

The efficiency % of the tube was calculated to be 1.33, which is within the expected range of 0-10.

Procedure **One**:

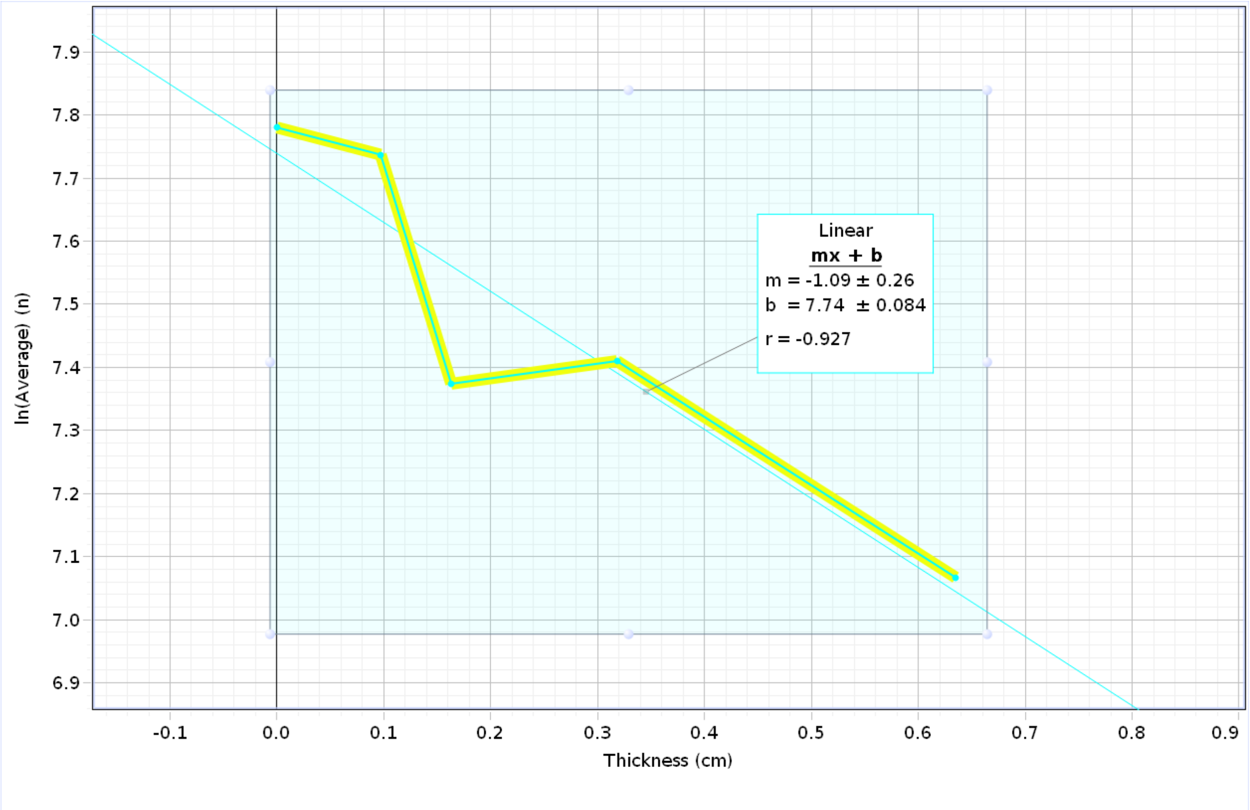

Figure 11: Linear regression Procedure One.

The slope as shown in **Figure 11** of the average natural log of the intensities vs the thickness of the slabs gave a linear attenuation coefficient of μ_{1slope} = 1.09 ± 0.26 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.096 ± 0.023 g/cm^2.

The **Figure 12** shows that since $I_0 = I_{1/2}$ at 1196 counts, the corresponding $X_{1/2}$ was 0.62 cm. Using equation *(4)* we get linear attenuation coefficient of $\mu_{1(X1/2)}$ = 1.12 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.099 g/cm^2.

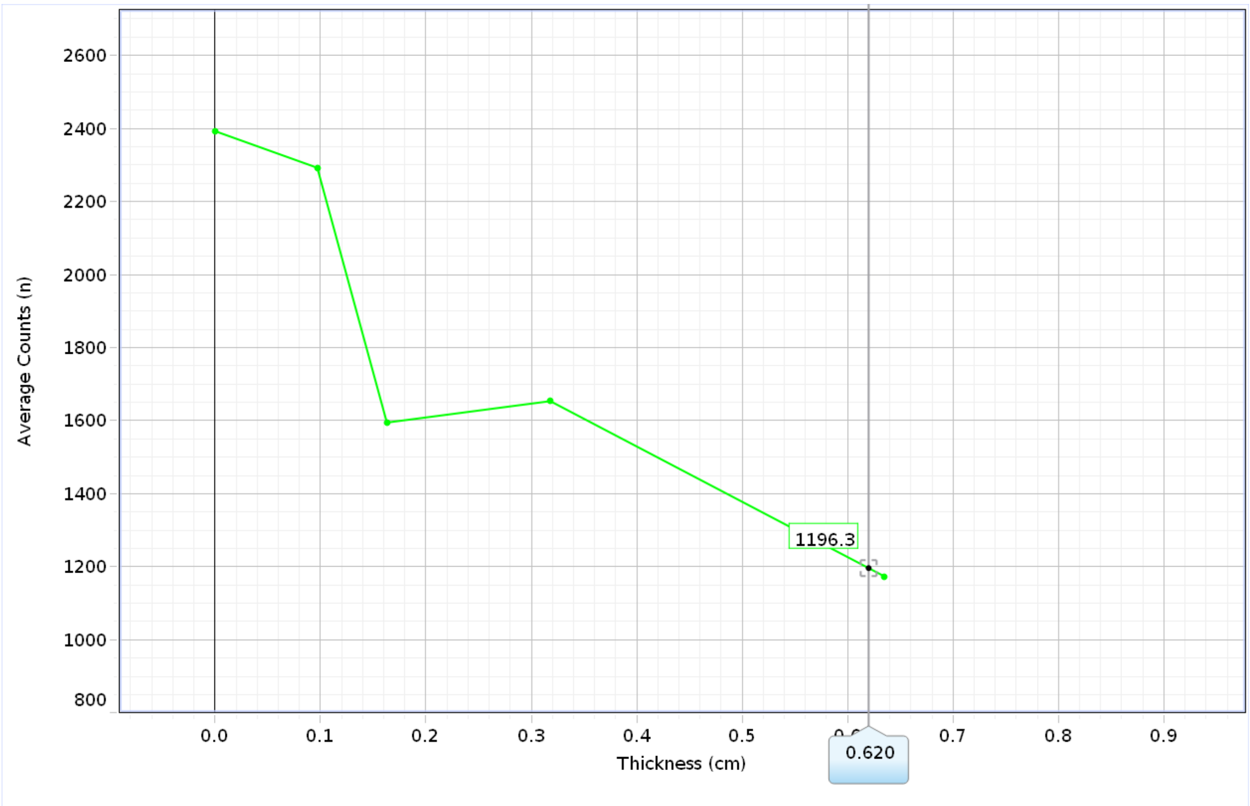

Figure 12: Half-intensity thickness procedure one.

Procedure **Two**:

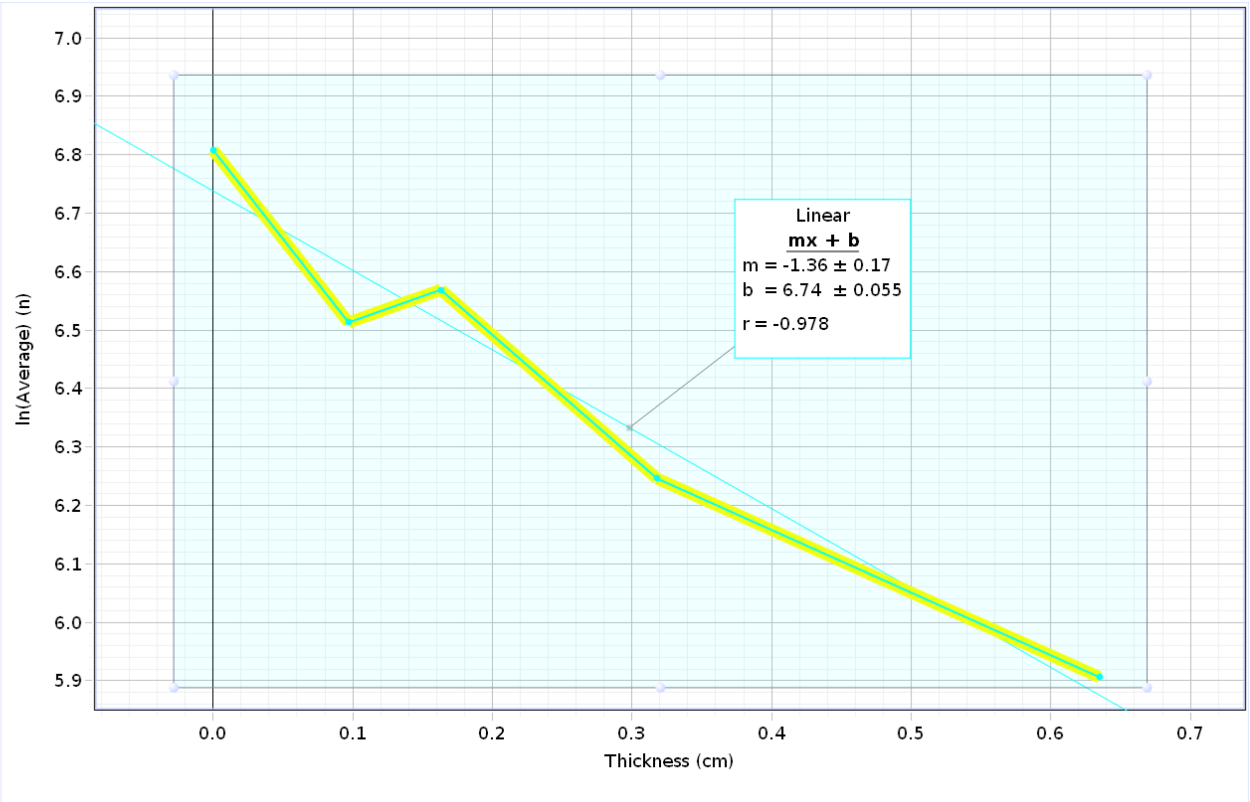

Figure 13: Linear regression Procedure Two.

The slope as shown in **Figure 13** of the average natural log of the intensities vs the thickness of the slabs gave a linear attenuation coefficient of μ_{2slope} = 1.36 ± 0.17 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.120 ± 0.015 g/cm^2.

The **Figure 14** shows that since I_0=$I_{1/2}$ at 452 counts, the corresponding $X_{1/2}$ was 0.453 cm. Using equation *(4)* we get linear attenuation coefficient of $\mu_{2(X1/2)}$ = 1.53 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.135 g/cm^2.

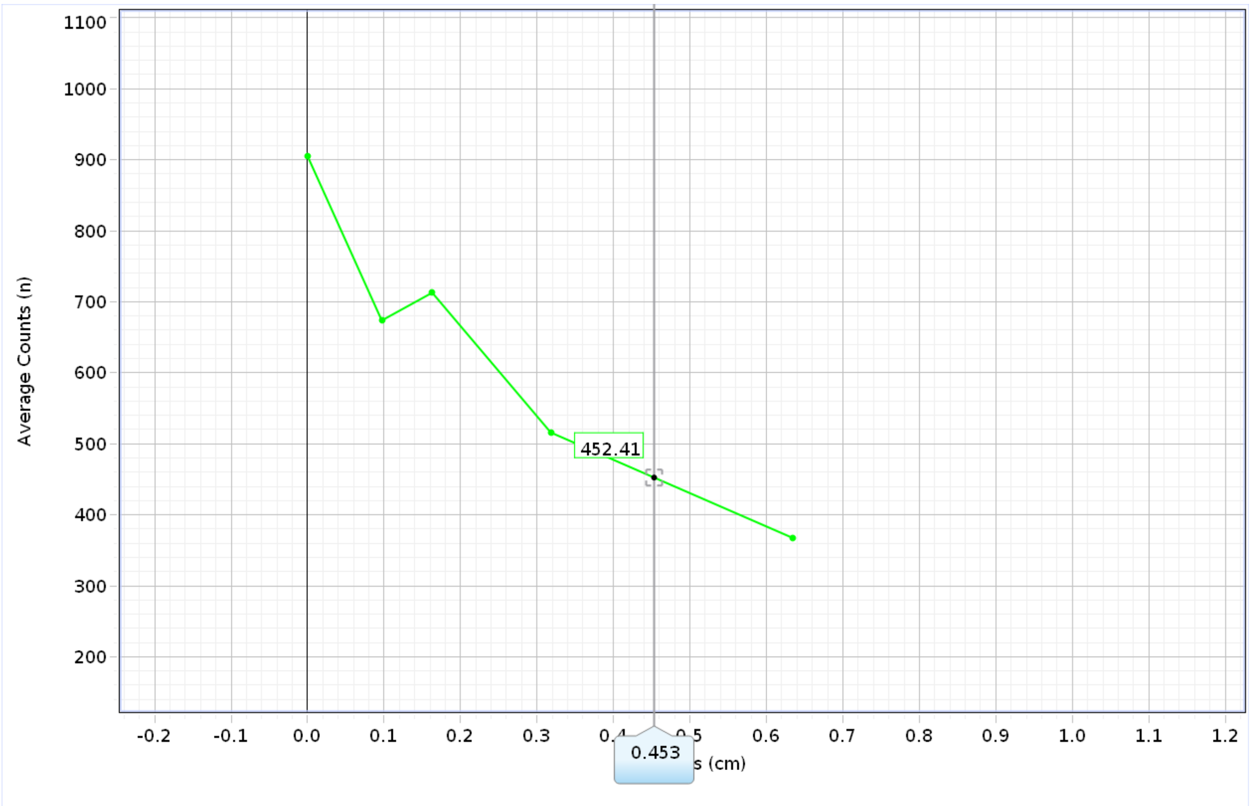

Figure 14: Half-intensity thickness procedure two.

Procedure **Three**:

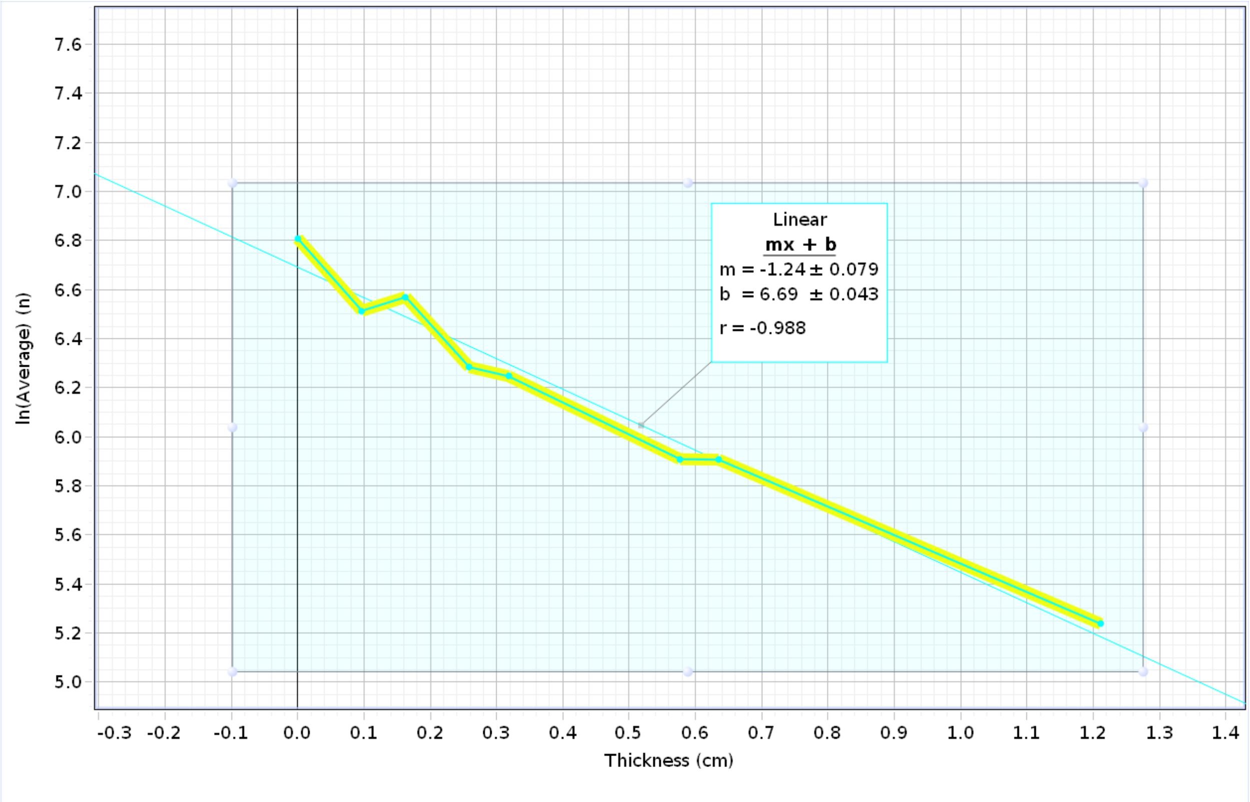

Figure 15: Linear regression Procedure Three.

The slope as shown in **Figure 15** of the natural log of the intensities vs the thickness of the slabs gave a linear attenuation coefficient of μ_{3slope} = 1.24 ± 0.079 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.109 ± 0.007 g/cm^2.

The $I_{1/2}$ was at 1196 counts and the corresponding $X_{1/2}$ was 0.429 cm. Using equation *(4)* we get linear attenuation coefficient of $\mu_{3(X1/2)}$ = 1.62 cm. This gives a mass attenuation coefficient *(μ/ ρ)* of 0.142 g/cm^2.

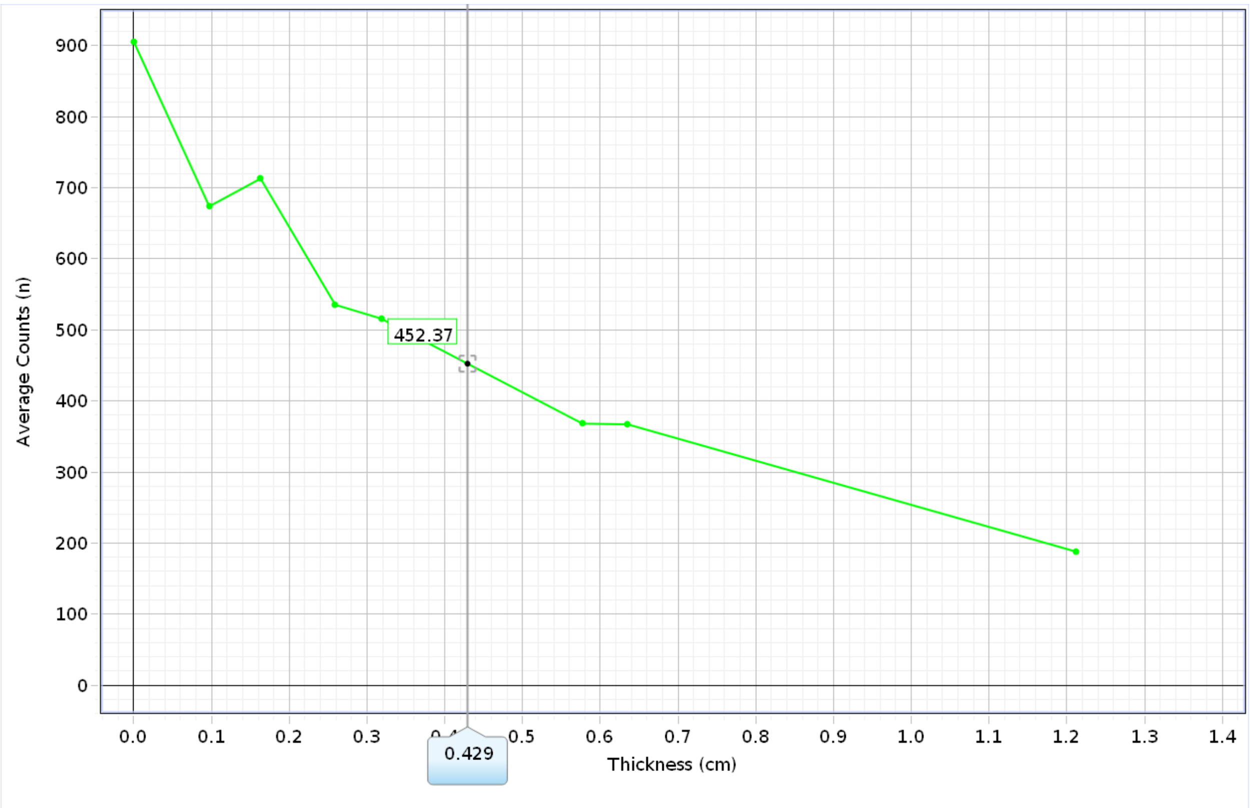

Figure 16: Half-intensity thickness procedure four.

Looking at the results and averaging them, the mass attenuation coefficients obtained through the slope of the $\ln(I_0)$ vs Thickness are more accurate and carry an uncertainty term based on linear regression of the graph, averaging these we get a mass attenuation coefficient (μ/ρ) of 0.108 ± 0.029 g/cm^2.

Error and Uncertainty:

Percentage Error: For the accepted mass attenuation coefficient (μ/ ρ) of 0.1136 g/cm^2.

$$\%\text{Error} = \frac{|Accepted\ Value - Obtained\ Value|}{Accepted\ Value} \times 100\%$$

$$= \frac{|0.1136\ \mathrm{g/cm2} - 0.108\ \mathrm{g/cm2}|}{0.1136\ \mathrm{g/cm2}} \times 100\%$$

$$= 4.93\%$$

Uncertainty in the performed experiment:

The combination of all uncertainty terms in the averaged values through error propagation gives

$$\Delta(\mu/\rho) = 0.029 \text{ g/cm2}$$

Uncertainty in the theoretical values:

Validity:

For the obtained results to be valid as per the 3δ test, the sum of the results and up to three times its uncertainty must be inside the range of the standard theoretical value and up to three times its uncertainty. We denoted Φ_{Ex} as the calculated experimental *(μ/ρ)*, $\delta\Phi_{Ex}$ as the uncertainty associated with it and Φ_{Th} as the theoretical value for *(μ/ρ)*.

$$\Phi_{Ex} \pm 3\delta\Phi_{Ex} = \Phi_{Th} \pm 3\delta\Phi_{Th}$$

$$or' \ \pm 3\delta\Phi_{Ex} = \Phi_{Th} + 3\delta\Phi_{Th} - \Phi_{Ex}$$

$$or' \ 3\delta\Phi_{Ex} = (0.1136 + 3 * 0.029 - 0.108) \text{ g/cm2}$$

$$or' \ \pm 3\delta\Phi_{Ex} = 0.0926 \text{ g/cm2}$$

$$or' \ \pm \delta\Phi_{Ex} = 0.0309 \text{ g/cm2}$$

Since the calculated value for $\delta\Phi_{Ex}$, i.e. 0.029 g/cm2, does fall between the range of -0.0309 g/cm2 to $+0.0309$ g/cm2 the obtained results are valid. If we calculate the percentage fractional uncertainty of our result, $\Delta(\mu/\rho)/(\mu/\rho)$, it is 26.85% which is higher than the percentage error of 4.93%, further suggesting a valid result.

Conclusions:

The experiment fulfilled its purpose of finding the mass attenuation coefficient of lead through two different approaches, one by finding the half-intensity thickness of lead and then obtained the coefficient using its relationship to intensity, and also through using the logarithmic nature of intensity attenuation. Averaging the results and comparing it to the accepted values showed that the latter was more accurate than the former, possibly due to it requiring less on the number of counts and more on the underlying nature of radiation absorption. The calculated results further support the conclusion that lead is an efficient material to absorb gamma rays which can be harmful to organic life, at least for low energy rays.

In terms of the experimental procedure itself, more investigation into the dead time of the GM counter would've been beneficial as even a low time of 20 milliCurie showed changes of more than twenty counts for the Cs-137 samples. Another potential avenue of analysis could have been actual measurements of the thickness of the lead slabs, as this would help give another term for uncertainty analysis.

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