Modern Physics: Absorption of Radiation by Barriers of Varying Thickness and Composition

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Abstract:

The investigators determined ‘u’ for lead, aluminum, and polyethylene and determined the half layer coefficient, the linear absorption coefficient, as well as the mass absorption coefficient for each of the samples respectively. The values for the mass absorption coefficient were, 0.023 for aluminum, 0.0423 for lead, and 2.92 for polyethylene respectively. The values for the linear absorption coefficient were 0.062 for aluminum, 0.48 for lead, and 2.89 for polyethylene. Half layer values were, 11.177 cm for aluminum, 1.44 cm for lead, and 0.23 cm for polyethylene respectively. Background radiation was found to be small at 81 counts per minute prior to the experiment. Some unusual variance in the radiation absorption performance of aluminum was discovered and discussed. The aluminum oxide layer coupled with substantial mean free path size in the bulk material of aluminum allows beta radiation to influence the counting of GM tube devices positioned too close to the absorber sample and so are influenced by the penetrating gammas and the compton scattered betas emitted by the sample. Additionally, the very large error values encountered demonstrated the dangers of limited sample size.

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Introduction:

The investigator's purpose in the experiment was to analyze and understand the process of radiation absorption, gamma, alpha and beta, in a variety of materials, to estimate the coefficients of linear and mass absorption for a given experimental environment, and to calculate the gamma ray emission of a sample from experimentally determined values.

The work done by the investigator would be impossible without the use of the Geiger-Muller tube apparatus; thus, a discussion of its history and function is in order. Sometime in 1908, Geiger and Rutherford et al. Published a paper outlining a method of detecting radiation via electron cascades, known as Townsend avalanches, between highly charged conductors in a gas filled chamber. This discovery led eventually to an additional publication in 1928 by Geiger and Muller implementing the concept in a more useful form factor that would allow more wide spread application of the "electronic radiation counting device" in research and industry. At its foundation, the Geiger-Muller tube is a set of electrodes held generally at several hundred volts in a rarefied gas atmosphere. When radiation penetrates the containment and ionizes the rarefied gas, it generates fast moving liberated electrons that in turn ionize more gas molecules, freeing even more electrons. Ultimately these electrons are drawn to the high positive potential on the central anode and form an electron cascade of sufficient magnitude to disturb the steep voltage potential between the electrodes and in turn the voltage across a measurement resistor in the detection device. The disturbances are then counted and translated to a audible beeping or clicking sound by the detector informing the operator of the approximate radioactive state of their surroundings. In the case of this study, the Geiger-Muller apparatus aids in the collection of radiation intensity data through an absorber or set of absorbers. With the radiation counting capabilities of the Geiger-Muller apparatus, the investigators are enabled to make quantitative observations and analysis of the gamma, alpha and beta emissions that pass through any absorbers placed between the detector tube and the radioactive sample, thus gleaning information as to how much radiation is absorbed by the intervening absorber material as compared to the source output, and the other materials in the sample set. Then, in conjunction with he radiometric data and using the known linear density, and known mass per unit area of the absorbers, the investigator's made calculations of the linear and mass absorbtion characteristics of the absorbers. The samples in the experiment, included a cobalt-60 radioactive source, and absorbers of air, aluminum, lead, and polyethylene. Thickness in cm ranged from 0.081, 0.163, 0.0318 , and 0.635 for lead, 0.127, 0.160, 0.203, 0.229, 0.254, and 0.318, for aluminum, 0.01016, 0.02032 for polyethylene and 1, 2, 3, 4, 5, and 6 for air. The background radiation I_0 was measured before any samples were examined, it was found to be 81 counts per minute.

Theory:

Preempting the exploration of radiation and absorption processes in absorber materials, is understanding the theory and history behind radiation and absorption processes themselves.

In 1896, A.H. Becquerel studied the effects of X-rays on photographic plates. He expected to find that uranium infused crystals emitted UV radiation when exposed to sunlight; however, when some cloudy days forced him to store his samples of bromide paper wrapped photographic plates and uranyl sulfate salts in the darkness of his office drawer, he discovered that the objects sandwiched between the plates were imaged almost as if they been exposed to sunlight regardless! A surprising discovery that led to his sharing a Nobel prize in physics for the discovery of spontaneous radioactive emission! Becquerel's discovery eventually led to the development and understanding of a wide variety of particle-light interactions that would heavily influence all modern physics and the modern world ever after.

As time went on, the work of Becquerel, and others such as Hertz and Marie Curie, would culminate in the construction of many descendant understandings, all highly interdependent, much like the work of Maxwell before them, The Photoelectric effect, Compton Scattering phenomenon, and Pair Production would just name a few of such descendant developments from Becquerels serendipitous discovery. Ultimately, Einstein and others of his day would piece together the details of those descendant developments into a cohesive picture of light-matter interactions, and other fascinating phenomena. For Einstein specifically, the Photoelectric effect showed that conductive materials could be stimulated to produce electrons and other energetic particles when struck with incident radiation. However, the current produced by the incident light on the conductor did not correspond with intensity of the incident radiation as expected, but instead with the frequency! This result proved counter intuitive to the scientific community of the day and forced the reconsideration of the theory of light as a whole! Eventually, it was discovered that electrons inhabited discrete energy states in their orbits around the nucleus and each energy state or "bound state" corresponded almost precisely with a specific frequency and thus, wavelength of light. Put precisely in mathematical terms,

$$E=hf \text{ and } f = c/\lambda.$$

That is, the energy of any given photon is directly proportional to its frequency and inversely proportional to its wavelength. Additionally, if a photon of the appropriate frequency interacts with the matter possessing electrons in the correct energy shells, the photon can be absorbed and dislodge the electron from its shell, resulting in an electric current and possibly, a re-emission of the photon at a greatly red shifted frequency. The second phenomenon, when a photon ejects an electron and is re-emitted with a significant red shift is called Compton scattering. More generally, when a photon undergoes an inelastic collision with some charged particle and is re-emitted at a longer wavelength following the collision, Compton scattering is at work. Compton Scattering is one of the processes responsible for the differing absorption of radiation by various materials. Compton scattering generally concerns the electrons in the electron cloud around atoms, and is responsible for the currents seen in photo voltaic cells even at relatively low light intensities. The Experiments done by Compton, for who the effect is named, proved to the scientific community of the early 20th century that light could behave as a stream of particles whose energy was proportional to the wavelength of the light wave, an early indication of the wave-particle duality of light. Look Compton scattering and the photoelectric effect are heavily interleaved, and depend on one another to mostly describe the light matter interaction seen when conductors are struck with incident radiation. However, the electron light interaction is only part of the story; The nucleus, while a small target does receive some incident rays on occasion and can undergo Compton scattering, in addition to phenomena at even higher energies. When exposed to photons with very high frequencies, and thus very high energy and short wavelength, nuclei can be struck hard and result in the production of particle antiparticle pairs, absorbing the photon, usually converting it temporarily into a positron and electron, and then being re-emitted at a redshift from its original wavelength, from the annihilation of the particle with its antiparticle partner. This effect is the final detail that makes up the whole of light matter interactions understanding in the early 20th century.

Each of the above processes act to reduce the amount of radiation that makes it through a given thickness of absorbing material. Which leads to another 20th century innovation in physics, Lambert's Law. Lambert's Law describes the exponential decrease in the intensity of radiation as it encounters some collection of absorbing material, It is expressed as ,

$$I = I_o e^{(-uX)} \quad .$$

Where I is the intensity of radiation after traveling a distance X through the material, I_o is the intensity of the incident radiation, and ‘u’ is the linear attenuation(absorption) coefficient. A graph of Lambert’s Law is provided below, it shows the linear absorption coefficient by graphing the natural logarithm of I versus X.

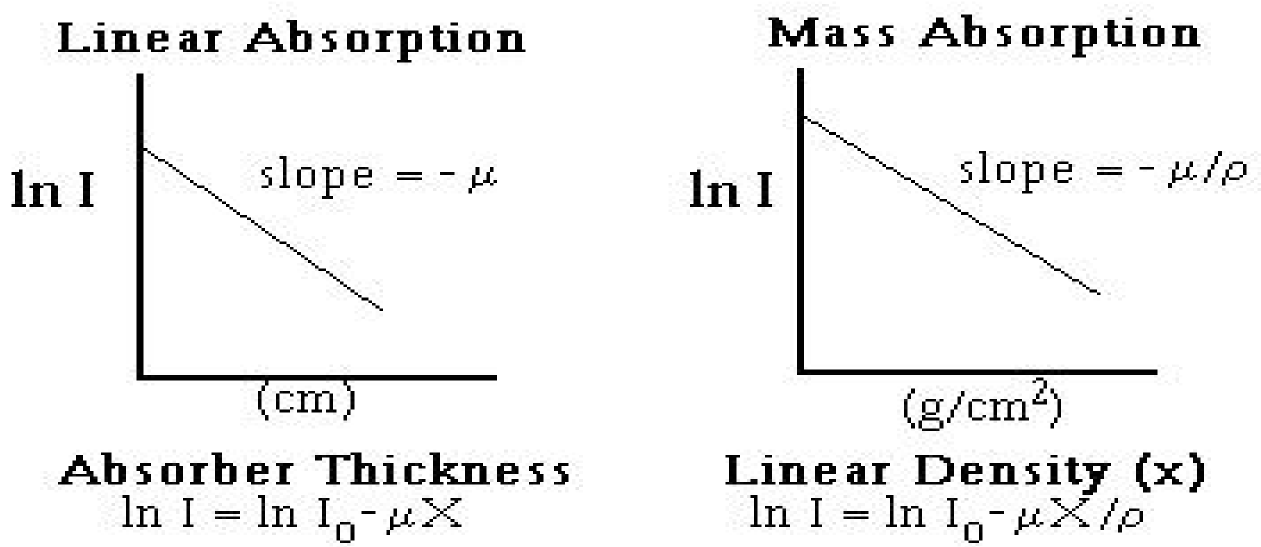


Figure 1.)

By finding the value of ‘u’ experimentally, one can then move on to the useful exercise of finding the thickness of a material in which the intensity of incident radiation is halved. Finding such a value can be useful in determining the amount of shielding needed for safe operation in hazardous environments, for the stable function of nuclear reactors and many other applications. The calculation goes thus,

$$\ln\left(\frac{I_o}{.5\,I_o}\right)=uX_{.5}$$

Then, with some algebra,

$$\ln(2)=uX_{.5}$$

further simplification yields,

$$X_{.5}=0.693/u \quad .$$

Thus, we have found the half value layer, or the point at which half of the intensity of the incident radiation has been expended by the photoelectric effect, Compton scattering, or pair production. In addition to linear absorption, 'u' the second graph above provides a view of u' or mass absorption. That is defined as u/p, the mass absorption is determined primarily by the linear density of a material as opposed to just the thickness of the material, allowing calculations of incident intensity reduction based on both thickness of an absorber as well as its density.

With the conclusion of the discussion of light-matter interactions and radiation absorption, begins the exploration of the operational theory specific to radiation detection and counting, and how the data sets, by which the effectiveness of the absorbers is determined, are collected. Radiation can be characterized as energized particles such as electrons, alpha particles, and photons, that, when they interact with other matter tend to deposit their energy into the particles of that matter, resulting in myriad effects, from ionization, to nuclear reactions, decay events, electric currents and heat. In the case of the Geiger-Muller apparatus, energized particles, pass through a thin "window" into a charged tube containing a thin charged wire and a certain amount of gas, usually helium or argon, but sometimes radon or xenon, at low pressure. When the energized radiation, whether electrons, alpha particles or photons, interacts with the gas molecules in the tube, the gas atoms sometimes become ionized and are drawn along the established voltage gradient in the tube, toward the outer wall. As they travel, the free electrons from other atoms and increase the number of liberated electrons in the tube. These liberated electrons travel at high speed along the established voltage gradient toward the center filament, sometimes freeing even more electrons as they travel. This electron cascade is referred to as a townsend avalanche and eventually results in a substantial spike in the current on the center filament. This process allows individual rays of radiation at sufficient energy to trigger short pulses of current which can be counted by the counting machine in order to establish the intensity of the radiation measured. Thus, "counts" are found in relation to the radiation intensity and the voltage of the tube. The process of ionization of the gas in the tube results in the accumulation of positive ions at the cathode(tube wall), and electrons at the anode(center filament) which, if left unchecked would result in continuous discharge and the ruination of the Geiger-Muller apparatus. To combat this problem, Geiger-Muller devices have various modes of "quenching", either by intermittently altering the voltage gradient in the tube, or through the addition of halogens or poly-atomic gases to the rarefied atmosphere to allow recombination of electrons with positive ions and allow recovery of steady state of charge even after large numbers of ionizing interactions with radiation sources. A depiction of the Geiger Muller tube is shown below.

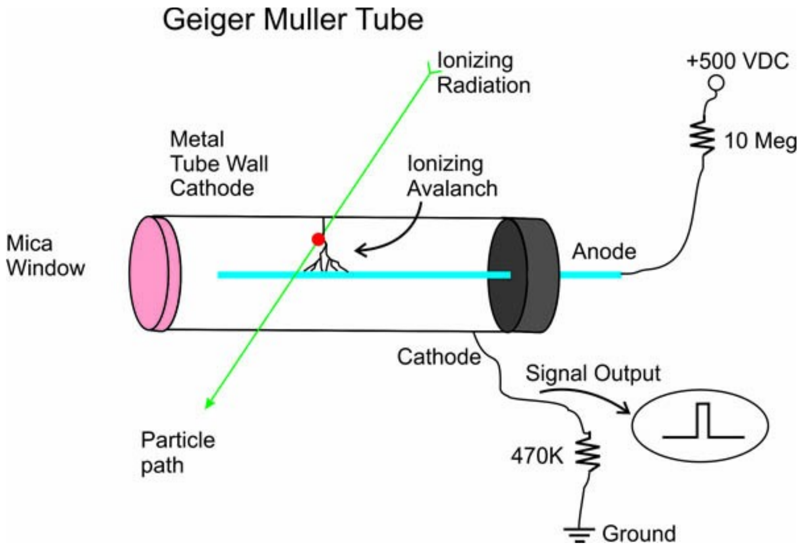


Figure 2.)

Experimental Procedure:

An experimental setup as shown below, was assembled from available equipment including, a Geiger Muller tube and counter, tube holder, test rack and radioactive samples. The counter was plugged into 120 volt AC power and connected via coaxial cable to the Geiger-Muller tube. The Geiger-Muller tube was carefully, especially with respect to the mica detection window, placed into the aperture of the sample rack, and hooked up to the counter on the appropriate port. The counter was then calibrated for 0 volts of control voltage, and 30 second intervals. The counter was first allowed to count with no radioactive sample on the shelf, so as to gain a reading for background radiation levels to use in data corrections later.

figure4.)

figure3.)

A gamma ray producing sample of cobalt 60, as shown in figure 4 above, was placed on the top shelf of the sample rack and the Geiger-Mueller tube placed in the aperture above the shelf as shown in figure 3. The investigators adjusted the height by one hundred volts per trial, and recorded the number of counts read out every 30 seconds. Eventually, the plateau voltage of the Geiger-Muller tube was achieved and the investigators reduced the voltage down to the initial increment.

The investigators then mapped the plateau response and the operating voltage of the Geiger-Muller tube in continuous 20 volt control increments. No disturbances of the Tube, counter or source were made throughout the experiment. Next, the radioactive sample was moved down one rung on the shelf, and a count was taken. This process was repeated 6 times for a reading at every cm up to 6 cm of air gap between the sample and GM tube to establish a baseline absorbency for air in addition to the background radiation. Then a set of samples like the one shown below in figure 5, was brought out and sequentially one at a time, by material type and thickness placed into the slot above the cobalt-60, between the sample and the GM-tube. The sample absorber material was consistently placed on the shelf one cm below the GM tube, and one cm above the radioactive sample.

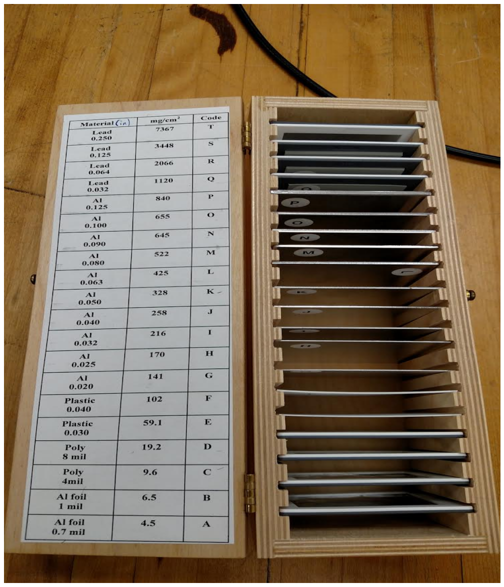


Figure 5.)

The gathered data, sorted by material thickness and radiation counts is below, in addition to the background and air baseline data.

Graphs and Charts:

Air

	Thickness (cm)					
Trial	1	2	3	4	5	6
1	1913	1205	898	700	549	437
2	1904	1238	873	671	518	376
3	1974	1330	896	655	524	430
Ave	1930	1257	889	675	530	414
ln(I)	7.565	7.136	6.790	6.515	6.273	6.026

Aluminum

	Thickness (cm)					
Trial	0.127	0.160	0.203	0.229	0.254	0.318
1	654	689	648	677	654	675
2	676	681	692	687	687	726
3	712	695	634	708	647	635
Ave	680	688	658	690	662	678
ln(I)	6.522	6.534	6.489	6.537	6.495	6.519

Lead

	Thickness (cm)			
Trial	0.081	0.163	0.318	0.635
1	645	607	613	493
2	697	657	605	513
3	661	674	617	532
Ave	667	646	611	512
ln(I)	6.503	6.471	6.415	6.238

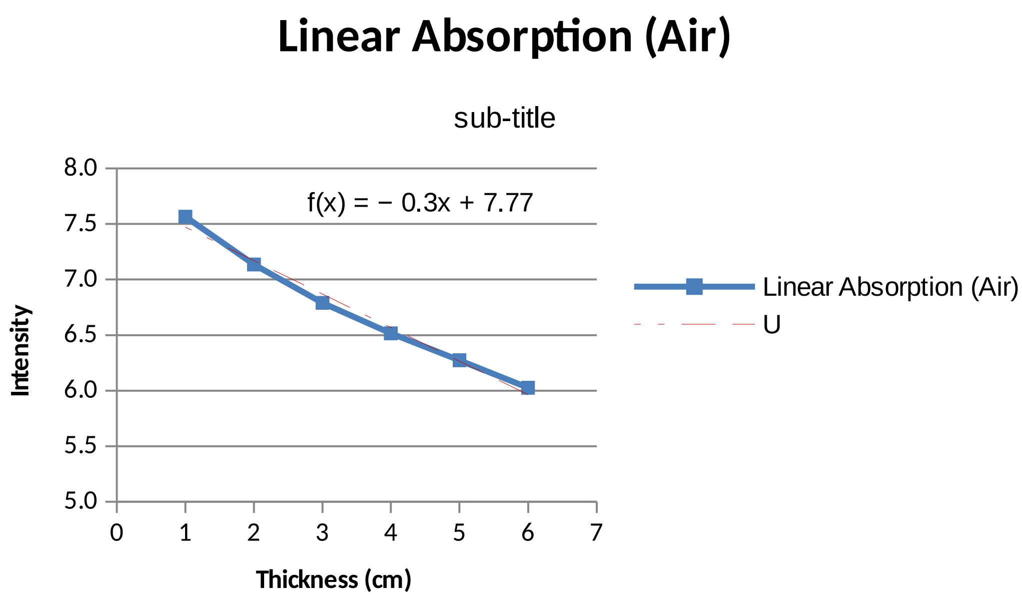
Polyethylene

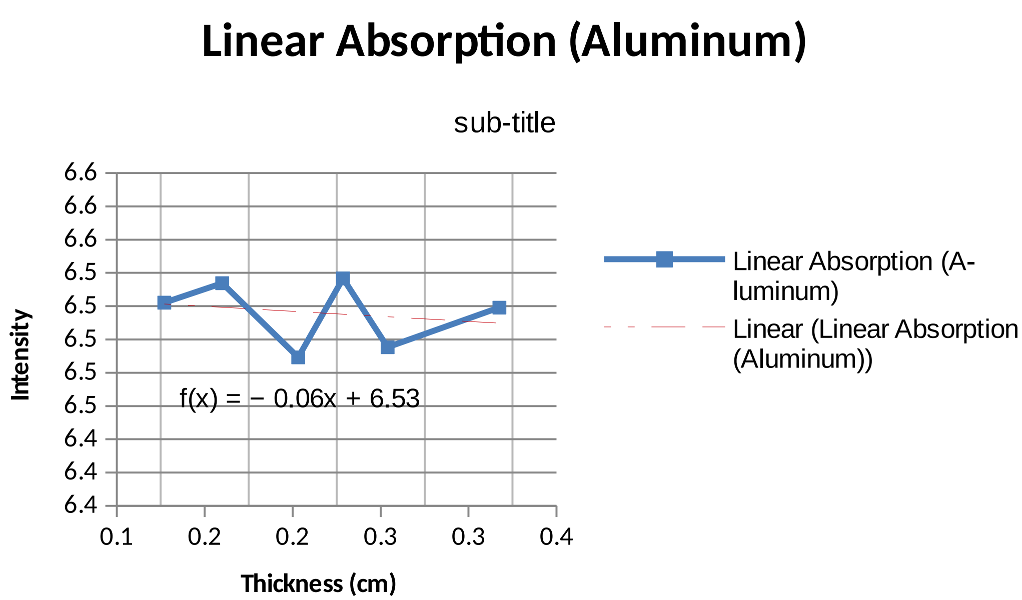
	Thickness (cm)	
Trial	0.01016	0.02032
1	819	922
2	877	809
3	899	789
Ave	865	840
ln(I)	6.763	6.733

Background

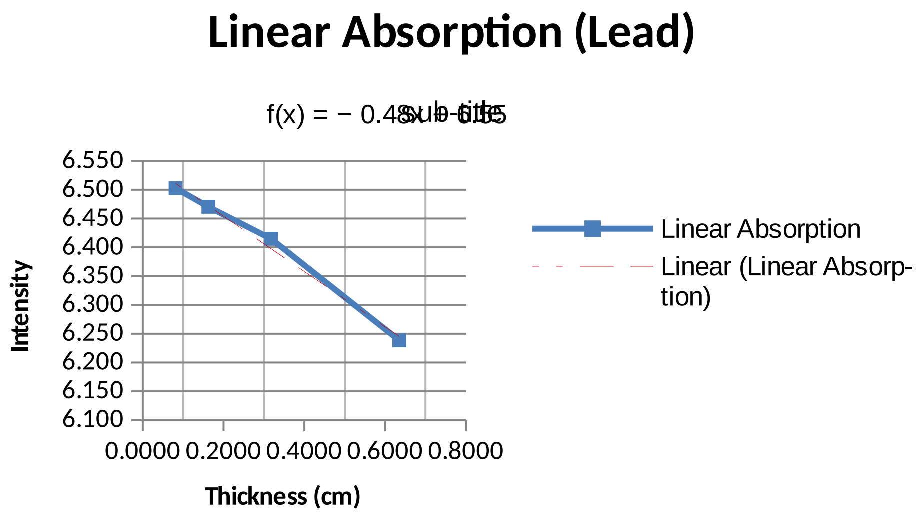
Trial	Intensity
1	83
2	82
3	80

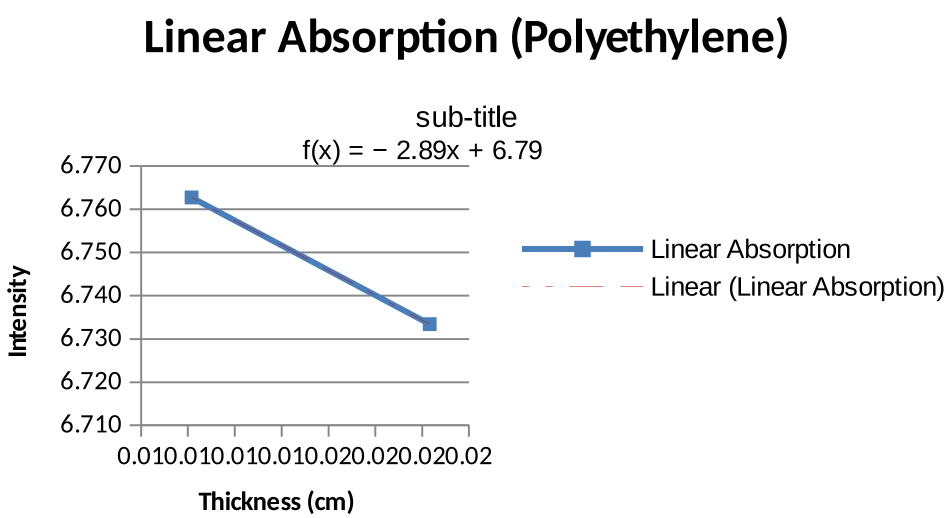
Ave	81


Linear Absorption (Air)
sub-title
8.0
7.5
7.0
6.5
6.0
5.5
5.0
0 1 2 3 4 5 6 7
f(x) = − 0.3x + 7.77
Intensity
Thickness (cm)
Linear Absorption (Air)
U


Linear Absorption (Aluminum)
sub-title
6.6
6.6
6.6
6.5
6.5
6.5
6.5
6.5
6.4
6.4
6.4
0.1 0.2 0.2 0.3 0.3 0.4
f(x) = − 0.06x + 6.53
Intensity
Thickness (cm)
Linear Absorption (Aluminum)
Linear (Linear Absorption (Aluminum))

Interesting effects were seen with the aluminum. Radiation intensity seemed to vary considerably, but did not appear to be correlated strongly with material thickness. This is probably an effect of the oxide layer on aluminum; this effect will be discussed in more detail in the conclusion.





Calculations:

To solve for the Linear Absorption Coefficient from collected data in mils...

$$u'=u/\rho$$

$$u=u'(\rho)$$

$$\mu=0.06146(2.699)\left(\frac{1}{0.3937}\right)\left(\frac{1}{1000}\right)=0.000421\,mils^{-1}$$

Now I will solve for the Half Value Layer in units of mils :

$$\ln\left(\frac{I_o}{.5\,I_o}\right)=uX_{.5}$$

$$\mathrm{Ln}(2) = \mu * X_{1/2}$$

$$X_{1/2} = \mathrm{Ln}(2) / \mu$$

$$X_{1/2}=\frac{0.693}{0.0013}=540\,mils$$

%Error Calculation:

$$\frac{|(Experimental-Theoretical)|}{Theoretical}*100$$

Analysis and Conclusions:

The collected data shows that increasing thickness of material is usually certain to reduce the intensity of radiation penetrating through that material. Generally, the effectiveness of an absorber is determined directly by its thickness and its linear density, that is, its number of atoms per unit volume in a line along the path of incident rays and the length of that path. As expected, Lead is a very effective absorber which increases in effectiveness with increasing thickness, due to its high density and high bulk resistivity. While polyethylene is a poor absorber by comparison at any thickness, due to its relatively low density. However, this simple interpretation of the results fails to explain the high variance seen in the aluminum test. Aluminum appears to have an absorbency that does not directly depend on its thickness but instead varies wildy, almost at random. In order to explain this phenomenon, one must examine the properties of aluminum as compared with the other samples. Aluminum posses a density between lead and polyethylene, and a conductivity between them as well. Additionally, aluminum is not pure at atmospheric temperature and pressure in an oxygen rich environment, such as open air in the laboratory. It is a widely known phenomenon that aluminum will build up a protective oxide layer ,when exposed to oxygen, that resists further corrosion and abrasion very well, making it a popular material choice for aircraft and anywhere else where corrosion resistance and excellent strength to weight ratio are preferred. However, this oxide layer somewhat complicates the testing of radiation resistance in the material as it adds a region whose density and conductivity is different from that of the bulk and whose radiation resistance and response to ionization may be very different from the larger structure. The literature on the topic points to the oxide layer and aluminum's relatively low resistance as factors for its unusual radiation absorption characteristics as viewed by a GM tube. When a gamma ray penetrates the aluminum plate, it either passes through the plate and is captured by the gm detector, or it is absorbed and its some of its energy lost in Compton scattering or pair production. Normally, absorption would be the end of the story; However, because aluminum has a relatively low resistance, meaning a relatively long mean free path for electrons in the bulk material, Compton scattering can result in the release of beta particles from the plate if it is not too thick. These beta particles could be picked up by the nearby GM tube as additional counts which adds to the radiation that is detected as penetrating through the aluminum. Additionally, the oxide layer on the aluminum's surface is positively charged and will assist in pulling the free Compton scattered electrons toward the surface, thus facilitating their escape. The GM tube does not distinguish between species of radiation, it merely responds to the Townsend avalanches produced when its internal atmosphere is ionized. Thus, when measuring radiation intensity with the GM tube relatively close to the aluminum absorber, it is possible that radiation counts would be skewed by the emitted beta radiation from Compton scattering and from the accelerating effect of the positively charged oxide layer. Hence, why the graph of aluminum above appears to have a high variance and virtually no direct correlation between thickness and intensity of radiation making it through the plate. This issue could be resolved by increasing the distance from the GM tube to the absorber sample, or by taking more measurements over a longer time period to facilitate statistical analysis of the data and removal of noise, if one wishes to examine purely gamma ray penetration with the gm tube. One might also use an alloy of aluminum that does not develop an oxide layer. Unfortunately, due to the small number of samples in each test, the percent error for each sample tends to be quite high, rendering the data unreliable. So the previous analysis and conclusions may be unnecessary in light of simply increasing the number of samples taken when observing the absorber samples.

The investigators determined ‘u’ for lead, aluminum, and polyethylene and determined the half layer coefficient, the linear absorption coefficient, as well as the mass absorption coefficient for each of the samples respectively. The values for the mass absorption coefficient were, 0.023 for aluminum, 0.0423 for lead, and 2.92 for polyethylene respectively. The values for the linear absorption coefficient were 0.062 for aluminum, 0.48 for lead, and 2.89 for polyethylene. Half layer values were, 11.177 cm for aluminum, 1.44 cm for lead, and 0.23 cm for polyethylene respectively. Background radiation was found to be small at 81 counts per minute prior to the experiment. Clearly the values obtained for ‘u’ are subject to substantial error due primarily to small sample size, precisely, 62.6% error for aluminum, 40.4% for lead, and 2891.8% for polyethylene. These extreme error values prove that larger sample sizes are preferable when considering the radiation absorption characteristics of materials. Additional causes of error would be the air gap between the sample and the source, and the GM tub and the source. Air acts as a relatively effective absorber and may have skewed the data by a substantial margin, proportional to its absorption compared to that of the absorber samples.

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Image of Geiger-Muller Tube:
http://www.imagesco.com/articles/geiger/build_your_own_geiger_counter_-_gm_tube.html

Credit Yael Mckorkle for the Image of experimental Setup.
Credit Connor Oleary for the Image of Cobalt-60 and Sample plates
Credit Lab manual for figures of linear and mass attenuation coefficients