Gamma Absorption

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March 17, 2017

1 Goal

We measure the absorption of gamma rays emitted by a ^{60}Co sample as they travel through Lead and Aluminum blocks of varying thickness. From these measurements, we calculate the absorption coefficient of each material. Then we further characterize the materials by determining the range of gammas, the equivalent matter, the half length, and the mass attenuation coefficient.

2 Introduction/Background

Electromagnetic waves are absorbed and dispersed when traveling through matter. The classical theory of electrodynamics predicts that EM waves approaching a conducting medium encounter a nonzero free current density, according to Ohm's Law. Although a good conductor is able to quickly dissipate any free charge, Maxwell's equations still depict the magnetic field as being dependent upon the material conductivity. This forces the magnetic field (of the traveling EM wave) to lag behind the electric field, and consequently the amplitude of incoming waves decreases exponentially as they travel through the medium [3].

A more accurate description of this process requires an understanding of the small scale interactions between each photon of the EM field and the material constituents. A photon can interact with matter in three ways: it may photoionize the atoms, undergo Compton scattering, or if the photon is of great enough energy it can spontaneously produce an electron anti-electron pair [5]. Additionally, and in contrast with the interactions of largely massive particles such as alpha rays, a photon may emerge from the material without losing any energy. These interactions cause photons traversing a material to be attenuated according to the density and thickness of the material, the photon energy, and the material's atomic number.

The intensity, I, of a photon beam passing through a material decays exponentially with distance,

$$I(x) = I_o\, e^{-\alpha x} \tag{1}$$

where I_o is the initial intensity, x is the distance traveled, and α (the absorption coefficient) is the probability per unit distance that a photon is lost due to an interaction. The point at which the beam intensity is reduced by e^{-1} is called the range of gammas, which corresponds to the mean distance before absorption and is calculated from

$$\lambda = 1/\alpha \tag{2}$$

where λ is the range.

It is convenient to introduce the change of variables from x to $\xi = \rho x$, where ρ is the material density and ξ is called the equivalent matter, because it is the number of atoms encountered by the photon that determines the likelihood of absorption, which is proportional to ξ. Then we can define the mass attenuation coefficient, μ, as $\mu = \alpha/\rho$, such that

$$I(x) = I_o\, e^{-\mu \xi} \tag{3}$$

A fortunate coincidence of this change of variables is that μ is approximately equivalent across many materials.

3 Procedures and Data

We used a radioactive ^{60}Co sample as a source of high energy gamma rays to investigate ray attenuation after passing through absorbing plates (Aluminum and Lead) of various thicknesses. As seen in Figure 1, the Co source is contained within radiation shielding which only allows radiation to escape through a hole drilled through a large brick that is resting against the shielding structure. The narrow hole acts as a collimator to feed photons into the absorbing plates. After passing through the plates, the remaining photons are collimated again before being detected by a scintillation crystal, which releases scintillations that are amplified by a photomultiplying tube (PMT).

Finally, the pulses created by the PMT are examined by a multichannel analyzer (MCA) and binned according to height. We measured the number of event counts by selecting a region of bins in the MCA software, which then reports values for the gross counts, the net counts (after subtracting background from the gross), and the fractional uncertainty within that region.

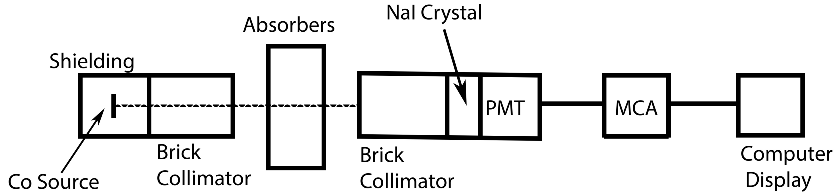

Figure 1: Block diagram of the experimental apparatus.

To begin, we set the MCA timer for 1-minute live time and recorded the decay spectrum of ^{60}Co, which is seen in Figure 3. Cobalt-60 decays into Nickel-60 through beta decay, a decay scheme is shown in Figure 2.

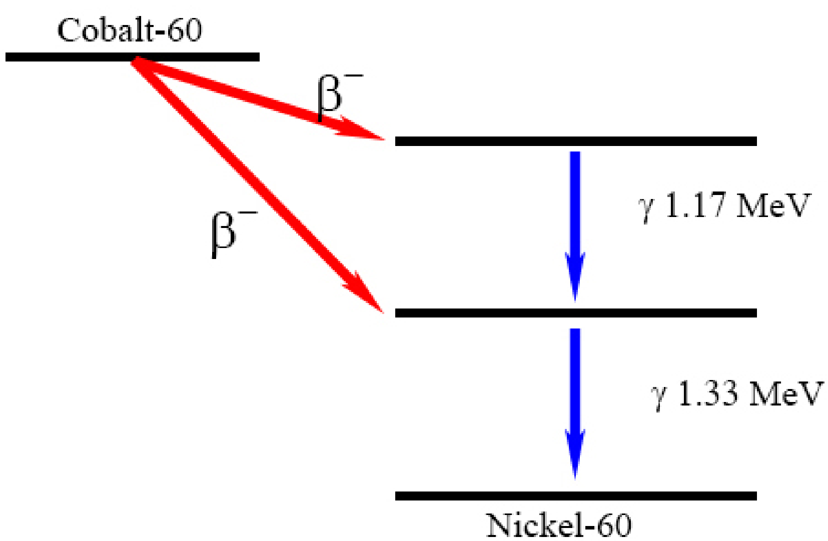

Figure 2: Decay scheme: $^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e$.

A neutron of the Cobalt nucleus transforms into a proton, electron, and electron anti-neutrino. The electron and electron neutrino are ejected, leaving the nucleus with 28 protons. Then the newly created, and excited, Nickel nucleus decays to its ground state by emitting photons. Cobalt-60 may undergo two variants of Beta decay, one leaves the Nickel nucleus in a twice excited state, which decays by releasing a 1.17 MeV photon and then a 1.33 MeV photon. The other variant expels more energy in the initial Beta decay, which allows the Nickle nucleus to reach ground state through a single photon emission of 1.33 MeV [1].

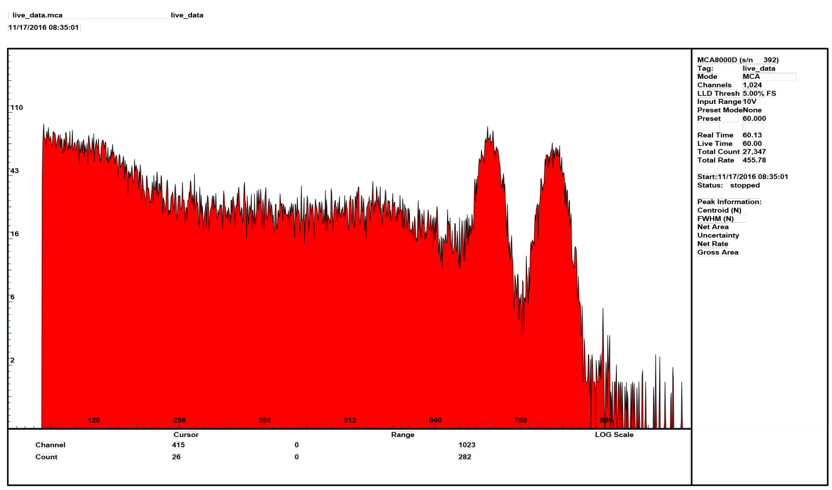

Figure 3: Log Scale decay spectrum of ^{60}Co. The left photopeak corresponds to the 1.17 MeV emission and the right photopeak is the 1.33 MeV emission.

Next, we set the timer on the MCA such that we would acquire approximately 10,000 counts in one minute in the absence of any absorbing plates. A high count rate is desirable as it significantly reduces the fractional uncertainty associated with counting. Then we recorded the computer reported values for the gross count, net count, and uncertainty after a measurement period of one minute with 0, 1,..., 8 absorbing lead plates, which is seen in Table 1 and Table 2. Before introducing a new plate to the system, we used calipers to measure the thickness of each additional plate. This procedure was repeated in order to obtain data with both lead absorbers and aluminum absorbers. The aluminum plates were very uniform in thickness, so we assumed they all had the same thickness and negligible measurement uncertainty.

Lastly, we removed the ^{60}Co source and placed a large lead slab over the first collimating hole. The brick provided more than five inches of shielding and so we took a one minute reading to determine the background count rate

Table 1: Measured counts for gamma rays traveling through lead absorbing plates as reported by our MCA analysis software.

Plate Thickness (mm)	Gross Ct.	Net Ct.	Uncertainty $\delta N/N$
0	12856	10802	1.13
5.35 ± 0.01	9432	6943	1.57
10.78 ± 0.02	6934	5828	1.54
16.23 ± 0.03	5049	4180	1.84
21.56 ± 0.04	3589	3115	2.05
26.87 ± 0.05	2773	2062	2.86
32.07 ± 0.06	2067	1514	3.38
36.78 ± 0.07	1627	1114	4.15
41.88 ± 0.08	1358	805	5.43

Table 2: Measured counts for gamma rays traveling through aluminum absorbing plates as reported by our MCA analysis software.

Plate Thickness (mm)	Gross Ct.	Net Ct.	Uncertainty $\delta N/N$
0	12856	10802	1.13
12.93	10683	8313	1.37
25.86	9001	7145	1.46
38.79	7368	5867	1.61
51.72	5990	4845	1.74
64.65	5087	4060	1.93
77.58	4336	3072	2.44
90.51	3391	2799	2.26

to find $N_{noise} = 250 \pm 20$. Ideally, this measurement of the background count rate would agree with the difference between the gross and net counts of Table 1 and Table 2. We believe this discrepancy is due to the MCA software, which uses an unknown algorithm in attempt to filter out background noise. Although this leaves us quite uncertain about the true number of net counts, it should not affect our characterization of the absorbers because those calculations only rely on the fractional decrease in intensity as more plates are added.

4 Analysis and Discussion

The net counts found in Column three of Table 1 and Table 2 are proportional to the incoming ray intensity. Then, Equation 1 holds when I is replaced by N, where N is the number of counts as a fucking of absorbent thickness. By taking the log of both sides, we find the linear relationship

$$\log N_{net} = \log N_o - \alpha x \tag{4}$$

where N_o is the initial number of counts (before being observed), N_{net} is the net counts from the Table 1 and Table 2, and x is the thickness of the absorbing stack. Then, we performed a weighted linear fit according to $y = b - \alpha x$, where $y = \log N_{net}$ and $b = \log N_o$. Uncertainty in y was estimated by

$$\delta y = \delta \log N_{net} = \frac{1}{N_{net}} \delta N_{net} = \frac{1}{\sqrt{N_{net}}} \tag{5}$$

From the weighted fit of Lead in Figure 4 and the weighted fit of Aluminum found in Figure 5, we found the absorption coefficients for Lead and Aluminum to be $\alpha = 60 \pm 2\ m^{-1}$ and $\alpha = 14.6 \pm 0.5\ m^{-1}$, respectively. These results reflect the large difference in density between the two metals and provides evidence as to the effectiveness of leaded radiation shielding.

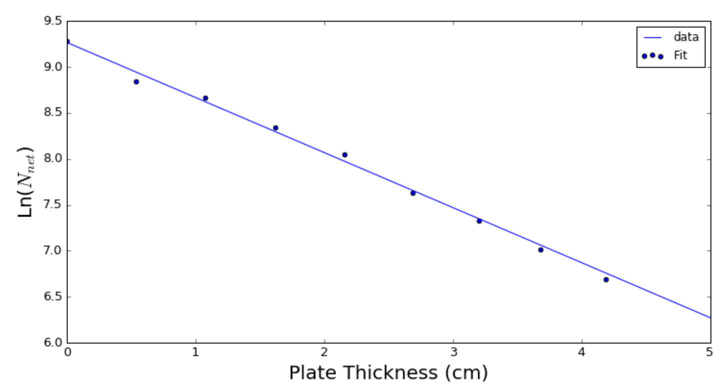

Figure 4: Weighted fit of the Lead absorption from the linearized Equation 1 and the net counts found in Column 3 of Table 1.

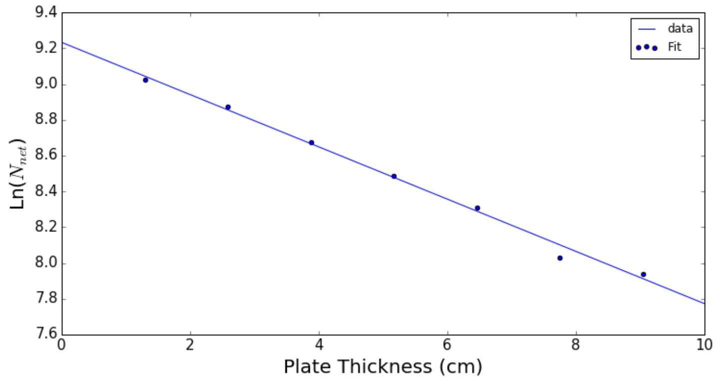

Figure 5: Weighted fit of the Aluminum absorption from the linearized Equation 1 and the net counts found in Column 3 of Table 2.

The range of gammas (Equation 2) within lead was $\lambda = 1.67 \pm 0.05$ cm and $\lambda = 6.9 \pm 0.2$ cm in Aluminum. The half length, which is the length at which ray intensity is reduced to half, can be calculated from Equation 1, which gives $L_{1/2} = 1.15 \pm 0.04$ cm in Lead and $L_{1/2} = 4.7 \pm 0.2$ in Aluminum. From the 84'th edition Handbook of Physics and Chemistry, we used the values of density, $\rho_{Pb} = 11.3 \times 10^3\ kg/m^3$and $\rho_{Al} = 2.7 \times 10^3\ kg/m^3$ to find the mass attenuation coefficients of each material to be $\mu_{Pb} = 0.54 \pm 0.02$ cm^2/g and $\mu_{Al} = 0.53 \pm 0.02\ cm^2/g$ [4]. These results are in great agreement with the accepted attenuation profile for these materials, which can be found on the NIST website [2]. NIST hosts plots of the total attenuation, which is the sum of all interaction possibilities , according to photon energy. An eyeball estimate of the 1.33 MeV point on the NIST plot gives $\mu_{Pb} = 0.53$ cm^2/g and $\mu_{Pb} = 0.50\ cm^2/g$. We see that μ is approximately the same for both materials, which highlights the importance of the equivalent matter, ξ, on absorption and scattering properties.

5 Conclusion

We showed that Lead is a significantly more effective radiation shield than Aluminum by measuring the decrease in gamma ray intensity after traveling through Lead and Aluminum blocks. By linearizing Equation 1 and applying a weighted fit, we calculated Lead's absorption coefficient to be $\alpha = 60 \pm$

2 m^{-1} and Aluminum's absorption coefficient to be $\alpha = 14.6 \pm 0.5\ m^{-1}$. Evidently gamma ray's traveling in Lead are about four times more likely to interact with matter per unit distance than when the rays are passing through Aluminum. Our measurement of the absorption coefficient also provided enough information to calculate the mass attenuation of each material. We found $\mu_{Pb} = 0.54 \pm 0.02\ cm^2/g$ and $\mu_{Al} = 0.53 \pm 0.02\ cm^2/g$, this result is great agreement with the accepted values for these materials, which can be found on the NIST website.

References

[1] Cobalt-60. URL `http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/betaex.html`.

[2] X-Ray Mass Attenuation Coefficients. URL `http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html`.

[3] David Griffiths. *Introduction to Electrodynamics*, volume 53. 2013. ISBN 9788578110796. doi: 10.1017/CBO9781107415324.004.

[4] David Lide. *Handbook of Chemistry and Physics*. 2003.

[5] Adrian C. Melissinos. *Experiments in Modern Physics*. Academic Press, 2003.