

GAMMA RAY ABSORPTION

Objective

In this experiment we will measure the absorption of gamma rays through different materials. From the measurements, we will determine the mass attenuation coefficients.

Background

- 1) Read Chapter 8 in Taylor on least-squares fitting. Give special attention to pages 194-196 on exponential functions.
- 2) Melissinos pages 312–315.

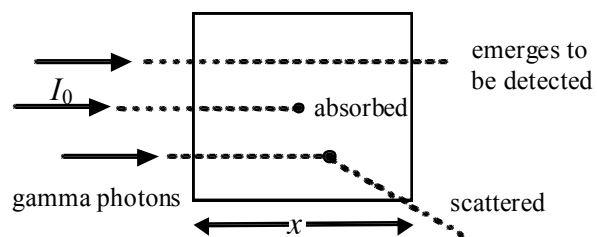
Theory and Apparatus

A beam of high-energy photons traversing a piece of material is attenuated depending on the density and thickness of the material, the energy of the photon, and the atomic number of the atoms in the material. The interaction of the photon with the material is an “all or nothing” process, meaning that either the photon is absorbed or Compton scattered at some point in the material, or it emerges with its full energy. This is very different than a charged particle, such as an alpha particle, which loses energy gradually.

The three interactions of photons in matter are: 1) photoionization of atoms; 2) Compton scattering; and 3) pair production, in which a photon of energy greater than 1.022 MeV creates an electron-positron pair. Interactions 1) and 3) cause a complete loss of the photon, whereas interaction 2) scatters the photon out of a collimated photon beam.

Suppose a collimated beam of gamma rays of intensity I are passing through matter, where I is in photons per second. As the beam traverses a small distance dx , the fractional change in the intensity is

$$\frac{dI}{I} = -\alpha dx,$$



where α is the probability per unit distance that a photon is lost due to one of the above interactions. This probability α will depend on the gamma ray energy and on the material. The negative sign indicates that I is decreasing. This equation is easily integrated to give an exponentially decreasing intensity:

$$I(x) = I_0 e^{-\alpha x}, \quad (1)$$

where I_0 is the initial intensity and x is the thickness of the material. Note that α has units of length^{-1} , cm^{-1} for example. It is called the **absorption coefficient**.

The fact that absorption is exponential applies to light of all wavelengths, not just gamma rays. This has been known experimentally for visible light for a couple of centuries, and Eq. 1 in ordinary optics is called Beer's law.

The **range** of gammas, or their mean distance before absorption, is

$$\lambda = \text{range} = 1/\alpha \quad (2)$$

This is the distance at which the intensity is reduced to e^{-1} . λ has units of length, say cm.

Nuclear physicists usually describe a material not by its actual thickness x but by the quantity $\xi = \rho x$, where ρ is the density. ξ is called the **equivalent matter**, and it has units of g/cm^2 or kg/m^2 . It's the mass of a 1 cm^2 (or 1 m^2) "plug" going all the way through the material. The number of atoms that a gamma ray photon encounters as it passes through a piece of matter is proportional to ξ , and it's the number of atoms that determines the photon's chances of being absorbed.

Lead has a density of 11.3 g/cm^3 . A thickness of 5 cm of lead (≈ 2 inches) has $\xi_{\text{lead}} = 56 \text{ g/cm}^2$. Air has a density of 0.001 g/cm^3 . A thickness of 56,000 cm (≈ 2000 feet) of air has $\xi_{\text{air}} = 56 \text{ g/cm}^2$. Although the thicknesses are quite different, a photon passing through 2 cm of lead will "see" about the same number of atoms as a photon passing through 56,000 cm of air. So to a first approximation, we would expect the absorption and scattering of gammas in 56,000 cm of air to be about the same as in 5 cm of lead.

Write Eq. 1 as

$$I(x) = I_0 e^{-(\alpha/\rho)\rho x}$$

We recognize ρx as ξ . Define the **mass attenuation coefficient** as

$$\mu = \alpha/\rho = 1/\lambda\rho \quad (3)$$

Then the gamma ray absorption is described by

$$I(x) = I_0 e^{-\mu\xi} \quad (4)$$

The advantage of this statement is that μ , unlike α , is largely independent of the target material. The mass absorption coefficient μ has been measured and tabulated for many materials. However, it does depend on the photon energy.

For example, at 1 MeV both aluminum and lead, from opposite ends of the periodic table, have $\mu \approx 0.06 \text{ cm}^2/\text{g}$. Knowing this, we can use the densities of lead and aluminum to predict the range (e^{-1} distance) of 1 MeV gammas:

$$\lambda_{\text{lead}} = \frac{1}{\rho_{\text{lead}}\mu} \approx \frac{1}{(11.3 \text{ g/cm}^3) \frac{0.06 \text{ cm}^2}{\text{g}}} = 1.5 \text{ cm}$$

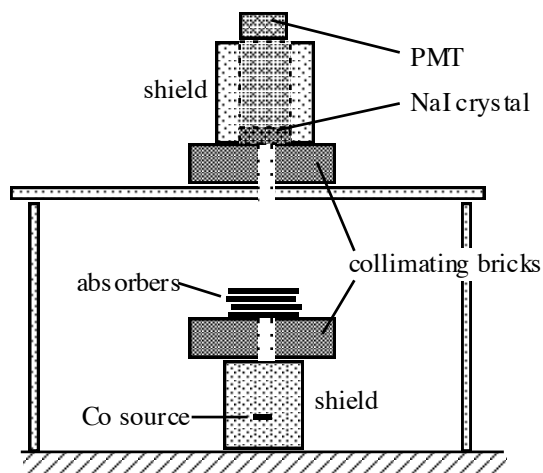
$$\lambda_{\text{Alum}} = \frac{1}{\rho_{\text{Alum}}\mu} \approx \frac{1}{(2.7 \text{ g/cm}^3) \frac{0.06 \text{ cm}^2}{\text{g}}} = 6.2 \text{ cm}$$

If we take the natural logarithm of Eq. 1, we get

$$\ln(I) = \ln(I_0) - \alpha x. \quad (5)$$

A graph of measured values of $\ln(I)$ versus absorber thickness x should be a straight line with slope $-\alpha$. This is how we will determine α experimentally, and from it will obtain λ and μ .

The apparatus for measuring the attenuation of the 1.17 and 1.33 MeV gamma rays from a ^{60}Co source is shown in the figure. Photons from the source pass through a collimator (a hole in a lead brick!), lead absorbers of various thickness, and then strike a NaI scintillation counter. The photopeak pulses are counted for a fixed time with a multichannel analyzer (MCA).



Procedure

CAUTION: The sources used in this experiment, about 0.1 mCi of ^{60}Co , are about 100 times stronger than any others used in this laboratory. One mCi of ^{60}Co produces a dose rate of 1.3 mrem/hr at 1 meter if unshielded. The sources will be well shielded during the experiment, but check carefully for stray radiation with the "micro-R" meter. **AVOID THE PATH OF COLLIMATED PHOTONS.**

1. Set the number of channels on the MCA to 1024, and initially the vertical scale to LOG.
2. The experiment is already aligned so that the gamma rays pass through the holes in the bricks and the shelf. So **DO NOT** move the source or the lead bricks.
3. Hold a ^{137}Cs source next to the detector by *carefully* moving the PMT out of the shield, and record the gamma spectrum as you did in Experiment 6. Turn the PMT high voltage to 500 V, then adjust the amplifier gain to position the 662 keV photopeak between channel 400 and channel 425. Then put the ^{137}Cs sample well away, so that it doesn't give you an unnecessary background.
4. Set the MCA timer for 1-minute *live* time, then record a ^{60}Co decay spectrum. The two prominent photopeaks are from the 1.17 MeV and 1.33 MeV gamma transitions in ^{60}Ni following the decay of ^{60}Co .

Record and print the entire spectrum. Pay careful attention to the details of the spectrum at energies just slightly less than the 1.17 MeV peak and just above the 1.33 MeV peak. Include a decay scheme for $^{60}\text{Co} \rightarrow ^{60}\text{Ni}$ in your report.

5. Set a ROI (region of interest) around only the upper peak (1.33 MeV), excluding all other channels. Using the net counts from your 1 minute data run, estimate how long you will need in order to acquire 10,000 counts. Set this on the MCA timer.
6. Do *not* change the time interval.

NOTE: Use gloves when handling the lead plates.
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Make timed runs to count gammas with 0, 1, 2, 3, 4, 5, 6, 7, and 8 absorbing lead plates. For each thickness record the gross and net counts, as well as the uncertainty. Note that the MCA reported uncertainty is actually the uncertainty of the net counts as a fraction ($\delta N_{\text{net}}/N_{\text{net}}$). The background is equal to the difference between gross and net counts. Measure the thickness of each plate, in cm. Note that you should *not* stack up several and measure the total thickness. Because they're not perfectly flat, a stack will likely include air gaps and is thicker than the lead alone.

7. While you are waiting during the timed runs, write a MATLAB code to confirm the results of the ROI tool. Export the MCA data from *one* run to an .mca file and use MATLAB to read in the data. Then, isolate the data around your ROI (about 50 channels below and above the edges of the region). Fit the following function

$$f(n) = ae^{-\frac{(n-\mu)^2}{2\sigma^2}} + b * n + c$$

where n is the channel number. Finally, use your fitted model to estimate the background counts; they should be equal to the integral of

$$g(n) = b * n + c$$

over your region of interest. Compare with your result from step 6 above. The MCA follows a simpler procedure: it assumes the background is defined by a straight line connecting the end points of the ROI and then uses this line to calculate the background counts. Then,

$$N_{\text{net}} = N_{\text{gross}} - N_{\text{bkg}}$$

The FWHM algorithm and the centroid are then estimated using the *Net* counts.

8. Repeat step 6 with aluminum absorption plates. Start with 0 plates, then steadily increase the thickness until the count rate has dropped by at least a factor of 8. The aluminum plates are quite uniform in thickness, so you just need to measure one.

9. *Carefully* place a big lead brick vertically over the collimating hole so that you have more than 5 inches of shielding. Be very careful not to move the brick with the collimating hole. Then make a timed run to get an reading for the background counts. Compare this number with your results from steps 6 and 7. Are they different? If so, why?

Analysis

The following analysis should be done *twice*, once for your lead data and again for your aluminum data.

1. The net counts, N_{net} , is directly proportional to the gamma ray intensity I . So from Eqs. 1 and 5, we expect $N_{\text{net}} = N_0 e^{-\alpha x}$ and thus

$$\ln(N_{\text{net}}) = \ln(N_0) - \alpha x.$$

A graph of $\ln(N_{\text{net}})$ versus x should be a straight line, and its slope will provide an experimental value for α . So for each thickness one would need to calculate

$$y = \ln(N_{\text{net}}),$$

then use error analysis to determine each δy . What will these uncertainties be? They will all be different.

2. You will need to do a *weighted* least-squares fit of the y data, using your δy as weights. There is a program provided by your instructor to do this in MATLAB. You need to enter your thickness values along with your gross counts, net counts, and net uncertainty percentage you recorded from the ROI tool. Determine the best value of α and the uncertainty $\delta\alpha$.

3. Print out the graph showing both your data, as points, *and* the fitted line.

4. Determine the range λ and the uncertainty $\delta\lambda$ for 1.33 MeV gamma rays in each of your target materials.

5. Determine the half-length $L_{1/2}$ at which the intensity is reduced by half.

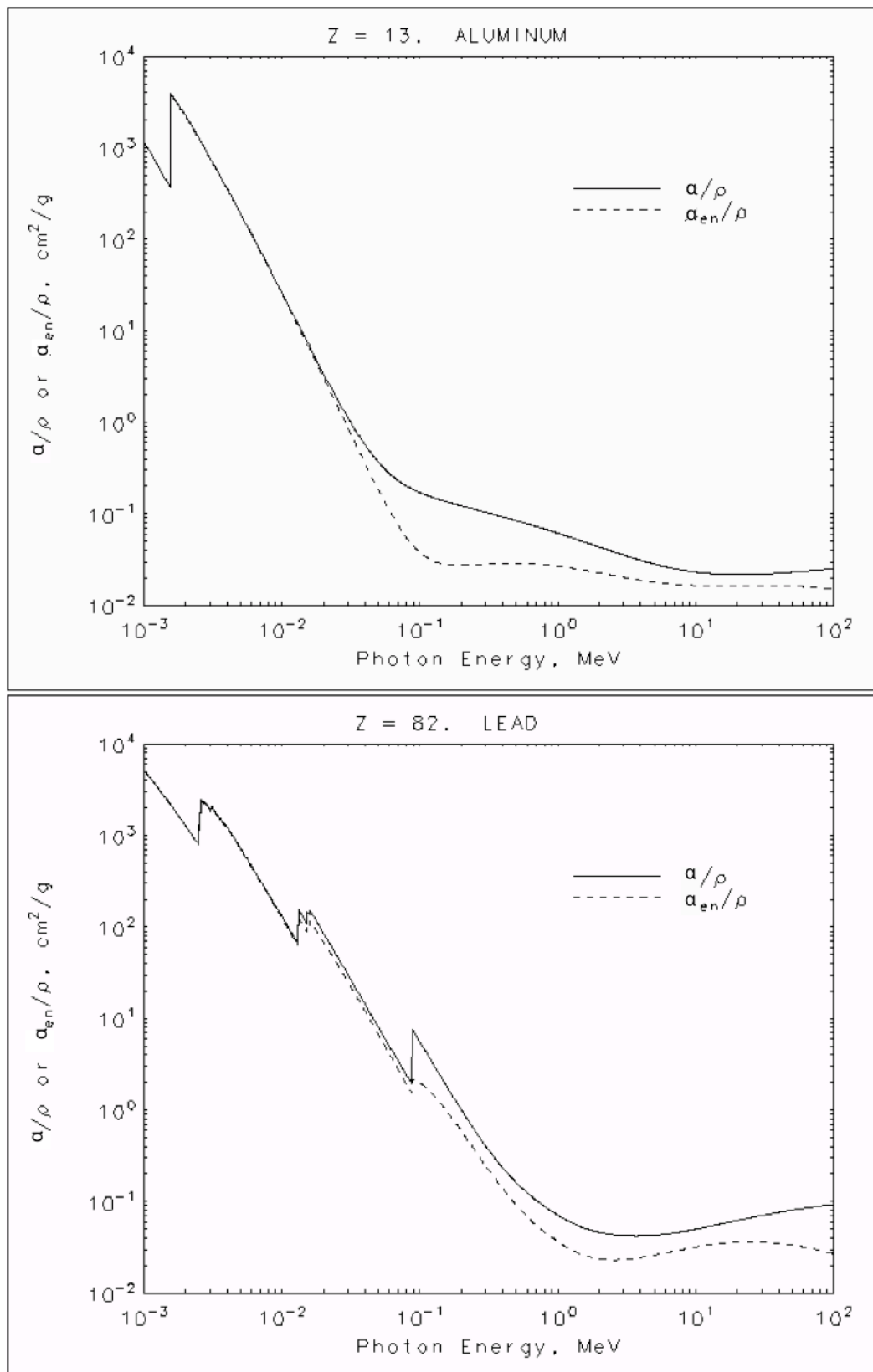
6. Look up accurate values of the densities of lead and aluminum in the Handbook of Chemistry and Physics (or similar). Then compute the mass attenuation coefficient μ and its uncertainty $\delta\mu$. Compare your measured results to the most accurate values you can get using the link under the charts at the end of this writeup. Read the heavy lines, labeled Total Attenuation, at 1.33 MeV. It's the sum of absorption probabilities for various different processes, which are shown separately as the lighter lines. Note that these are log-log graphs. Think carefully about how to read them.

Additional Questions

1. In Step 4, did you notice any difference in the spectrum between energies just a bit below the 1.17 MeV peak and energies just above the 1.33 MeV peak? Can you explain your observations?

2. Did the *energies* of the gamma photons change as you increased the absorber thickness? Explain why or why not? Do you think the same would be true if you measured the energy spectrum of alpha particles passing through matter?

3. Is 5 inches of lead sufficient shielding to insure that your background count was a true background and that it isn't "contaminated" by gammas from the source? Either demonstrate that this thickness is sufficient, or determine a thickness that would be more appropriate.



data from: <http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html>