Radioactivity II: Absorption of Radiation

Introduction

In this experiment you will use the equipment of the previous experiment to learn how radiation intensity is influenced by its passage through matter. **This subject is described in the "Introduction to Radiation" handout in the section titled "Interactions with matter".** We will use two sources during this lab (^{137}Cs and ^{60}Co) which both emit β's and photons, although in different ratios and with different energies. It will be possible to see the β's from one of the sources, but not from the other. Their decay schemes are described in the Appendix B of this handout. We will measure the quantity (μ/ρ), the mass attenuation coefficient, which characterizes how much the radiation is absorbed by the material. This coefficient is quite different for different types of radiation, as discussed in the "Introduction to Radiation". Alpha particles are absorbed very readily, beta particles less so, and gamma particles least, for a given amount of absorber. We measure the amount of the absorber by ρx, the density of the material times its thickness, which essentially measures the number of nucleons (and the number of atomic electrons) per unit area, which the particle is passing through.

Part 1. Background

Recheck the operating point of your Geiger tube and adjacent points, by measuring the plateau using the ^{137}Cs source. Remember that the maximum counting rate should not exceed 1000 counts/sec. After establishing the operating point, measure the background rate keeping all sources of radiation at least 5 or 6 feet away. Count for a time period sufficiently long to determine the background to 5% accuracy. **Hint**: this lab is long. Plan spreadsheets and the rest of your measurements while the background is counting.

Q1. How would you try to reduce the background?
Q2: What is the minimum count necessary to get 5% fractional statistical precision? Hint: see the "Counting Statistics" section of "Introduction to Radiation" from last week.

Part 2: Absorption

Start with the Cs source on a shelf towards the top where the counting rate for the bare source does not exceed 1000 counts/sec. But: check that you have left enough space for a full stack of absorbers between the source and the counter! Point the thin β window of the source towards the counter and count the bare source for 1 minute. <u>All counting measurements with both the bare source and with the absorbers in place should have at least 2% statistical precision</u>.

Your box with absorbers contains a variety of lead and polyethylene absorbers of three thicknesses, given in inches and in [g/cm^2]. If you are not sure of the values, measure the absorber thickness with a caliper and calculate the thicknesses in g/cm^2. For this, you will need the density of lead (11.3 g/cm^3) and of polyethylene (0.96 g/cm^3). All the thin polyethylene sheets are 0.004 inches thick (one inch = 2.54 cm; you can convert in Excel). ***Important note***: wash your hands after this lab, to remove any lead dust from your hands. Another reason to not eat in lab!

For the ^{137}Cs source with its thin β window pointing towards the counter, measure the count rate for 1 layer, 2 layers, 4 layers and 8 layers of the thin plastic foil absorber (9.6 mg/cm^2). Then measure the count rate for plastic absorbers of about 1.6 mm, 3.2 mm, 6 mm

and 12 mm in thickness. **Hint**: start your spreadsheets and plots *now* while taking data: the lab is long. You can do a significant part of the analysis with only the polyethylene data for Cs. Next measure the count rate for lead absorbers of *about* .8 mm, 1.6 mm, 3.2 mm, 6 mm and 12 mm in thickness.

Repeat the latter measurements for the lead absorbers using the ^{60}Co source. You should not need to measure the absorption of ^{60}Co radiation with the polyethylene (you can check by verifying that there is no measureable absorption for a thin poly sheet). Subtract the background from each count for both polyethylene and Pb absorbers. Make sure you express all your results in the same units e.g. counts/sec and that your measurements have at least 2% statistical precision.

Using *Kgraph*, plot the counting rate against $x = \rho t$ in [g cm^{-2}] of absorber using a logarithmic "y" axis. ***See Appendix A on Interpretation of Semi-Log Graphs*** *for help with this analysis.* To start, make 3 plots: all data from Cs source, and lead data from Cs and Co. From the lead data, determine μ/ρ, the mass attenuation coefficient, for each source.

Q3. Can you tell from your curve or otherwise whether you have appreciable alpha particles?
Q4. Do you have substantial beta rays? How do you know?
Q5. Does your data indicate that Cs emits gamma rays? Does Co? Justify your answer.
Q6. Is there evidence of gamma rays of several different energies present in Cs? Justify your answer.

If the *gamma ray part of your polyethylene* data curve is approximately a straight line (exponential absorption), fit an exponential to that part of the data. *Hint*: See semi-log graph discussion, below, and look at the reference material from last lab to decide which parts of which curves represent alpha, beta, or gamma absorption. **Subtract** the values from the fit curve for gamma ray counting rate, determined by this line, from your total curve to get a curve for beta rays only. Now plot beta rays only on a 10 or more times expanded [g·cm^{-2}] scale and fit for the absorption coefficient for beta rays.

Note: The reason we try to identify the gamma-ray dominated part of the polyethylene curve is that the absorption coefficient for poly is sufficiently different than lead that it can't be used for the subtraction accurately.
Further note: if you run out of time in the lab, a short-cut substitute is to draw a straight line by hand on the graph and extrapolate it back to x=0, then subtract the extrapolated value from the smaller-x count rates. This is not as accurate as the suggested subtraction procedure, and requires you to interpolate the value of the x intersection.
Warning: do not attempt to fit a straight line to the semi-log plot: this is *not* equivalent! Drawing a line on the semi-log plot instead approximates fitting an exponential to the data, as described below.

Q7. Are beta rays absorbed exponentially?
Q8. If the Cs source emits approximately equal numbers of beta and gamma rays, what is the approximate efficiency of the counter for gamma rays if you assume every beta ray is counted? (The efficiency is just the fraction of gamma rays counted, if they hit the counter).

Appendix A: Interpreting the Semi-log graphs as absorption.

Exponential Absorption. In the "Introduction to Radiation" handout under "Interactions with matter", we predicted behavior for the radiation intensity as a function of distance into an absorber:

$$R = R_0 \exp\left[-(\mu/\rho)\cdot(\rho t)\right] \qquad (1)$$

where

R = no. of counts per unit time after passing through material of thickness t

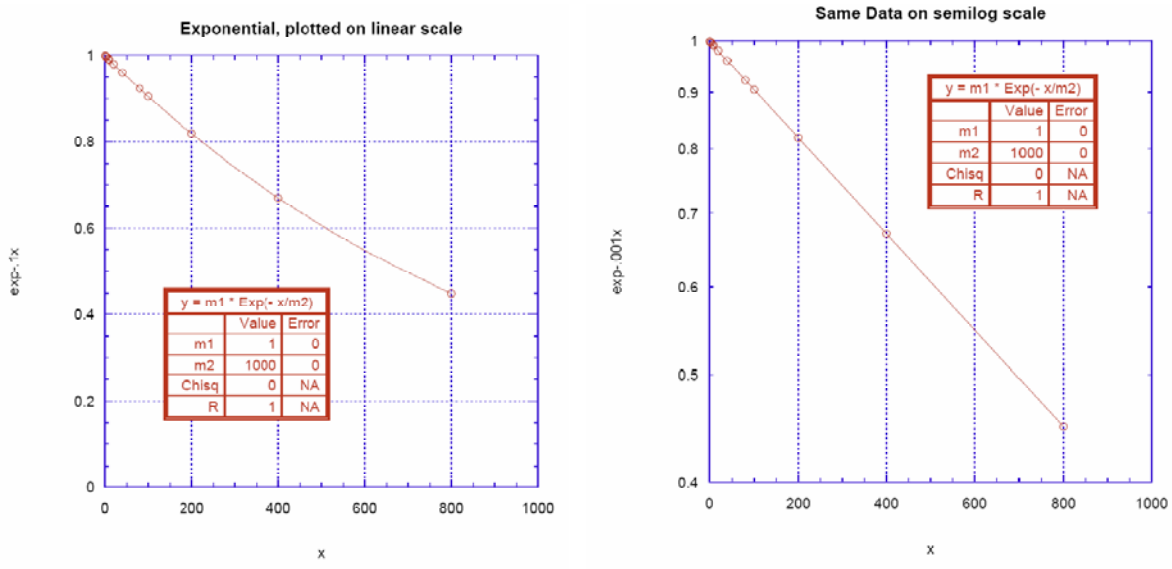
R_0 = no. of counts per unit time before passing through material

(μ/ρ)= mass attenuation coefficient.

ρt = "thickness" in [g/cm^2];

ρ= density of the material [g/cm^3].

The mass attenuation coefficient depends strongly on the kind of particle being absorbed, and more weakly on the kind of material doing the absorbing, and the energy of the particle being absorbed. We choose the peculiar combination μ/ρ because the combination $x = \rho t$ is a good-first approximation description of the absorption effects of a material: a lot of material of low density ρ has about the same effect as a smaller thickness of a much denser material. This happens because ρt the number of protons per unit area through which the radiation passes: most of the weight of atoms is in the nucleus, and about half the weight of the nucleus is in protons. The number of protons is also the number of electrons, so whether the absorption is happening mostly due to interaction with the charged protons in the nucleus, or the number of electrons in the atom, the probability of such interactions should be proportional to the number of protons the particle encounters.



Semi-log Graphs. We want to determine absorption of nuclear radiation, especially β's andγ's, obeys this law, and to determine (μ/ρ), if it does. To do this, we make a graph of R vs. (ρt) using a logarithmic y-axis. Taking natural logarithms of both sides of Eq. (1):

$$\ln(R) = ln(R_0) - (\mu/\rho)\cdot(\rho t) \qquad (2)$$

which is the equation for a straight line, y = b + mx, with b, the y-intercept, equal to log N_o (N_o can be read from the non-linear logarithmic scale at that point) and $-(\mu/\rho)/2.3$ as the slope. Thus you should expect to observe a straight line if you plot with a logarithmic y-axis.

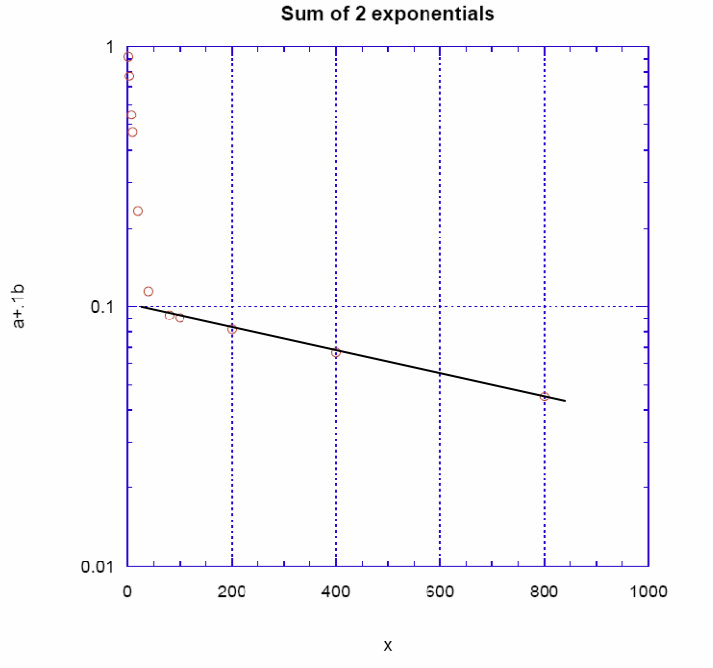
In the example plots above, we have plotted the *same* data (an exponential curve) on both a linear and a semi-log scale; we use the term "semi-log" when only the y axis is logarithmic, and "log-log" when both the x and y axes are logarithmic. Notice the unequal spacing of the tick marks on the semi-log scale on the right. The semi-log plot allows you to simply enter data without taking the logarithm, but displays the y axis with y-coordinates data points spaced logarithmically instead of linearly.

For the chosen range of x, the curvature is only strongly visible for the last data points on the linear scale, though it is clearly linear on the semi-log scale. This is a warning that you may need to use a sufficient range of x axis values to observe the curvature.

Some further hints for using *Kgraph* successfully for this experiment:
Semi-log plotting in *Kgraph*:
Axis Options | Y | Scale | Log then Ticks | Minor Interval |Display Tick |In General Fits:

1) You must give non-zero starting values for all parameters
2) For nonlinear fits, you may actually have to give a decent guess as a starting value
3) Think about whether you need a + b Exp(-cx), or just the exponential.

Subtracting two absorption curves. When your data is curved on a semi-log plot, that probably is a hint that you are dealing with two sources of radiation with different attenuation curves, one steeper than the other.



A good way to deal with this situation is to fit data for the flatter attenuation curve first (ie at larger x), since the other radiation source will have died out and not contaminate the second, "slower" attenuation curve very much. In the example curve above, the last 4-5 points lie on a good straight line, even though the data is actually a sum of two exponentials,

f = Exp(-.1x) + .1 Exp(-.001x).

These last 4-5 points would correspond to absorption of the harder-to-absorb component of the combined radiation. Because in the example the absorption coefficients differ by a factor of 100, under the last 4-5 points, the first (easier-to-absorb) component has died out to an almost completely negligible level. In fact, for the 4^{th} and 5^{th} points the two exponentials contribute (.00034 + .09231) and (.000045 and .090484) respectively.

If you fit only the data points at larger x, where the first component is negligible, then you can take the resulting fit curve and, point for point in x, *subtract* the fit from your data at smaller x, where the first radiation source is commonest: this removes the effects of the second (harder to absorb) kind of radiation from the data describing the more easily-absorbed (soft) radiation. Fitting to a sum of 2 exponentials, while elegant, seems to be hard to get right. And if you started including too many points at small x, you would not only get a poor fit, but you would also be subtracting not just the hard component, but also some of the soft component as well—so that subtracting this combination would seriously distort the subsequent fit to the easy-to-absorb component.

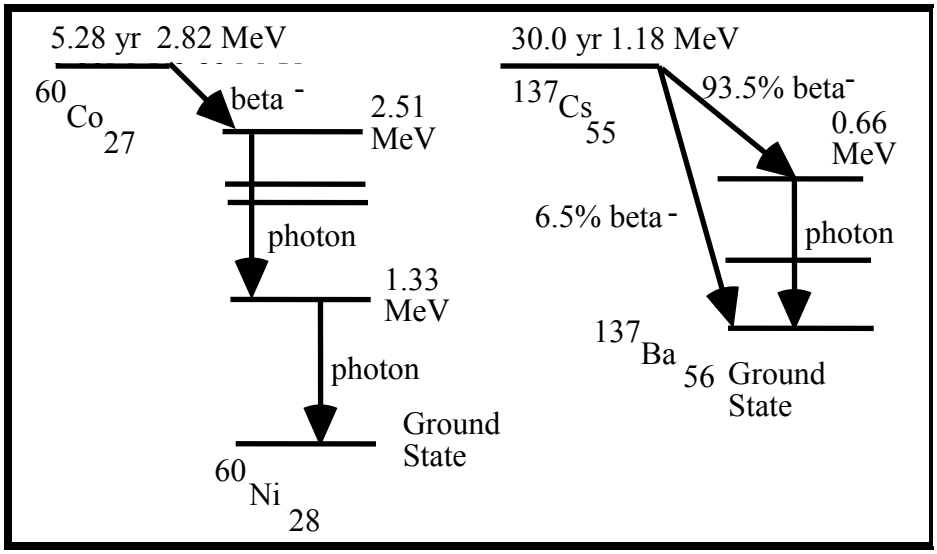
You will have to be sure to select only points not contaminated by the first kind of radiation in order to get the curve for the harder-to-absorb radiation right; selecting only Pb points would not help, since μ/ρ but differs between Pb and polyethelene (even for the same type of radiation). You need to find polyethelene points which are unaffected by the easily-absorbed component. You should also check to be sure that all the points you are going to fit lie on a straight line on the semilog plot.

Next: how can we fit to only selected points? One way is just to erase data points at low x which are contaminated. A more elegant way is to mask them off:

Masking data in *Kgraph* provides a way to leave data in the data window but not have it used in any calculations, curve fits, or plots. Any cells that are masked have a red frame in the data window. Data can be masked in the data window by clicking them and clicking the left red grid-looking Mask frame button; the other buttons reverse the mask or unmask.

APPENDIX B (Keep for reference in later experiments)

Decay schemes for ^{60}Co and ^{137}Cs



The isotope notation $^{137}Cs_{55}$ indicates an isotope of Cesium (element 55, with 55 protons) which has 137-55=82 neutrons. Vertical arrows represent simple transitions from one nuclear energy level to another, which result in emission of a photon whose energy is equal to the difference in energy levels. The sloped arrows represent a beta decay which results in an electron and a neutrino being emitted. The beta electron does not have a fixed energy but rather a spectrum which has a maximum value; a typical value might be about half the maximum value.

The Cs sources we use have thin windows (for easier transmission of betas), while the Co sources do not have a beta window. Also the Co beta energy is much less than for Cs. Some more details of the decays are given below:

^{60}Co: This isotope has a half life of 5.28 years and beta decays to the excited states of the stable nucleus of **^{60}**Ni. In 99.9% of the cases the ^{60}Ni (2.51 MeV 4th excited state) is formed, with a maximum beta energy of 0.31 MeV. The excited state subsequently decays in less than 10^{-12} sec to the ground state via the emission of 2 photons, one with energy 1.17 MeV and one with 1.33 MeV.

^{137}Cs: This isotope beta decays with a half-life of 30.0 years, with 93.5% of the decays creating ^{137}Ba in its 2nd excited state at 0.66 MeV and 6.5% creating ^{137}Ba in the ground state. The maximum beta energy is 0.52 MeV for the decay to the excited state, and 1.18 MeV for the decay directly to the ground state. The excited state has a half-life of 2.55 min. and decays 90% of the time through the emission of a 0.66 MeV photon and 10% of the time with the emission of an atomic conversion electron of a similar energy, equal to 0.66 MeV minus the binding energy. So 84% (= 0.935 * 0.90) of all beta decays of this isotope produce a photon in the final state.