Energy Loss and Range of Alpha Particles

References: W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd ed.*, Ch. 10 for discussion of semiconductor detectors and Ch. 2, sect. 2.2 for discussion of energy loss of heavy charged particles; also G. F. Knoll,* Radiation Detection and Measurement, 2nd ed.*, Ch. 2 and Ch. 11, and A. C. Melissinos,* Experiments in Modern Physics, 1st ed.*, pages 208-217 covers similar topics.*

When a "heavy" charged particle (i.e., other than an electron) passes through matter the primary mechanism for energy loss is ionization of atoms through collisions with electrons. At very high energies the kinetic energies, where KE $\geq Mc^2$, where M is the mass of the particle, the energy loss rate dE/dx of a particle depends, to first order, only on the number of electrons per cm^3 of the material. Hence, virtually all materials incur roughly the same energy loss per mass thickness, defined as the material's density ρ times the distance traveled x (units of g/cm^2), for a given particle species and particle energy. (The big exception is hydrogen, for which the energy loss per g/cm^2 differs from other materials by a factor of $\sim$2. Why do you think this would be?) However, when particles that have low energy, with v much smaller that c, pass though different materials the energy loss rate depends more strongly on the nature of the material. This dependence arises because some of the atoms of higher Z atoms are harder to ionize because of the electrons' greater binding energy.

Exercise 1 *Americium-241* (^{241}Am) *emits alpha particles of 5.49 MeV. Is a 5 MeV alpha particle non-relativistic? What is v/c? How are the Kinetic energy and velocity related for a 5 MeV alpha particle?*

Use the setup described below to study the energy loss of alpha particles passing through various amounts of gases. Three quantities may be directly measured: (a) the energy of the alpha particle after it has passed through a known amount of gas, (b) the spread in its energy, and (c) the total count rate (regrdless of energy). These may be obtained from a pulse height spectrum from the solid-state detector output.

From these you can obtain the rate of energy loss, $dE/d(\rho x)$ as a function of gas thickness ρx in grams/cm^2 (to see the so-called "Bragg curve"), the energy loss as a function of energy E (to compare with the prediction of the Bethe-Bloch formula, as given in Leo section 2.2), and the "range" or penetration depth of the alpha particles in air or another gas. You may also be able to measure the energy and range "straggling," which is the variation in energy loss and range.

1 *Aspects of the apparatus*

1.1 Solid State Detectors

In both gaseous ionization chambers and solid-state detectors the ion pairs that are created by the passage of a charged particle contribute to the electrical signal. The number of ion pairs created is proportional to the energy loss of the particle in the material. The resolution depends on the number of ion pairs created although not in a very simple way. A solid-state detector is, in essence, a solid state "ionization chamber" formed by the depletion region of a back-biased silicon semiconductor diode. Under normal circumstances and temperatures very little reverse current flows in the detector diode. A charged particle that passes through the diode creates, on average, one electron-hole pair for every 3.6 eV of energy loss. An important difference between solid-state detectors and gaseous ionization devices is that in a gas about 30 eV of energy loss is required per ion pair. Thus in a solid-state detector a very much larger number of ion pairs will be created and the energy resolution will be substantially better. Strong electric fields in the junction sweep the electrons and holes to the electrodes and create a current pulse in the detector.

Each particle that passes through the detector produces a pulse of reverse current with the total charge in the pulse being proportional to the energy lost by the charged particle. The total charge in the pulse is measured by an electronic system consisting of a charge sensitive preamp producing a long "tail pulse" whose amplitude is proportional to the charge of the current pulse in the detector. This pulse is shaped and amplified by a pulse amplifier to give an output suitable for the pulse height analyzer.

1.2 Practical considerations

Never touch the active region of the alpha source. It is bad for you and the source. Unlike gamma sources, alpha sources cannot be encapsulated in plastic because the alpha particles are so heavily ionizing that nearly all would be stopped in such a material. (As you will see, even a few centimeters of air will stop all of the alphas from ^{241}Am.)

With the lid off the chamber, check that the alpha source is positioned above the detector. Put the lid on the vacuum chamber and make sure it is tightly pressed against the rubber gasket. (There is a very light coating of grease on the rubber to improve the seal.) Turn on the power supply for the pressure gauge, the gauge itself, and the digital multimeters. With all valves initially closed, start the vacuum pump. Then open the valves to evacuate the chamber; you should leave the pump running during the experiment; just use the valve to engage the vacuum pump to the chamber when needed.

Check that the input of the small ORTEC 121 preamp is connected to the detector, the preamp output is connected to the input of the shaping amplifier (ORTEC 485 or 575A), and the bias input is connected to the interface box to the HP power supply.

The shaping amp polarity should be "POS" and you should use the "UNI OUT" output to the pulse height analyzer. The back-bias voltage for the detector is supplied by the HP Harrison DC power supply. The DC supply feeds the bias voltage into the preamp through a 1 MΩ resistor. This resistor helps protect the detector in case of a short circuit. The DC supply should be OFF when you hook things up. Never change the preamp connections with bias voltage ON. The input circuits of the preamp are quite delicate and are easily damaged. **Under no circumstances exceed a bias voltage of +40 V. It may destroy the detector.** The detector is sensitive to light so it must be biased and operated in the dark (inside the vacuum can).

Look at the output of the shaping amplifier on a scope and observe the positive pulses. You can see these even without any bias voltage. To start, adjust the amplifier gain so that the amplitude of the pulse is $\sim$7 V. Turn the scope gain up so that you can see the noise level of the amplifier output. Now slowly raise the bias voltage in the Harrison DC supply to +35.00 volts. You should see the noise level decrease somewhat. Connect the amplifier output to the pulse height analyzer. You are ready to take data.

Before using the compressed gas cylinders to add gas to the vacuum chamber check with the TA for procedure. When you finish the experiment and leave be sure that the vacuum pump is off and the main valves on the gas cylinders are closed.

Carefully measure the source to detector distance using a plastic caliper. Do NOT touch the surface of the detector or the underside of the Am-241 source. (Your value should be between 43 and 47 millimeters, but attempt to determine it to within ± 0.2 mm.)

2 *Calibration and Data Collection*

Calibration of the measurement can be done with two points, if we assume linearity in the detection system. The zero can be found by sending in a series of known amplitude pluses from a pulser unit, like the ORTEC model 480. Use a good digital scope to measure the pulse amplitude, and find the intercept of pulse height versus PHA channel/voltage to get the voltage/channel corresponding to zero pulse height. The other point comes from the known energy of the alpha particles, which you can measure when the chamber is at its best vacuum. (For quick analysis, you can use the single point of the full-energy alpha if you are confident that the zero-offset is small.)

Before running the calibration, adjust the pulse amplifier gain so that the peak under good vacuum is a little bit below the top of the pulse height analyzer range. (You need to be able to see the whole peak.) Since most pulse height analyzers have a maximum input of 10 volts, the amplifier gain should be set to make a pulse height of about 9 volts or a bit higher.

Zoom in on your calibration peak from the alpha source. Can you see more than one particle energy? Look in a table (or chart of nuclides) to see the known particle energies and relative decay frequencies (also called "branching ratio"). Check the energy spacing, peak width and relative amplitude, and compare with tabulated values. Record the energy resolution in percent. Apply your calibration to the measurements to get the resolution in keV.

Once you have established the energy scale and checked that the resolution is acceptable you may proceed with the rest of the measurements, of course without changing any amplifier/PHA gains or detector bias voltage.

Recommendations on data collection: (1) Save your raw data sets. You may want to go back and look at them. (2) Record the peak widths and peak positions in channel-numbers or voltages (depending on the PHA system you use), and use the PHA's analysis software to get these. (3) Record your data with at least 4 significant figures. You will be taking differences of numbers that are close together to get $dE/d(\rho x)$, so if you round up too early, you may get a poor final data set. (4) Set the PHA to count for a fixed time or fixed number of counts. This will make it easier to calculate the total count rate.

One particular challenge: due to noise, you may see a lot of "counts" at the very lowest end of the pulse height spectrum. You should set the PHA discriminator to block these, but not by too much, or else you will not be able to follow the alpha-particle peak at the low end.

Measure the peak position E and peak width w as a function of the pressure of the gas, reported as volts from the pressure gauge. You will want to take first differences $(\Delta E/\Delta(\rho x))$ when you analyze the data set, so make sure that your data points are closely spaced enough to follow the change in slope of the curve. (Your data set should have 25-30 points to cover the full range of pressure.)

When you get to the higher-pressure end of the data set, you will need to proceed carefully in order to obtain good data for range and energy straggling. Keep an eye on the signal with the scope, and if necessary, make adjustments to the pulse height analysis system so that you can measure the much smaller peak distributions.

Also: Record counting rates: *total counts* in unit time (regardless of energy). You will need this information for the range and range-straggling data set. Again, this information requires dealing with the noise pulses at the low end first.

Repeat the measurements so that you have a full data set for both air (mostly nitrogen gas, N_2) and helium.

3 *Analysis*

First make three graphs from your raw data:

- a graph of the energy measured E (in MeV) of the 5.49 MeV alpha particles as a function of the mass thickness ρx (in gm/cm^2). You will need to convert the pressure measurements in volts from the pressure gauge to density ρ and apply your energy calibration to the peak positions. (Hint: use the ideal gas equation of state $PV = nRT$, the pressure reading at one atmosphere, and the molecular mass of the gas.)
- a graph of the difference in peak width from zero pressure, Δw (in MeV) also as a function of mass thickness. This quantity should be calculated from the width w and the width at vacuum w_0 by subtracting them in quadrature:

  $$\Delta w = \sqrt{w^2 - w_0^2}\ . \tag{1}$$

  (The reason for this method of subtraction is discussed below.) Then plot the increase in the width, Δw, as a function of gas thickness ρx.
- a graph of the total counting rate (or counts per unit time) as a function of ρx. For air, you should see the counting rate be almost constant, and then drop suddenly. Where it drops is the "range" of the alpha particles for this particular source.

Make these graphs for air and helium, with data from both gases on the same plots so they can be compared. (Note: if the x-axis ranges of the data sets from helium and air are the same, you have made a mistake. You should understand why.)

To derive the curve of energy loss from these curves, you need to take first differences of E vs. ρx, to find $-\Delta E/\Delta(\rho x)$. (Note the minus sign. Why is it there?) Do this, and compare your curve to the Bragg curve for energy loss (Fig. 2.5 in Leo or Fig. 2-2 in Knoll).

The curve of energy loss from first differences should resemble the curve of Δw vs. ρx. To see why think about the rule for uncertainty propagation. Assume you measure the energy as a function of mass thickness, $E = E(\rho x)$ and that the peak at that energy has a width $w(\rho x)$. The uncertainty in the energy σ_E should be related to the uncertainty in the mass density $\sigma_{\rho x}$ and the uncertainty due to the detector resolution σ_R via the formula

$$\sigma_E = \left[\left(\frac{dE}{d(\rho x)}\right)^2 \sigma_{\rho x}^2 + \sigma_R^2\right]^{1/2}\ . \tag{2}$$

If we associate the peak width w with the uncertainty σ_E and the peak width at zero pressure w_0 with the uncertainty due to detector resolution σ_R, then we see, by squaring both sides of the

Substance	I (10^{-6}MeV)	ρ_0 (g/cm^3)	Z	A (g/mol)
He	41.8	1.663×10^{-4}	2	4.0026
N_2	82.0	1.165×10^{-3}	7	14.0067
Air	85.7	1.205×10^{-3}	0.4992	(Z/A average)
Ar	188	1.662×10^{-3}	18	39.948

Table 1: Data of gases used in the alpha particle energy loss experiment. Z and A are per atom, not per molecule. Note: the density of the gas ρ_0 is given at $T = 20°$ C and $P = 1.0$ atmosphere. The Z, A data for air is a weighted average of its constituents, mostly nitrogen (N_2). For this material, only the ratio of Z/A is given. Data come from Sternheimer et al, Phys. Rev. B, vol. 26, pp. 6067–6076 (1982).

above and rearranging, that Δw as defined earlier is proportional to $|dE/d(\rho x)|$, if the uncertainty in ρx is constant. Thus, a plot of Δw versus ρx should mirror the $dE/d(\rho x)$ curve derived from first differences.

When you make the plots with the results from the different gases on the same plots, you may notice that the curves lie near each other, but not on each other. This is because the assumptions described above are only approximate. In fact, the energy loss does depend on chemical species that the alpha particles pass through. For energy above a couple of MeV, the energy loss is better described by a formula that takes both relativistic effects and a "mean excitation potential" of the material in the gas. This formula is called the Bethe-Bloch formula. For relatively low energy alpha particles (below 100 MeV), a simplified form of this formula is

$$-\left(\frac{1}{\rho_0}\right)\frac{dE}{dx} = K\left(\frac{Z}{A}\right)\frac{4}{\beta^2}\left[\ln\frac{W_{\rm max}^2(\beta)}{I^2} - 2\beta^2\right] , \tag{3}$$

in which $K = 2\pi r_e^2 m_e c^2 N_{\rm a} = 0.153535$ MeV-cm^2/g, Z is the atomic number of the atoms in the gas (unitless), A is the atomic weight of the gas molecules (g/mol), $\beta = v/c$ of the alpha particle, and I is the "mean excitation potential" of the atoms in the gas (MeV). (See Leo, p. 24 for the full formula.) The parameter $W_{\rm max}(\beta)$ (also MeV) is a function that gives the maximum possible energy transfer between an alpha particle and an electron. This function (again in the lower energy range) is given by

$$W_{\rm max}(\beta) = \frac{2m_e c^2\beta^2}{1-\beta^2} , \tag{4}$$

in which $m_e c^2$ is the rest-mass energy of an electron, 0.5110034 MeV.

Use your results to compare against the Bethe-Bloch theory by calculating the theoretical curve of Eq. (3) versus deposited energy E against your data for E and $-dE/d(\rho x)$. You will need a computer to do this, either with a spreadsheet or language like Python or Matlab. For reference, the constants in Table 1 come from *Sternheimer* et. al, reference [2.3] in Leo.

Some things to consider and discuss in your notes and report:

- The Bethe-Bloch theory is supposed to break down at very low energy, when the velocity of the alpha particle can steal electrons from the gas atoms to become helium atoms. At what energy in your data do you see this breakdown? How does this compare to the (approximate) value described in Leo?

- How important is it to use the full relativistic energy expression to get β? Calculate the error you make if you use the classical energy $M_\alpha v^2/2$, where M_α is the mass of the alpha.
- Discuss the range data you collected for air as the medium. Can you also find the range straggling curve?
- In your raw data, the peaks themselves have an asymmetric shape. Describe this, and compare what you see to the energy loss distribution theory discussed in Leo in section 2.6 (pp. 49–53).

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`alpha_range.tex -- Updated 8 December 2021`