Physics 4780: Atomic and Nuclear Physics Laboratory, Fall 2010

Experiment B5: Alpha Particle (He^{2+}) Spectroscopy with Surface Barrier Detectors

A. Introduction to Surface Barrier Detectors

The surface barrier detector is a semiconductor solid-state detector. Like the high purity germanium (Ge) detector, it is essentially a p-n junction device. However, it is made out of a silicon (Si) wafer rather than a large Ge crystal. These differences (Si vs. Ge, and a wafer versus a thick crystal) are closely related to the fact that we are detecting charged particles (very short range due to strong interaction) in the surface barrier detector and (uncharged) high energy photons in the Ge detector (quite long range). When a charged particle passes the p-n junction, it ejects electrons from the Si, slowing itself down. This process repeats until the charged particle losses all of its kinetic energy and stops inside the Si (if the thickness of the Si is enough to stop the particle). The average electron ejection energy in Si is about 3 eV. For a 5 MeV alpha particle, the stopping distance in silicon is about 25 μm, and about 1.67 million electrons will be produced. Usually, the p-n junction is biased such that generated electrons are collected and together create a pulse indicating passage of a charged particle. For a sufficiently thick Si wafer that stops a charged particle, the number of electron-hole pairs generated will be proportional to the incident energy of the charged particle.

The Si diode surface barrier detector used for this lab in Spring 2010 is 150 mm^2 in area (with the assistance of the instructor or TA, this should be confirmed the first week at the start of each lab session, and prior to initiating the vacuum pump).

B. Energy loss of alpha particle in matter

For alpha particles coming naturally out of radioactive nuclei, their energies are typically between 3 and 7 MeV. The β-factor (β =v/c) of these particles is very small (e.g., ~0.05 for 5 MeV alpha particles). In this case, the nonrelativistic formula for energy loss *dE* of charged particle in matter of length *dx* can be written as (see Reference 1):

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} n_e \ln\left[\frac{m_e v^2}{\bar{I}}\right] \qquad (1)$$

where all units are in c.g.s. system with:
z: charge of the incoming particle (in integral units of the electron charge, e);
v: velocity of the incoming particle;
n_e: electron density of the scattering material;
I: average ionization energy of the scattering material;
m_e: electron mass.

Since the numerical number inside the logarithm changes slowly, the energy loss is characterized as proportional to ($z^2 n_e$) and inversely proportional to (v^2). For a given alpha source then, the energy loss is proportional to the electron density of the scattering materials n_e.

C. Range of alpha particles in matter

Equation (1) can be integrated to get the range R of the alpha particle in matter. The range is defined as the total length of material in which the alpha particles traverse before coming to rest. [We will measure the range of our specific alpha particles (emitted from ^{241}Am) in air and in CO_2, at 1 atmosphere pressure. See below.] From this definition, we can write:

$$R = \int_0^R dx = -\int_{E_0}^0 \frac{dE}{f(E)} \qquad (2)$$

where $f(E)$ is the right-hand side of Equation (1) and $E = \frac{1}{2} M v^2$ with M being the mass of the alpha particles.

For a given alpha source, the range can be easily figured out from the definition of the $f(E)$ to be inversely proportional to the electron density of the scattering materials n_e.

This experiment consists of four parts:

1. Calibration of the MCA channels by pulser and ^{241}Am source;
2. Measurement the activity of the ^{241}Am;
3. dE/dx curves for ^{241}Am alpha particles in air and in CO_2.
4. Measurement of ranges of alpha particle in 1 atmosphere of pressure of air, and of CO_2.

For the convenience of using the calibration results, you may do part 1 and part 3 first and then part 2 and part 4.

D. Electronics setup:

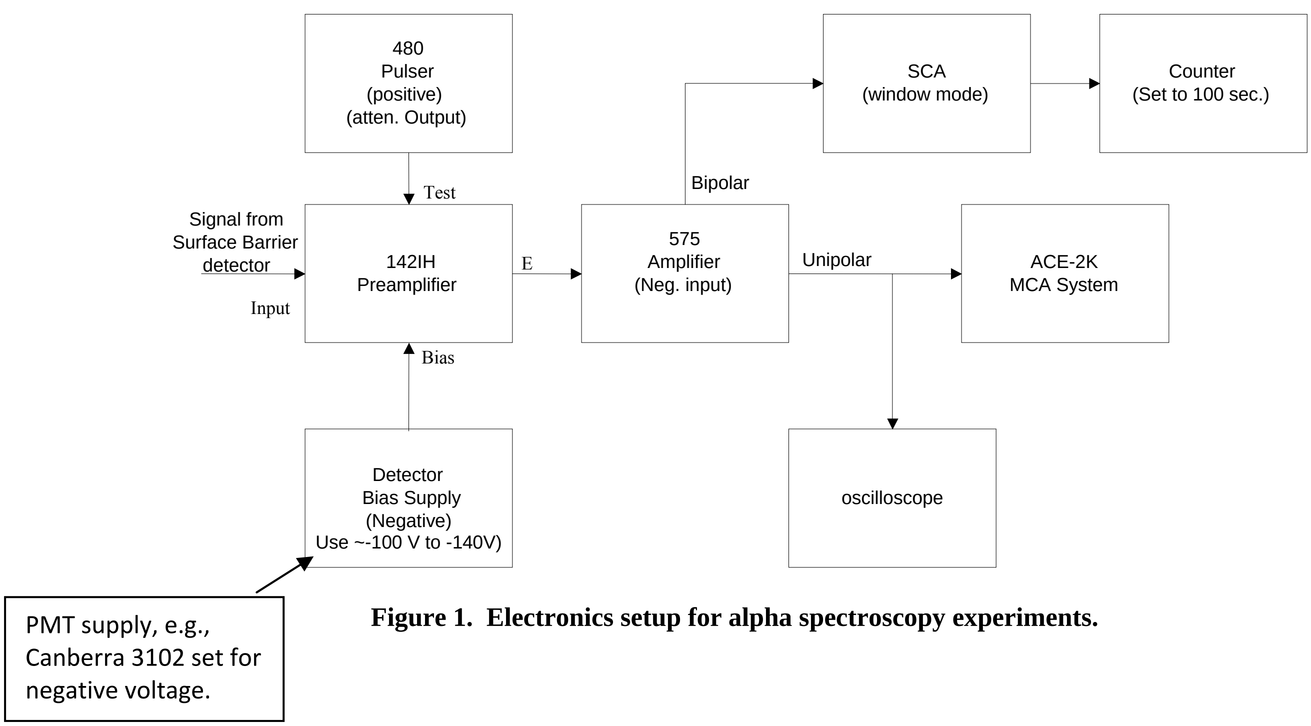

Figure 1. Electronics setup for alpha spectroscopy experiments.

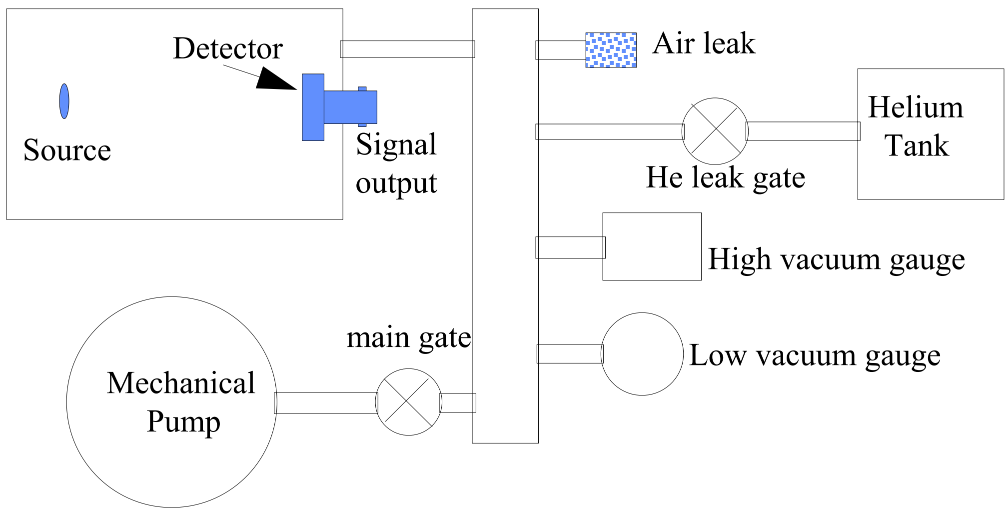

Figure 2. Vacuum chamber and monitoring configuration

Procedures:

Part One: Energy calibration using pulser and ^{241}Am source:

1) Prior to beginning the experiment, ensure that you can read the source-detector distance accurately from outside the vacuum housing. With assistance from the instructor or TA, establish the position calibration using a ruler and the distance scale attached to the chamber. Record the position and corresponding distance scale reading so that you can determine the source-detector distance without again opening the vacuum chamber.

2) Connect the electronic modules according to Figure 1. Set the position of the ^{241}Am alpha source to be about 1 cm in front of the surface barrier detector. Before pumping down the vacuum inside the chamber, check the following (refer to the Figure 2): close the air leak valve; close the leak valve; and open the main gate valve to the mechanical pump. Start pumping the chamber and watch for the reading on the vacuum gauge. In about 2 minutes, the reading, which indicates the magnitude of the pressure differential relative to atmospheric pressure (1 atm = 760 mm Hg), should approach 740 mm Hg. Our gauge reads 740 mm Hg at our lowest vacuum (i.e., ~ 0 mm Hg), while one would expect it to read 760 mm Hg, so either the gauge is off by 20 mm Hg at an actual pressure of 0 mm, or the vacuum only reaches 20 mm Hg. If the relative vacuum does exceed 740 mm Hg at that time, it likely indicates a leak somewhere. Check the seal of the main chamber and the tightness of the air leak valve and CO_2 leak valve. If the relative vacuum exceeds 700 mm Hg, (i.e., if the value on the gauge is < 700 mm Hg) let the pumping continue for another 5 minutes.

3) Slowly raise the bias voltage to the surface barrier detector from 0 V to -150 V. Do not supply more than -150 V to this detector. Adjust the gain of the 575 amplifier so that unipolar signal height in the oscilloscope is about 5.48 volt.

4) Accumulate the spectrum with the multichannel analyzer (MCA) long enough to have about 400 counts in the peak channel. Use the utilities in MCA to determine the centroid channel number for the peak. Record this centroid channel as C_0.

5) Turn on the 480 pulser and set its pulse-height dial at 548/1000. (The ^{241}Am alpha particle is emitted with 5.48 MeV energy). Adjust the attenuators and the calibration control until the pulse on the oscilloscope is about 5.48 V. Accumulate the pulse from the pulser for about 20 seconds. Check if the peak from the pulser has the same centroid channel as the C_0, the centroid peak from the ^{241}Am alpha source. If not, carefully adjust the calibration control on the pulse generator such that the pulse peak is the same as the C_0. After this calibration, the reading of the pulse-height represents an energy scale, that is, 548/1000 represents 5.48 MeV and 600/1000 represents 6.00 MeV and so on.

6) Erase the MCA and get channel numbers for the energies from 1.00 to 8.00 MeV at 1 MeV interval by setting the pulse-height at 100/1000 to 800/1000. Accumulate at each point for about 30 seconds. Record the peak location and peak width for each energy. Perform a linear fit to find the energy calibration equation for the run and the energy resolution in keV.

Part Two: Measurement of activity of the ^{241}Am source:

1) Set the source-detector distance to about 5 cm by moving the source. The scale outside the vacuum chamber can be used for this purpose. (Note the maximum separation is 7 cm.)

2) Accumulate the spectrum for long enough to have the peak counts about 1000. Set the region of interest using the MCA utilities and find the total counts under the peak. Using the results for the number of counts under the peak, together with the Live Time for that measurement, calculate the activity in μCi from the definition:

$$1\ \mu\text{Ci} = 3.7 \times 10^4 \text{ disintegrations/sec (into } 4\pi \text{ steradians)}.$$

The surface area of the circular surface barrier detector used in this experiment is 150 mm^2.

3) Repeat the activity calculation twice more using source distances of 3.5 cm and 2 cm. Use these three measurements to establish the best value for the activity of the source.

Part Three: Energy loss of Alpha particle in air and CO_2: (Parts three and four may be combined using one set of data.).

1) Notice that when we have air in the chamber, we see that the alpha particles do not arrive at the detector. Alpha particles lose energy as they travel through the air, due to interactions between the alphas and the molecules in air. The density of air molecules in the chamber is controlled by allowing air to enter the chamber with the air inlet valve. The density can be determined using the ideal gas law:

$$PV=nRT \qquad (3)$$

Where P is pressure (which we decrease by evacuation and then increase again by leaking air (or CO_2) into the chamber, V is volume (fixed for the case of our chamber), n is the amount of substance, R is the universal gas constant ($8.314472\ \text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$), and T is the temperature in Kelvin. Although you won't need to compute any absolute values from the ideal gas law, note that it can be written also as:

$$\frac{n}{V} = \frac{P}{RT} \quad (4)$$

Which shows that for fixed temperature (and remembering that R is a constant), the density (proportional to n/V) of gas molecules in a fixed volume (e.g., our chamber) varies linearly with the pressure. So when compared to atmospheric pressure (760 mm Hg), the density of air (or CO_2) molecules is ½ that when the pressure drops to 380 mm Hg. This relates directly to the concept of "effective air length" (or just "effective length") referred to in item 6) below and again in Eqn. (5) also below. In particular, the effective length in air varies linearly with pressure in the chamber, so that if t he actual distance from the source to the detector is x, then when the pressure is zero, the effective distance (length) is zero since there are no (or almost no) molecules in the path. When the pressure is increased to one tenth of an atmosphere, the effective length is one tenth of the actual length since the density is one tenth that of atmosphere. So we're talking about <u>the effective length in air at one atmosphere</u> when the pressure is something other than one atmosphere (in our case the pressure is always less than one atm).

2) The energy loss of alpha particles in air can easily be measured by changing the pressure of the air which the alpha particle traverses. The lower the pressure inside the chamber, the fewer the air molecules that alpha particle will encounter when an alpha particle travels from the source to the detector, therefore, the smaller the energy loss for alpha particles.

3) Set the source-detector detector to about 4.0 cm. Close all leak valves and open the main gate to pump down the vacuum inside the chamber. After 5 minutes pumping, the vacuum inside the chamber should be in the range of -744 mm Hg (relative to atm), which is low enough that all alpha particles will reach the detector without measurable energy loss.

4) Close the main gate to stop the pumping on the chamber. Slowly leak in some air by slowly open the air leak valve. Watch the MCA for the energy peak to be about 0.5 MeV below the full energy peak (use the calibration to determine how many channels is equivalent to 0.5 MeV). Erase the spectrum and start to accumulate the spectrum for this energy loss for long enough such that the peak channel reaches about 100 counts. Stop and save the spectrum. Record the pressure in the high vacuum gauge.

5) Repeat the step 3) for the energy loss values of roughly 1.0 1.5,... 4.0 MeV. Do not forget to save the spectrum for each energy loss.

6) Determine the centroid of each energy loss peak and convert them to energies by the calibration curve. Convert the 4.0 cm source-to-detector separation into <u>effective length</u> in air by the equation 3. Plot the average energy of the alpha particle vs. the effective air length. This is an E(x) curve. By taking the difference of ΔE vs. Δx, you can also plot the dE/dx curve.

7) Pump down the vacuum again and repeat the steps 2) to 5) with CO_2 gas. Plot the dE/dx curve for CO_2 and compare it to that for air to verify the electron density dependence as predicted in equation (1). In which gas (air or CO_2) do the alpha particles lose energy most rapidly (for example, at 1 atm)?

Part Four: Range of alpha particles in air and in CO_2:

1) Although the range can be measured by changing the distance from the source to the detector until the counting rate drops to zero, this approach introduces unnecessary normalization procedures due to the fact that the solid angle seen by the detector changes as the source-detector separation changes. A more appropriate arrangement is to fix the source-detector separation and pump down the vacuum inside the chamber and then let some air in. In this way, one can control the "thickness" of the air by monitoring the pressure inside the chamber. If the actual pressure inside the chamber is p and the distance traversed by alpha particles (i.e., the source-detector distance) is R_p, then the effective length (or equivalent length at 1 atm) in atmosphere is R_0 with:

$$R_0 = R_p\left(\frac{p}{p_0}\right) \qquad (5)$$

where p_0 is the atmospheric pressure (e.g., ~745 mm Hg based on our gauge).

2) Set the source-detector detector to the maximum, about 6.5 cm and record this distance as R_p (to be clear, R_p is the source-detector distance for these measurements). Close all leak valves and the main gate.

3) Open the main gate to pump down the vacuum inside the chamber. After 5 minutes pumping, the vacuum inside the chamber should be in the range of -744 mm Hg (again, relative to 1 atm = 760 mm Hg) which is low enough that all alpha particles will reach the detector without being stopped. Get the counts (in a known interval of time) for this vacuum and keep the number for reference. In this case, you'll be using the pulse counter instead of the MCA.

4) Close the main gate to stop the pumping on the chamber. Slowly leak in some air by slowly opening the air leak valve until the vacuum gauge reading is 700 mm Hg. Close the air leak valve and get the counts for this air pressure.

    5) Repeat step 4 for other pressures (carefully dropping through the pressures 600 mm Hg, 500, 400, …) until the counts begin to drop apparently. At this point, you need to get counts for pressures at smaller steps until the count rate is totally zero. Record this pressure as p. Calculate the range in air R_0 by the equation 3 for the pressure at which the count rate drops just to zero (or very nearly zero).

    6) You may wish to repeat the steps 1) to 5) to verify your data. This time use greater care by taking smaller steps when approaching the point where counts begin to drop.

    7) Repeats steps 1) to 6) by using CO_2 gas. Compare the range R_0 in air and in CO_2 to confirm the dependence of range on the electron density as shown in equations 1 and 2.

    8) Stop the mechanical pump. Open the main gate and open the air leak valve. Don't leave the mechanical pump under vacuum.

Safety Issues:

(a) Handling of alpha source: Since alpha particles are easily stopped by almost any macroscopic objects, the alpha source are shipped as an OPEN source. That means the alpha source is exposed without any coverage. Neither the students nor the TA should handle the source unless they have been trained and certified by the University of Toledo Radiation Safety Office. If you suspect you may have touched the source, wash with soap immediately before more areas get contaminated.

(b) Handling of the surface barrier detector: For the same reason that an alpha particle can not penetrate any material with a considerable thickness, the surface barrier detector is not covered by any coating except a thin gold coating that serves as an electrode and part of the p-n junction. Do not touch the gold coated surface with your finger or any tools.

Reference:

1. Experiments in modern physics, by A. C. Melissinos, pp.155-163.

Notes on your write-up:

A. Be sure to include values for the Activity (values at each source-detector spacing, one "best" value for the Activity and the corresponding uncertainty), and for the <u>range</u> of the Am-241 alpha particles in air and in CO_2 at 1 atmosphere pressure. Include uncertainties for your range values as well, of course.

B. Include the radioactive decay equation accounting for the source of alpha particles we're using here (^{241}Am) . In analogy with a chemical reaction, reactant(s) on the left hand side, and products on the right hand side. For example, the decay of tritium looks like this:

$$^3_1H \rightarrow ^3_2He + e^- + \nu_e$$

C. Although you will not open the vacuum chamber nor actually do this, assume that you held your hand (in air, at 1 atm pressure) at a distance of 1 cm from our ^{241}Am source for a duration of 30 seconds. Calculate the *hypothetical* dose equivalent you would receive *to your hand* from our alpha particle source, clarifying your assumptions for the solid angle of the hand, the mass of the hand, etc. Know (and use) the proper units of, and procedure for calculating, the "dose equivalent". Keep in mind that the energy of the alphas may very well *not* be 5.47 MeV after 1 cm in air… Express your answer in units of Roentgen Equivalent Man (rem). Repeat the calculation for the same conditions, replacing the air with CO_2.

D. Comment briefly on the application, if any, of alpha particles in medicine. What types of therapy have used alpha particles, and are they an accepted form of treatment bin some cases? Please explain the unique characteristics of alpha particles for medicine.