Operation and Characteristics of a Semiconductor Detector I

The Silicon Surface Barrier Detector

I. Basic Description of Detector.

One of the most important advances in nuclear instrumentation in recent years has been the development of semiconductor radiation detectors. In this laboratory exercise, we shall begin by measuring some of the characteristics of one class of these detectors, silicon surface barrier detectors. A simple explanation of the mechanism of operation of these devices should suffice (a more detailed discussion is given in Chapter 8). Basically, semiconductor radiation detectors consist of a piece of semiconductor (germanium or silicon) that has been doped with impurity atoms to form a p-n junction*. A reverse bias voltage is applied to this junction to create a depletion region near the front of the device in which there are no free charge carriers. To function as a particle detector, this depletion region must be greater than the range of the particle in the detector material ($\sim 15\ \mu$ for 5 MeV α-particles in silicon). Thus we have the crude representation sketched below. The depth of the depletion region is controlled by the magnitude of the applied reverse bias. More specifically:

$$d = \text{depletion depth} \propto \frac{1}{\sqrt{V}} \qquad \text{VII-1}$$

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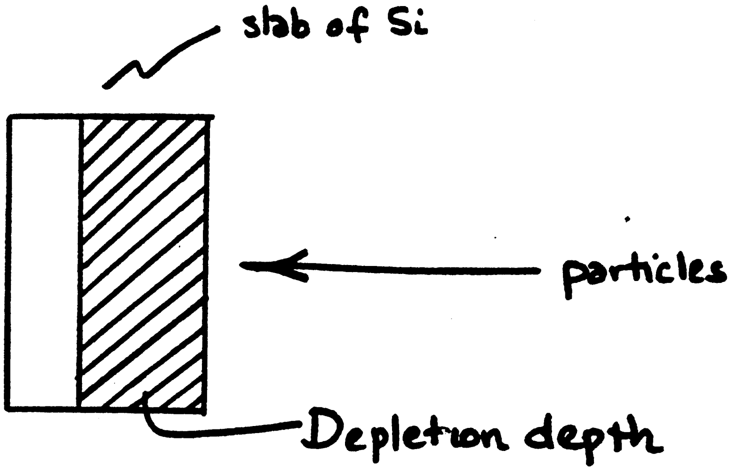
*In the silicon barrier device, the p-n junction is formed by oxidation of the surface of n-type silicon to form surface states. (See Chapter 8 for discussion).

where V is the applied bias voltage.



When a particle enters the detector, it loses its energy by the creation of electron-hole pairs in the depletion region (similar to ionization in gases). The average energy necessary to create an electron-hole pair is ~ 3 eV for Si and thus the number of electron-hole pairs created when a 5 MeV α-particle stops in a Si detector is $\frac{5 \times 10^6}{3} \simeq 1.7 \times 10^6$ electron-hole pairs. This number of electron-hole pairs is thus proportional to the particle energy deposit in the detector and is a factor of ~ 10 greater than the number of ion pairs created when a 5 MeV α-particle stops in a gas. The electric field in the depletion region sweeps away the electrons to one side (and the hole to the other). The resulting charge pulse created produces a signal from the detector indicating

(a) The arrival of a particle

(b) The energy deposit of that particle in the detector.

A plot of the number of signals of a given pulse height coming from a detector (when a monoenergetic α-particle is striking it) vs the signal pulse height is shown in Figure VII-1.

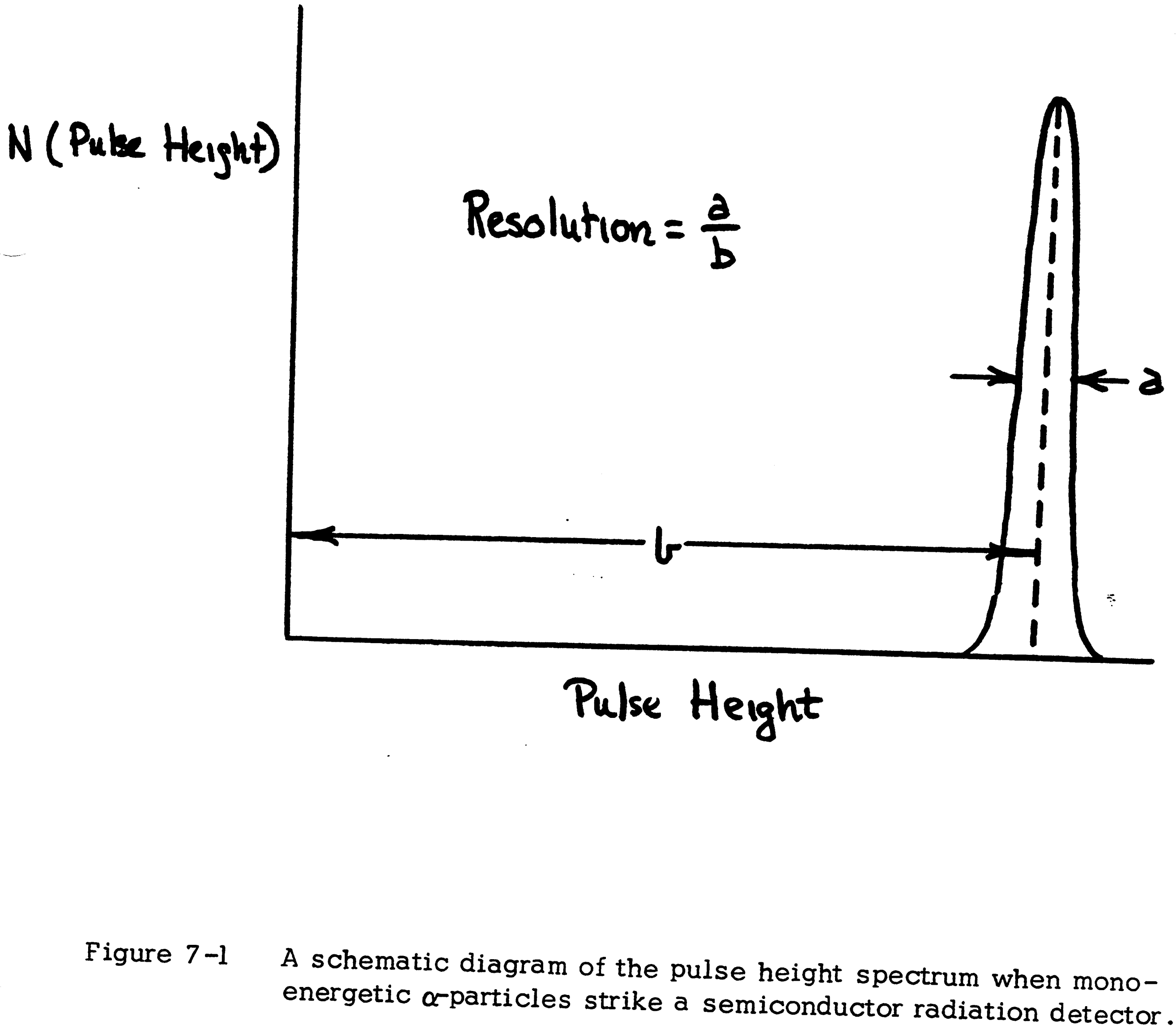


Figure 7-1 A schematic diagram of the pulse height spectrum when mono-energetic α-particles strike a semiconductor radiation detector.

A figure of merit used in evaluating radiation detectors is the resolution of a detector which is defined (usually) as the full width at half maximum of the peak (a) shown above divided by the maximum pulse height (b). The smaller this number is, the better the quality of the detector. Since the origin of the spread in pulse heights is due primarily to statistical fluctuations in the number of electron-hole pairs created when a given energy α-particle interacts with the detector, the greater the number of pairs created, the better the resolution, i.e.

$$\text{Resolution} \propto \frac{1}{\sqrt{N}} \qquad \text{VII-2}$$

where N is the number of charge pairs created. Thus one can immediately see that semiconductor detectors have superior energy resolution when compared to gas ionization detectors because more charge pairs are created per event in semiconductor detectors.

II. Operating Characteristics of a Semiconductor Detector.

Let us now measure some of the properties of these detectors. But first we must describe the apparatus we will use (see Figure VII-1). The detector and α-source (^{241}Am (E_α = 5.477 MeV) for this experiment) are placed in the vacuum chamber and the chamber evacuated. (Remember the short range of α-particles in air.) Bias voltage is applied to the detector through special circuitry in the preamplifier. Electrical signals from the detector are amplified and shaped by the preamplifier and amplifier and are fed to a multichannel pulse height analyzer. This latter device then gives

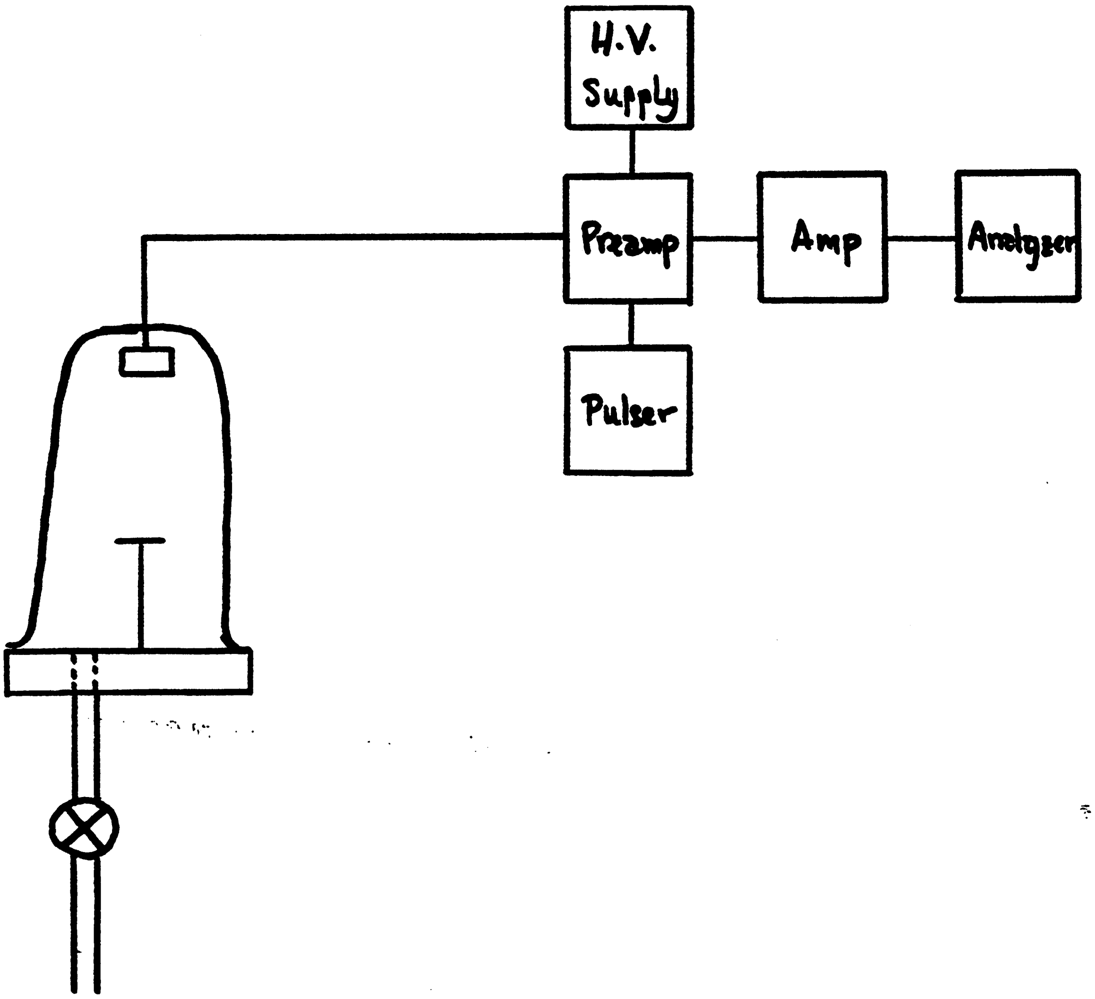


Figure VII-1 A schematic diagram of the apparatus used for α-particle spectroscopy with a semiconductor radiation detector.

a plot of number of counts of given energy deposit vs. energy deposit.

Procedure:

1. Set up the detector and the ^{241}Am source in the chamber and evacuate the chamber. Be careful not to touch the front face of the detector with anything, especially your fingers. The front surface of the detector is a very thin layer of gold that will be irreparably damaged by contact with any foreign material. Always handle the detector by its case. Be equally careful not to touch the ^{241}Am source with your fingers (to prevent spread of α-contamination). Always handle this source with tweezers.

2. Increase the applied bias voltage to the value recommended by the manufacturer for the detector you are using.

3. Adjust the amplifier gain so that main peak in the pulse height spectrum falls at ~2/3 the maximum spectral range covered in the analyzer memory.*

4. Measure the pulse height spectrum of the ^{241}Am source with the multichannel analyzer and obtain a printed copy of the spectrum. Be sure to record ~1000 counts per channel near the peak maximum.

5. Repeat the measurement outlined in step 4 above for applied bias voltages of 90, 70, 50, 30, 10 and 5% of the initial voltage.

6. Plot the pulse height spectrum for each voltage. Calculate the peak position (as a channel number) and peak resolution (in terms of channel numbers) for each applied voltage (using the relationships shown in Figure VIII-1) and enter the data in Table VII-1.

* As in Experiment VII, we are assuming that the reader is familiar with the operation of a multichannel analyzer. If not, the instructor should operat the analyzer controls during the experiment.

7. Plot two graphs, one of peak position vs. applied voltage, the other one of peak resolution vs. $1/\sqrt{\text{applied voltage}}$. The data should look like Figure VII-1 and Figure VII-2.

You should observe a broadening of the peak as the bias voltage is lowered. This is due to changes in detector capacitance (i.e., depletion depth) as a function of applied voltage. Note that $R \alpha 1/\sqrt{V}$. Note also the downward shift in peak position with applied voltage. As the voltage is lowered the charge collection in the detector becomes incomplete. Electron-hole pairs in the detector recombine before being swept away to the detector electrodes. A loss of collected charge results and thus the downward shift in peak position.

Table VII-1

Applied Voltage (volts)	$\frac{1}{\left(\text{Applied Voltage}\right)^{1/2}}$	Peak Position	Peak Resolution

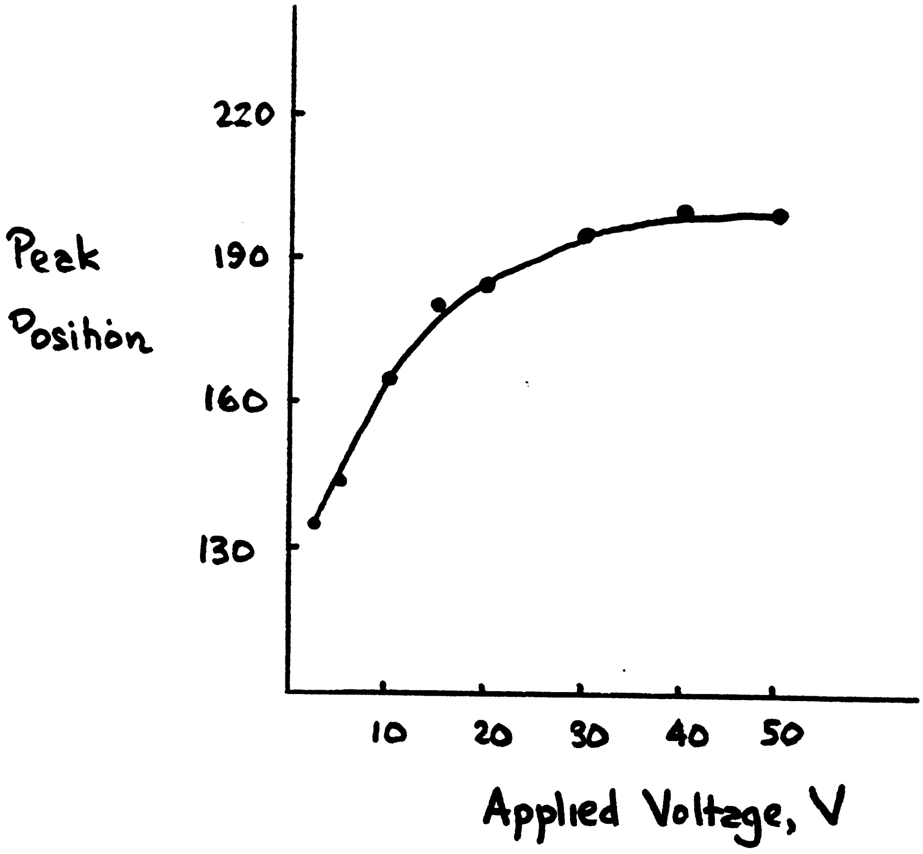


Figure VII-1 Peak Position vs. Applied Voltage

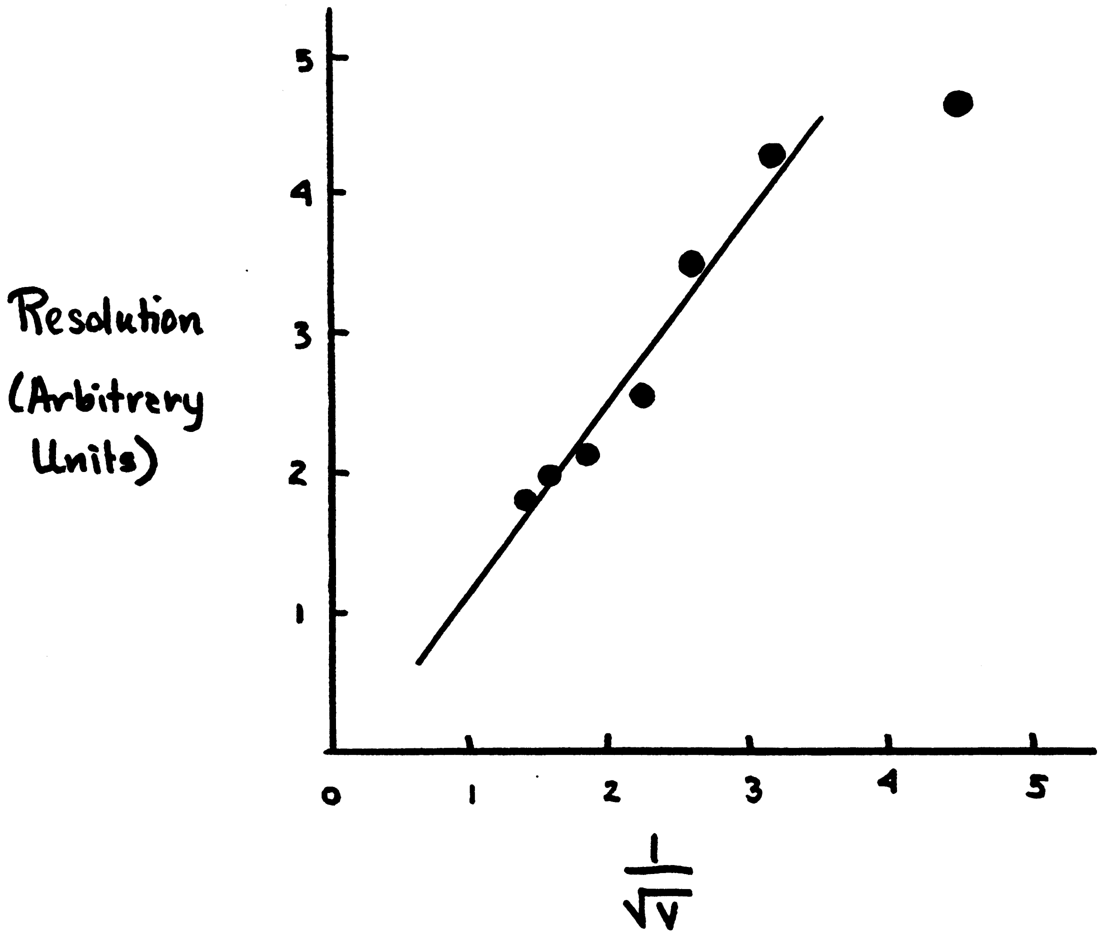


Figure VII-2 A plot of peak resolution vs. applied voltage.

III. Alpha Particle Spectroscopy

From what we have discussed in Chapter 8 about semiconductor radiation detectors, the energy response of these devices should be linear. The problem we now have is similar to that encountered in Experiment VI, i.e., to find the energy calibration of our spectrometer. If we know the energy corresponding to two channels in the analyzer memory, we can write down a simple linear equation to relate analyzer memory channel and α-particle energy. We already know one point, the analyzer memory channel corresponding to $E_\alpha = 5.477$ MeV. We can use a pulser (see Chapter 4) to obtain another pc on the calibration curve, the zero intercept. Then we can measure the energies of unknown α-emitters.

Procedure:

1. Turn off the detector bias voltage. Connect pulser into preamplifier if you haven't already done so. Turn on pulser and adjust pulse amplitude until pulser peak is stored at ~ the full range of the analyzer memory. Record the analyzer channel number, P_F, corresponding to the midpoint of the pulser peak

$$P_F = \underline{\hspace{4cm}}.$$

2. Reduce pulse amplitude by <u>exactly</u> a factor of 2.00 using precision controls on pulser. Again record analyzer channel number, P_H, corresponding to midpoint of pulser peak.

$$P_H = \underline{\hspace{4cm}}.$$

3. Plot a graph of pulse height vs. channel number for your system using the P_F and P_H values. (See Figure VII-3.) Draw a straight line between the two points and extend it until it crosses the abscissa (Z).

4. Using the value of Z you have just obtained and the ^{241}Am peak position at full bias voltage, A (from Table VII-1) the energy calibration for your system (at full bias voltage) is given by $E_\alpha = mN + b$

where

$$m = \frac{5.48\cancel{Z}}{A + Z}$$

$$b = \frac{5.48Z}{A + Z} \tag{VII-3}$$

and N is the analyzer channel number.

5. After making sure that detector bias voltage is zero, let air into chamber. Replace the ^{241}Am source with an unknown α-source. Evacuate the chamber and apply the manufacturer's full recommended bias voltage to the detector.

6. Record the unknown α-emitter spectrum with the multichannel analyzer. Plot the unknown spectrum and calculate the energies of the peaks in the spectrum using equation VII-3. From use of Appendix IV of the text, identify the unknown α-emitter.

Unknown α-emitter ______________________.

Peak Energies ______________________.

IV. Interaction of α-particles with Matter.

In Chapter 3, we have talked of the interaction of α-particles with matter. Let us now see if we can use our semiconductor α-particle

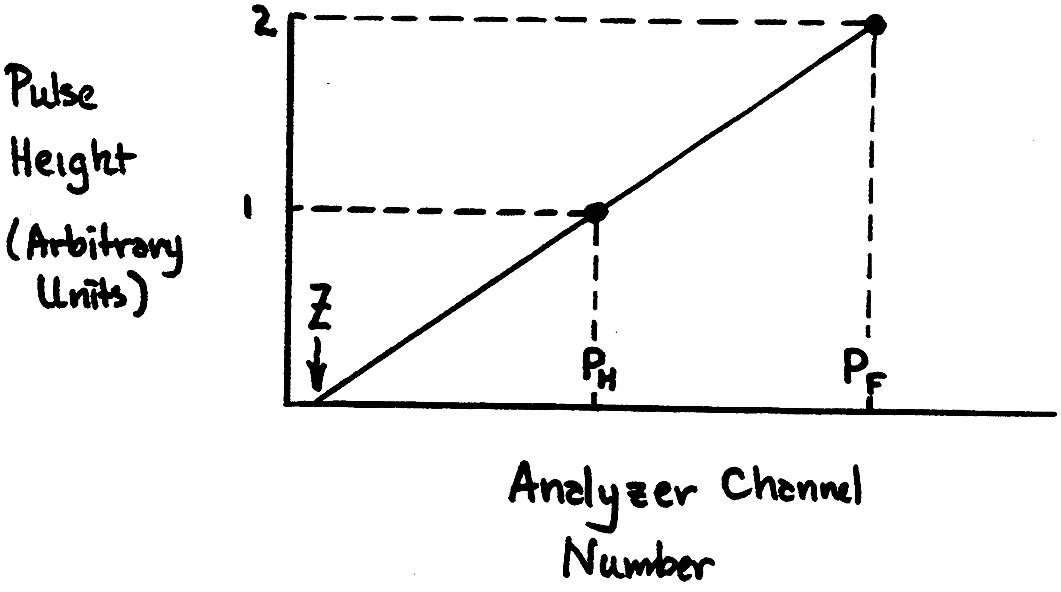


Figure VII-3 Calculation of zero intercept, Z.

detector to verify some of this discussion. In particular, we shall try to measure the range of an α-particle in air.

Procedure

1. Turn off detector bias voltage and let **air into chamber. Place** Am^{241} source on platform in chamber. Install collimator system between source and detector as shown in Figure VII-4. Measure carefully the distance between the detector and the source. DO NOT TOUCH SOURCE OR DETECTOR. Apply **recommended bias voltage and measure the number of counts in the** Am^{241} **peak in** the analyzer for a fixed counting time. Record data in Table VII-2.

2. Turn off bias voltage and move source further away from detector. Record change in source-detector distance. Apply bias voltage and re-measure the number of counts in Am^{241} peak for fixed counting time.

3. Repeat step (2) until **you reach** the distance at which counting rate falls to zero. (Hint: Calculate range of 5.477 MeV α-particle in air before you start). Measure counting rates for several 1 mm increments in source-detector distance about range.

DO NOT TO EXPOSE DETECTOR TO LIGHT WITH BIAS **VOLTAGE APPLIED.**

4. Plot counting rate vs source-detector distance. (Note that since beam of α-particles from source was collimated, one need not correct for changes in detector solid angle during experiment.) You should get a plot similar to that shown in Figure VII-5.

5. From this plot, calculate range of α-particle in air and compare it to that given by

$$R^{\alpha}_{air} = 0.309\, E^{3/2} \quad \text{(cm)}$$

Discuss any discrepancies.

R (calc) = ______________________cm.

R (expt'l) = ______________________cm.

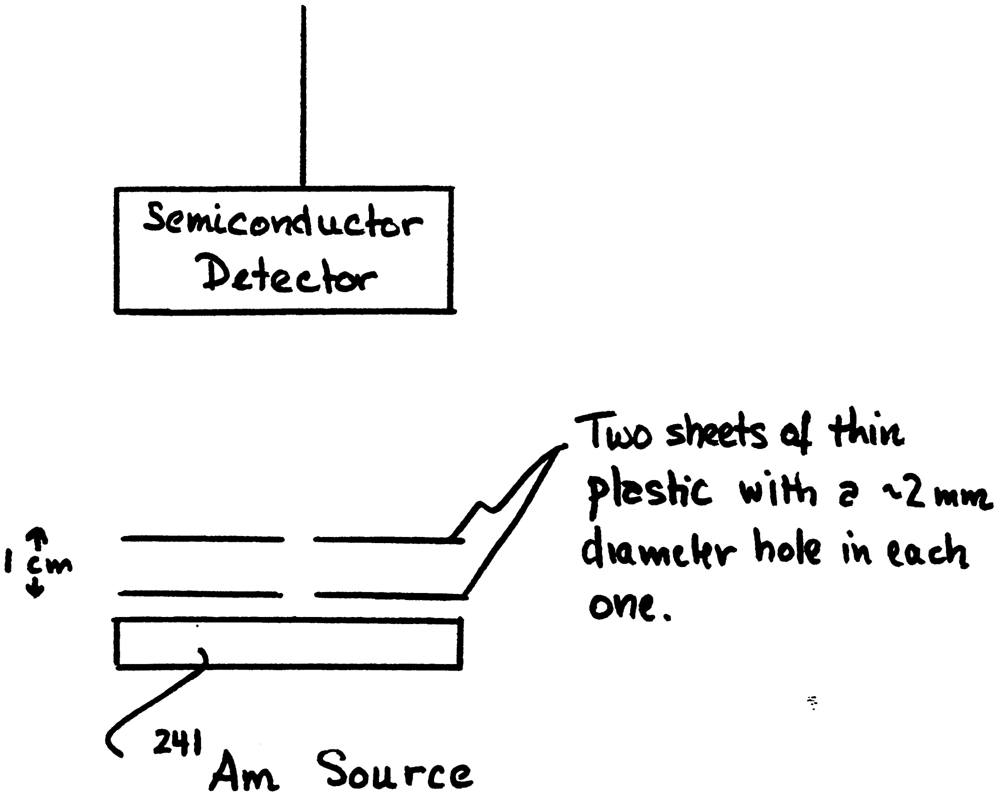


Figure VII-4 Schematic diagram of collimator system for α-source for measurement of α-range in air.

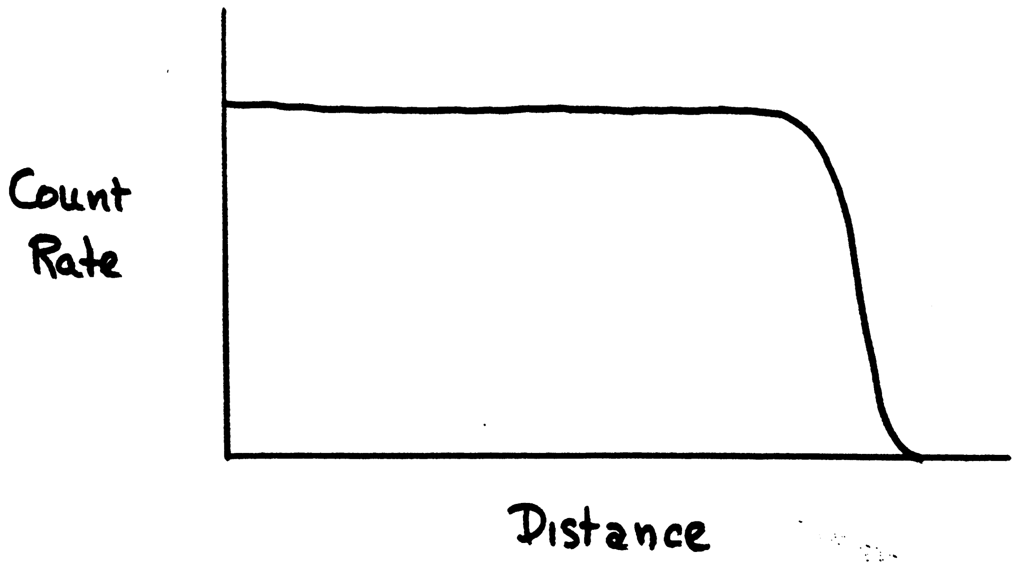


Figure VII-5 A plot of detector count rate vs. source to detector distance.