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RANGE OF ALPHAS

Advanced Laboratory, Physics 407
University of Wisconsin
Madison, Wisconsin 53706

Abstract

A silicon solid state detector is used to measure the energy of alphas which have passed through air from an Am^{241} source. The air pressure may be varied and so the alpha particle Bethe-Bloch formula for dE/dx may be verified and the alpha particle range and straggling can be measured.

Theory

A charged particle moving through a neutral medium will interact electromagnetically with both the electrons and nucleii of the material. The electromagnetic interactions with the nucleii cause Rutherford Scattering and are seen as small (and occasionally large) changes in directions. The interactions with the electrons are far more frequent and are seen as a fairly steady loss of kinetic energy.

There are, of course, statistical fluctuations in the rate of the interactions and this is seen as "straggling" of the range of monoenergetic particles. For example, alphas with a mean range of 20 cm will have range fluctuations (straggling) of about $\pm 1\%$.

The rate of loss of energy can be calculated (see Ref.[1], pg. 637 and Ref.[2], pp. 155-162.)

$$\frac{dE}{dx} = -\frac{1}{(4\pi\epsilon_o)^2}\frac{4\pi e^4 z^2 N B}{m_e v^2} \qquad \text{(mks)}$$

where

$$\begin{aligned}
e &= \text{charge on electron (coulombs).} \\
z &= \text{Atomic number of moving particle.} \\
N &= \text{the number of atoms/unit volume (meter}^{-3}\text{).} \\
m_e &= \text{mass of electron (kg).} \\
v &= \text{velocity of the moving particle (meter/sec).} \\
E &= \text{kinetic energy of the moving particle (joules).} \\
x &= \text{distance travelled by the particle (meter).} \\
\epsilon_o &= \text{permittivity of free space.} \\
1/(4\pi\epsilon_0) &= 8.988 \times 10^9 \text{ Newton meter}^2/\text{coulomb}^2. \\
B &= \text{Atomic stopping number (dimensionless).}
\end{aligned}$$

The factor B is not constant but varies slowly with energy in a logarithmic manner. The theoretical calculations for B become difficult when allowance is made for the partial screening of the nuclear charge by the inner (K) electrons.

The best formula for B is probably that of Ref.[1], pg. 638.

$$B = Z \left[\ln\Big(\frac{2m_e v^2}{I}\Big) - \ln(1-\beta^2) - \beta^2 \right] - C_K$$

where

$$\begin{aligned} C_K &= \text{the correction term for the K-shielding. The equations and a} \\ &\quad \text{plot of } C_K \text{ are shown on pg. 639 of Ref.[1]} \\ \beta &= \text{the usual relativity factor - veloc particle/veloc light} \\ I &= \text{“average” ionization potential of the stopping medium} \\ Z &= \text{(average) atomic number of the stopping medium} \end{aligned}$$

If we assume that the velocity is non-relativistic, then $E = \frac{1}{2}mv^2$ and so:

$$\frac{dE}{dx} = -\frac{1}{(4\pi\epsilon_0)^2} 2\pi e^4 z^2 N \left(\frac{M}{m_e}\right) \frac{B}{E}$$

where M is the mass of the particle.
β^2 is also small so that $\ln(1-\beta^2) \approx -\beta^2$ and so

$$B = Z \ln\left(\frac{4m_e E}{MI}\right) - C_K.$$

Fortunately in our experiment with alpha particles in air, the calculated value of C_K is nearly constant near 0.90.

The particle range can be determined by integrating $\frac{dE}{dx}$ over the particle energy.

$$R(E) = \int_0^E \frac{dE'}{-\frac{dE'}{dx}}$$

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Statistical fluctuations lead to a distribution of ranges about the mean R_0 with a straggling parameter α defined by the probability distribution for the ranges:

$$P(R) = \frac{1}{\alpha\sqrt{\pi}} \exp[-\frac{(R-R_0)^2}{\alpha^2}]$$

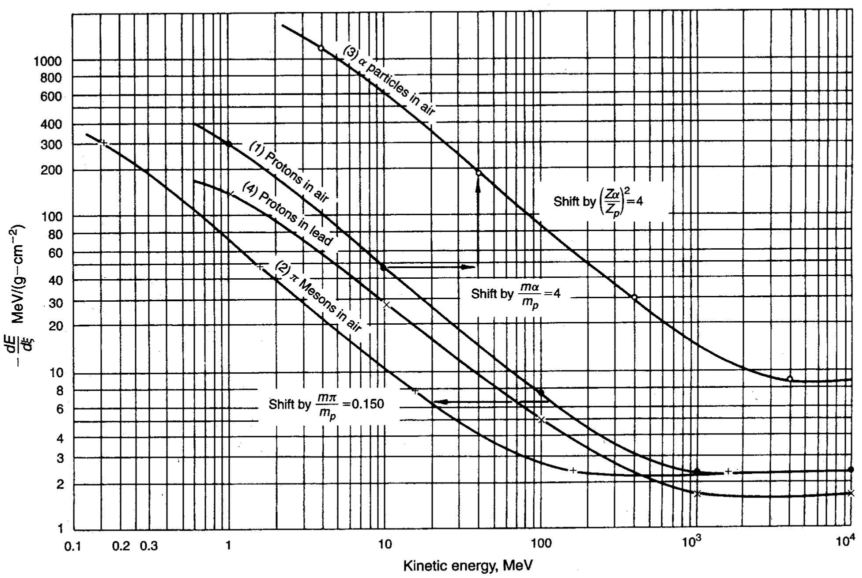

FIGURE 8.4 Energy-loss curves for different charged particles in air and in lead. Note how all the curves are related to each other.

Figure 1: Energy Loss Curves for Different Particles in Air and Lead.

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Numerical values for $\frac{dE}{dx}$ as a function of energy are shown in Fig. 1 for various particles. A 5 Mev alpha particle has a $\frac{dE}{dx}$ value of about 1000 $\mathrm{MeV/gm-cm^{-2}}$. $\frac{dE}{dx}$ has minimum for all particles at a kinetic emergy of about twice the rest mass. For singly charged particles this value is about 2 $\mathrm{MeV/gm-cm^{-2}}$.

Fig. 2 shows differential and integral probability distributions for heavy particles ranges. The extrapolated range R_{ex} is related to the straggling parameter α as explained later in the text.

Fig. 3 shows range vs energy for alpha particled in air at standard conditions. The range for a 5486 keV alpha in dry air at 15° and 760 Torr is 4.051 cm.

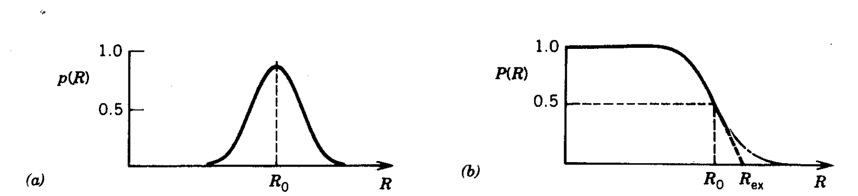

FIGURE 20.3 (*a*) Distribution of ranges for charged particles. (*b*) Probability of a particle having a range larger than *R*.

Figure 2: The differential and integral probability distributions for heavy charged particle range.

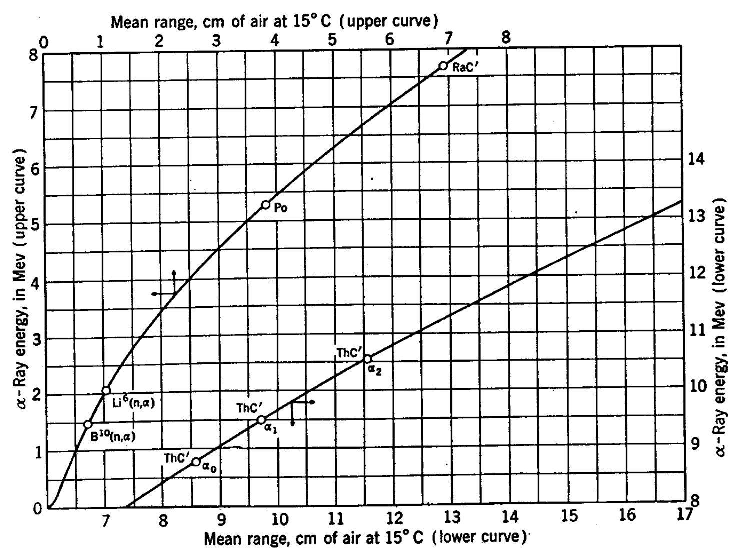

Fig. 3.2 Range-energy relationship for α rays in dry air at 15°C and 760 mm Hg. The curves agree with those of Bethe (B44) and with the tables by Jesse and Sadauskis (J12). Two low-energy calibration points (J12) are provided by the α rays emitted in the thermal neutron reactions $B^{10}(n,\alpha)Li^7$ and $Li^6(n,\alpha)H^3$.

Figure 3: Alpha Range-Energy in air

Apparatus

1. <u>Vacuum Chamber.</u> The vacuum chamber is made of pyrex glass and is mounted inside a dark wooden box. The Silicon detector must be protected from room light since photons cause a noise background which spoils the resolution of the detector. <u>Do not open the glassware</u>. The alpha source could, over a long time, shed some radioactive dust. The system has been designed to ensure that any dust is trapped inside the glass system vacuum. The source to detector surface was remeasured in 2005 and determined to be 6.65 ± 0.05 cm.

2. <u>Filter.</u> An automobile oil filter is used to check for possible source leakage. The filter is periodically tested to check for activity. The filter has an internal rubber gasket which blocks the gas flow at low pressure differentials (10 Torr). A copper wire has been inserted to hold the internal rubber gasket open. <u>Do not open or disconnect the filter</u>.

3. <u>Pressure Gauge</u>—MKS Baratron type 122A. The pressure gauge is an absolute pressure transducer based on measuring the capacitance of a sample chamber. The accuracy is rated at 0.5% of reading from $0 - 50°$C. The readout is in Torr.

4. <u>Vacuum Pump.</u> The pump is a 2 stage rotary pump enclosed in the standard cart to reduce acoustic noise. Notice that a flow of warm air is exhausted from the cart by an electric fan to prevent the pump and motor from overheating.

5. <u>Alpha Source.</u> The decay scheme of Am^{241} is shown in Fig 4 This source is not sealed and so must remain inside the vacuum enclosure. (Usually sources are sealed with very thin metal skins. In this experiment, a skin would slow the alphas slightly. As the skin could not have a perfectly uniform thickness, the alphas would emerge with a broader range of energies.) The 5486 and 5443 keV alphas will not be resolved due to the finite thickness of the source. A 5486 keV alpha has a range in dry air at 15°C and 760 Torr of 4.051 cm and so the source alphas cannot reach the detector until the chamber pressure has been reduced.

6. <u>Solid State Detector</u> - (Ortec A-040-200-300, Serial 9-129B). The detector is a surface barrier detector consisting of an extremely thin p-type layer on the face of a high purity n-type Si wafer. The rated energy

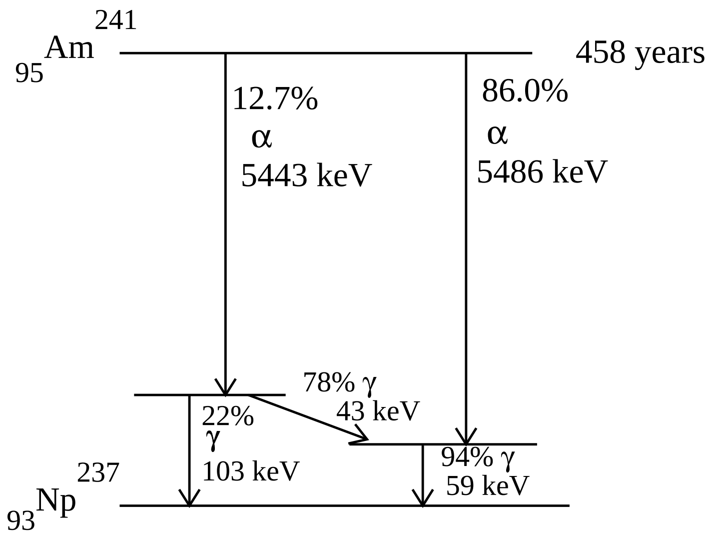

Figure 4: Decay Scheme of Am^{241}

resolution of the detector is 40 keV and the active thickness when fully depleted is 300μ. The p-type surface of the detector is gold plated with a layer approximately 40 μg-cm^{-2} thick. The detector has a sensitive diameter of about 16 mm and is mounted on a BNC connector within the vacuum system. Although the detector can operate with a bias of +100V in a very good vacuum, we will use the detector in the dangerous 10^{-2} Torr to 10 Torr region. Set the bias to 30 V but do not use a bias greater than +30 V. Some useful properties of Si are listed in Fig. 6.

7. Pre-amplifier - (Ortec model A576). This is a charge sensitive pre-amplifier which also supplies the bias voltage for the Si detector. The pre-amplifier is designed to have a large effective input capacitance C_a so that most of the charge drains from the detector and cable into the pre-amplifier and is amplified. If the capacitances of the detector and cable are C_d and C_c, then:

$$Q_a = Q_{\rm tot}\left(\frac{C_a}{C_d + C_c + C_a}\right) \ ,$$

where $Q_{\rm tot}$ is the total charge collected by the detector, and Q_a is the charge delivered to the charge sensitive pre-amplifier.

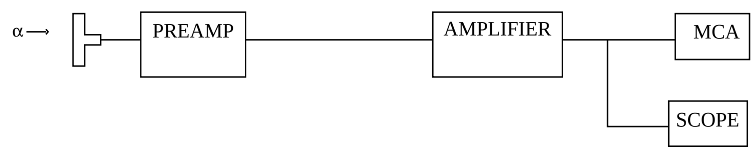

Figure 5: Apparatus Schematic Diagram

Although C_a is large, the charge seen by the pre-amplifier depends upon C_c and so the same short cable should be used to connect the detector and pre-amplifier for all measurements.

8. Amplifier. ORTEC Model 570. Use the input set to POS and the unipolar output. The amplifier gain is adjustable so that the gain can be matched to the full scale range of the PC MCA System. The amplifier also shortens the pulses so that a typical alpha pulse out is $\sim 2\ \mu sec$.

9. Pulse-Height Analyzer - Ortec 916A board inside the PC using the Maestro MCA software. Usually set for 512 channels full scale.

10. Scaler - (Ortec Model 484).

Procedure

1. Read Ref.[2], pp. 208-217, and the theory in Ref.[1], Chapt. 22.

2. Pump down the vacuum chamber. The filter has a low pumping speed and so the time to reach 10 Torr is several minutes. Practice using the air inlet valve or the vacuum pump valve to obtain and hold any pressure you wish.

3. Connect the detector to the FET pre-amplifier with a short (1 foot) cable. The TEST-OFF switch should be set to the center position. Connect the rear pre-amplifier output to the input of the pulse amplifier. Connect the pulse amplifier output to the pulse height analyzer input and scope. Do not terminate the cable to the scope, since the pulse height analyzer input has a relatively low input impedance. The schematic is shown in Fig. 5.

4. The amplifier should be set for POS input pulses. Lower the pressure to less than 5 Torr and look for positive pulses (5 μsec) at the MCA and scope inputs. Adjust the gain of the amplifier so that the pulses are being counted near the upper end of the 512 channel MHA. The MCA requires positive pulses and full scale corresponds to 10 Volt input pulses. Record all parameters so that you can later reproduce the same gain. The Si detector output will be pulses whose amplitude is proportional to the alpha particle energy less the energy lost in the air. Since these pulses are fed to the MCA we have:

   Energy = constant×pulse height = constant×(channel number+constant)

5. Compare the pulse height (channel #) of pulses produced with a bias of +20 V with those produced with a bias of +30 V. Estimate the error in the channel # due to your error in setting the bias at +30 V.

6. Use the amplifier attenuator to measure the linearity and zero offset of the MCA.

7. Measure the full-width half maximum resolution of the alpha particle peak and compare to the intrinsic resolution of the Si detector.

8. Measure the count rate and the mean energy E and energy straggling (full width at half max) of the alphas as a function of the air pressure (P). Take fine steps near the end of the range so you can determine the range accurately. The count rate can be determined from the sum of the counts in the MCA peaks. However it is much better to measure the count rate using a scaler to avoid the MCA dead time correction.

   Plot count rate against P. Determine the mean range R_0 and the extrapolated range R_{ex} of the alpha particles as shown in Fig. 2. Compare your result to the predicted value based on Fig. 3. Remember that you have to correct the range predicted value for the temperature and atmospheric pressure of your data. From the quantity $R_{\text{ex}} - R_0$ determine the <u>effective</u> straggling parameter α. The quantity α is defined by the probability distribution for the ranges:

$$P(R) = \frac{1}{\alpha\sqrt{\pi}} \exp[-\frac{(R - R_0)^2}{\alpha^2}]$$

and $R_{\text{ex}} - R_0 = \frac{\sqrt{\pi}}{2}\alpha$. Measure the source-detector distance and calculate the expected pressure for the range using the one-atmosphere range given above. Compare the measured straggling parameter to the value given in Fig. 7 below and the measured resolution of the alpha peak.

9. Now use the MCA to measure the alpha particle energy as a function of air pressure. Plot E against P. From this data compute dE/dx and plot dE/dx against 1/E. If the factor B in the formula for dE/dx were perfectly constant, then the dE/dx versus 1/E plot would be a straight line through the origin. SigmaPlot has a nice Spline tool to determine the derivatives of a set of x-y numbers.

10. Plot $E\left(\frac{dE}{dx}\right)$ against ln E to verify that the ln term is energy dependent. From the dE/dx vs ln E data determine the average Ionization Potential I of dry air. Compare to the expected value.

11. Both the source and the detector have finite widths and so some particles will travel slightly different path lengths to the detector. Discuss this contribution to the observed energy resolution.

12. From the count rate and by estimating the source and detector dimensions (without opening the chamber), estimate the source strength in microcuries (μCi).

13. Use the range-energy data sheet in Fig. 8 to check that the solid state detector has a depletion depth greater than the range of 5.5 MeV alphas.

References

[1] R.D. Evans, “The Atomic Nucleus,” McGraw–Hill, 1955.

[2] A.C. Melissinos, “Experiments in Modern Physics”, Academic Press, 1966 (2nd Ed. 2003).

2.1 Selected Physical Properties of Silicon

TABLE 1

Selected Physical Properties of Silicon

Atomic Density	5.0×10^{22} atoms-cm^{-3}
Density	2.33 gm-cm^{-3}
Dielectric Coefficient	12
Energy Gap	1.1 eV
Energy per Electron-Hole Pair	3.6 eV-pair
Mobility	
Electron	1350 cm^2 – volt^{-1} – sec^{-1} (2.1×10^9 $T^{-2.5}$ cm^2 – volt^{-1} – sec^{-1})
Hole	480 cm^2 – volt^{-1} – sec^{-1} (2.3×10^9 $T^{-2.7}$ cm^2 – volt^{-1} – sec^{-1})
Thermal Expansion, linear coefficient	4.2×10^{-6} (°C)$^{-1}$

Unless otherwise indicated, above quantities correspond to 25°C.

Figure 6: Silicon Properties

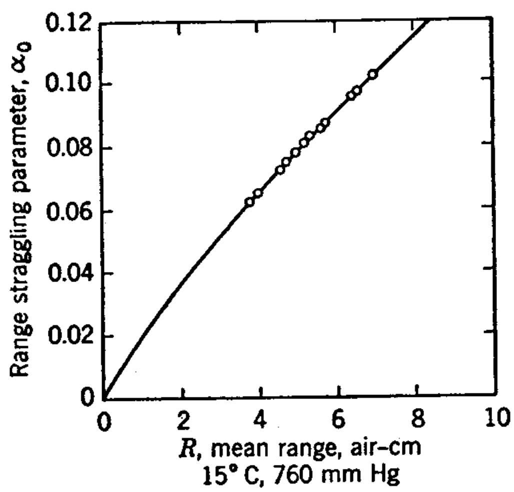

Fig. 5.3 **Range-straggling parameter α_0 for natural α rays in air (L25).**

Figure 7: Alpha Particle Straggling Parameter in Air

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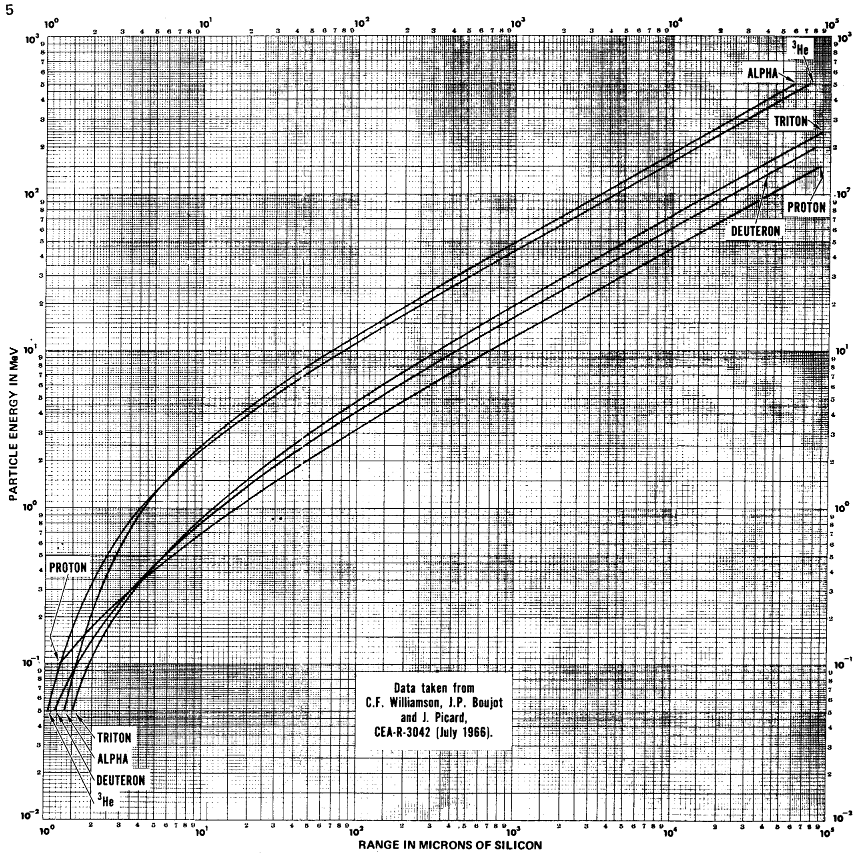

Figure 6A. Range-Energy Curves for Charged Particles in Silicon

Figure 8: Alpha Range-Energy in Silicon