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RANGE OF ALPHAS

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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 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 and is expressed by the Bethe-Bloch formula.(see Ref.[1], pg. 637 and Ref.[2], pp. 155-162.)

$$\frac{dE}{dx} = -\frac{1}{(4\pi\epsilon_o)^2}\frac{4\pi e^4 z^2 NB}{m_e v^2} \quad (mks\ units) \tag{1}$$

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.

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

where

C_K = the correction term for the K-shielding. The equations and a plot of C_K are shown on pg. 639 of Ref.[1]

β = the usual relativity factor - veloc particle/veloc light

$< I >$ = "average" ionization potential of the stopping medium

Z = (average) atomic number of the stopping medium

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

$$\frac{dE}{dx} = -\frac{1}{(4\pi\epsilon_0)^2} 2\pi e^4 z^2 N \left(\frac{M}{m_e}\right)\frac{B}{E} \tag{3}$$

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

$$B = Z\ln\left(\frac{4m_e E}{M < I >}\right) - C_K. \tag{4}$$

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

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 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 MeV/gm/cm^{-2}. The derivation of the Bethe-Bloch equation assumes that the projectile velocity is much larger than the characteristic orbital electron velocities. When the projectile velocity is lower than the requirements of this condition, dE/dx must go to zero as the particle energy approaches zero. A plot of the energy loss of the ionizing radiation as the particles travel through matter is called a Bragg plot. The Bragg plot will show a peak just before the particles come to rest. Fig.2 shows a Bragg plot for 5.49 MeV Alpha particles in air at STP. The peak in this case corresponds to an Alpha particle energy of about 1 MeV.

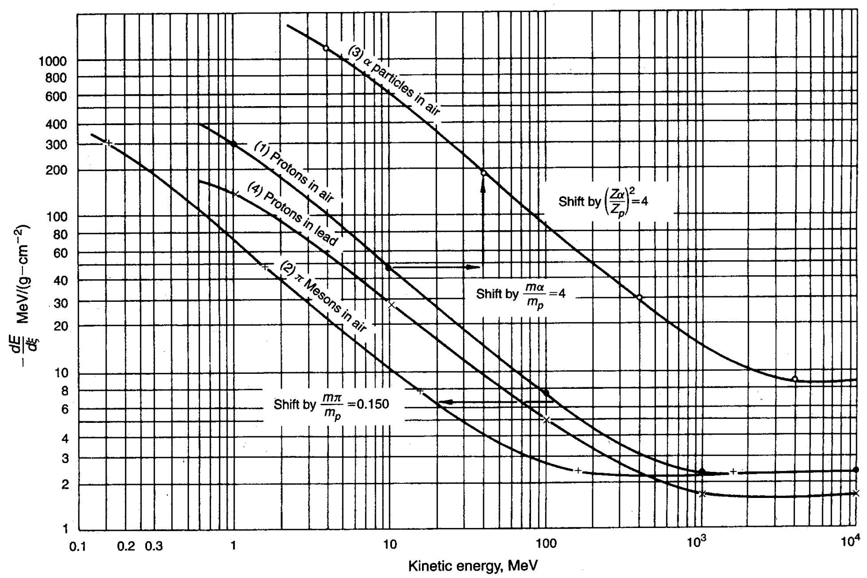

FIGURE 8.4 Energy-loss curves for different charged particles in air and in lead. Note how all the curves are related to each other.

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

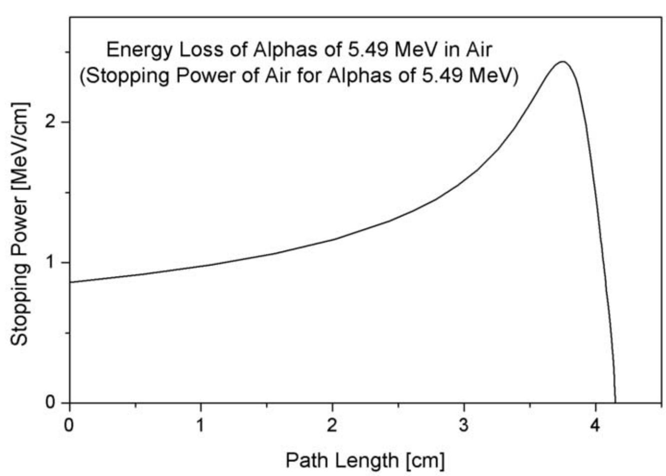

Figure 2: Bragg Curve for 5.49 MeV Alpha Particles in air at STP

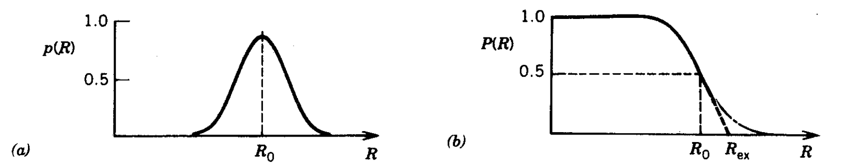

FIGURE 20.3 *(a)* Distribution of ranges for charged particles. *(b)* Probability of a particle having a range larger than *R*.

Figure 3: The differential and integral probability distributions for heavy charged particle range.

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

$$R(E) = \int_0^E \frac{dE'}{-\frac{dE'}{dx}}. \tag{5}$$

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:

$$P(R) = \frac{1}{\alpha\sqrt{\pi}} \exp[-\frac{(R-R_0)^2}{\alpha^2}]. \tag{6}$$

Fig. 3 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. 4 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.

Apparatus

1. Vacuum Chamber. 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. Do not open the glassware. The alpha source could, over a long time, shed some radioactive dust. The

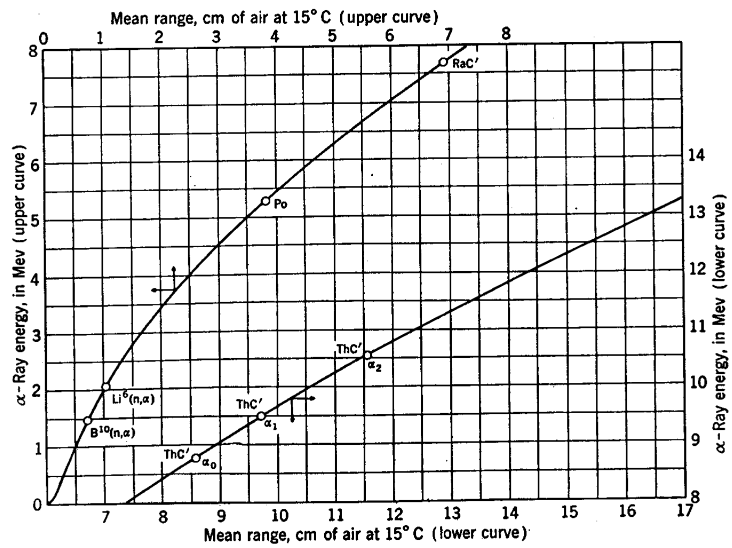

Fig. 3.2 Range-energy relationship for α rays in dry air at 15°C and 760 mm Hg. The curves agree with those of Bethe (B44) and with the tables by Jesse and Sadauskis (J12). Two low-energy calibration points (J12) are provided by the α rays emitted in the thermal neutron reactions $B^{10}(n,\alpha)Li^7$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

Figure 4: Alpha Range-Energy in air

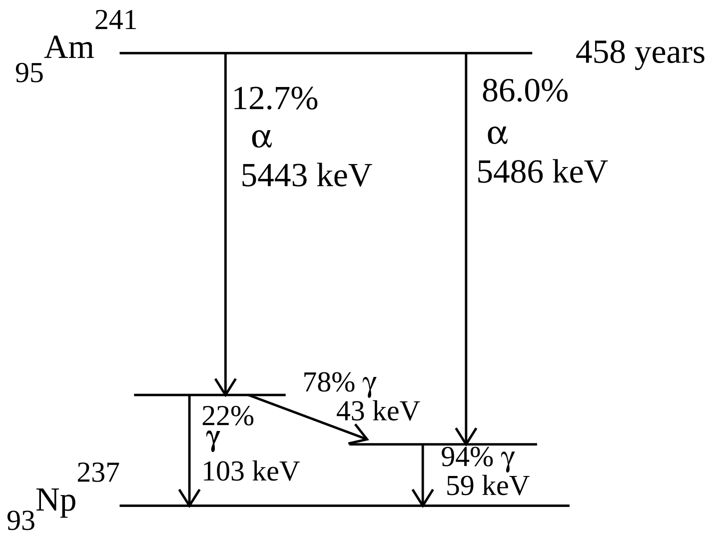

Figure 5: Decay Scheme of Am^{241}

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. Pressure Gauge—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.

3. Vacuum Pump. 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.

4. Alpha Source. The decay scheme of Am^{241} is shown in Fig 5 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.

5. Solid State Detector - (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 resolution of the detector is 40 keV and the active thickness when fully depleted is 300 μ. 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. 7.

6. 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.

   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.

7. 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 $\sim 2\ \mu sec$.

8. Pulse-Height Analyzer - The PHA (Spectrum Techniques UCS30) is an external circuit component with a USB connection to the computer.

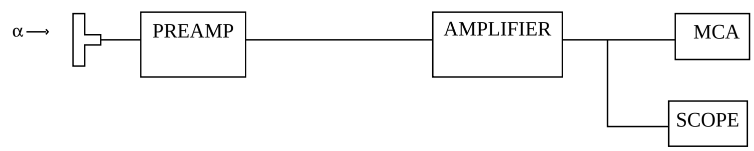

Figure 6: Apparatus Schematic Diagram

The full scale voltage is 8 V and the circuit is usually set for 512 channels full scale.

9. 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 0 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. 6.

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 PHA and scope inputs. Adjust the gain of the amplifier so that the pulses are being counted near the upper end of the 512 channel PHA. The PHA requires positive pulses and full scale corresponds to 8 Volt input pulses. Record all parameters so that you can later reproduce the same gain. The Si detector output will be pulses whose amplitudes are

proportional to the alpha particle energy less the energy lost in the air. Since these pulses are fed to the PHA we have:

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

5. The bias voltage required to fully deplete the Si detector is 30 V. Check to see that the voltage is correct.

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

7. Measure the range vs pressure using the scaler. In principle, the PHA could be used by integrating the number of counts in the alpha peak as a function of pressure, but the pulse heights are too small near the end of the range and the dead time correction will be very large due to the high alpha particle counting rates. To configure the scaler-amplifier system, set the amplifier gain to the maximum value and set the pressure above the alpha particle range. Lower the amplifier gain so that the noise pulses are barely counted by the scaler. Measure the count rate as a function of pressure starting at the high pressure end. The pressure steps will have to be very small near the end of the range to accurately measure the range and straggling parameter.

   Plot count rate against P. Determine the mean range R_0 and the extrapolated range $R_{\rm ex}$ of the alpha particles as shown in Fig. 3. Compare your result to the predicted value based on Fig. 4. Remember that you have to correct the predicted range to the current air temperature. From the quantity $R_{\rm ex} - R_0$ determine the effective 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 $R_{\rm ex} - R_0 = \frac{\sqrt{\pi}}{2}\alpha$. Check that the source-detector distance is consistent with the value given earlier in the writeup. Compare the measured straggling parameter to the value given in Fig. 8 below.

8. Now use the PHA to measure the alpha particle energy as a function of air pressure. Start at 0 Torr (or as far as the system will pump down) and record the channel peak as a function of pressure in about

25 Torr steps. The channel number at 0 Torr will correspond to the alpha particle energy of 5.49 MeV. Record the channel peak down to the highest pressure at which you can still determine the peak channel. Plot E (channel number) as a function of pressure. This is the primary data from which you will determine dE/dx by numerically evaluating the derivative from the E vs pressure curve.

Evaluating the derivative of the E vs P curve can be done numerically by taking the differences between successive E (channel number) points and dividing by the pressure difference. Plot dE/dx vs P and dE/dx vs E. Note that dE/dx is energy dependent and rises as the energy decreases. The energy dependence would go as 1/E if not for the ln E dependence.

9. Plot $E\left(\frac{dE}{dx}\right)$ vs lnE. Since there is no additional E dependence, this procedure should result in a straight line from which the average ionization potential of air, $< I >$, can be determined. This can be readily done by extrapolating the straight line to zero and finding the intercept on the ln E axis. Determine this value of E and use it to solve for $< I >$ in eV. Compare to the expected value of about 100 eV. You will have to provide a value for $\frac{m_e}{M}$.

10. 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.

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

12. Use the range-energy data sheet in Fig. 9 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^{-8} $(^{o}C)^{-1}$

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

Figure 7: Silicon Properties

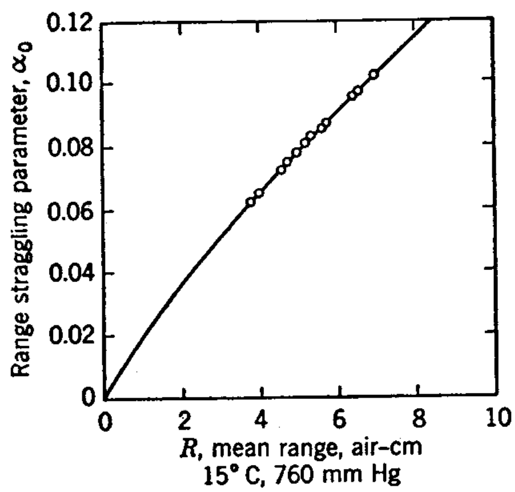

Fig. 5.3 **Range-straggling parameter α_0 for natural α rays in air (L25).**

Figure 8: Alpha Particle Straggling Parameter in Air

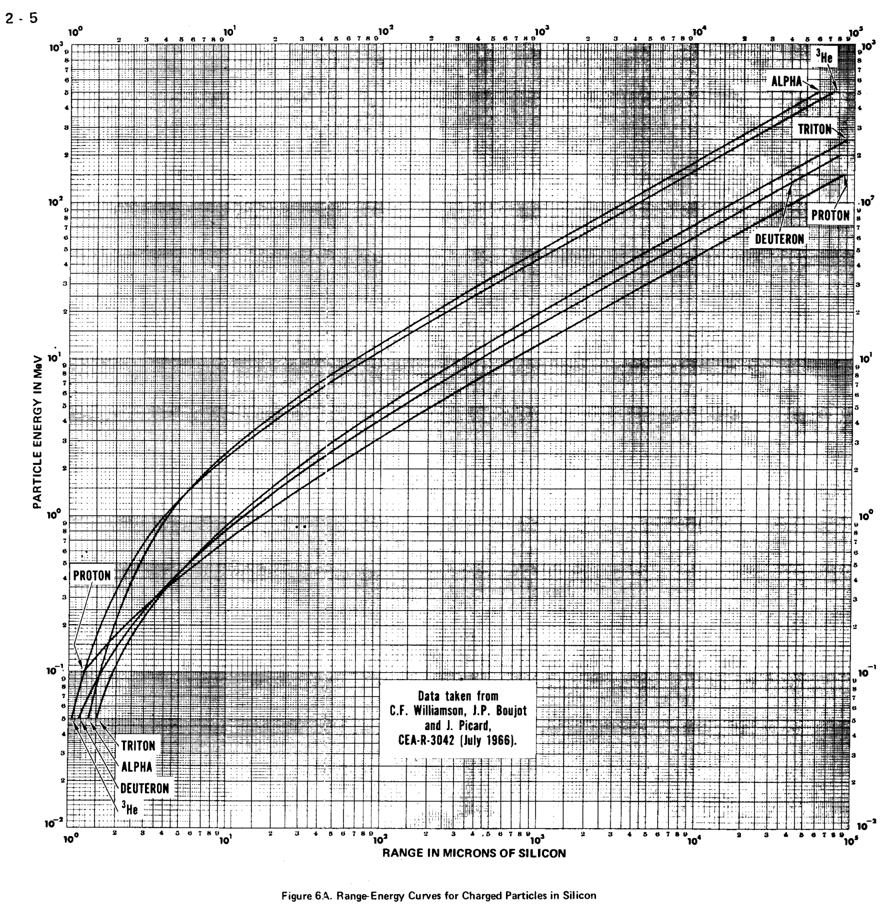

Figure 9: Alpha Range-Energy in Silicon