The Range of 18-Mev Protons in Aluminum*

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The circulating beam of protons in the cyclotron was multiply scattered upward by a strip of Th suspended vertically inside the dee. The energy of the scattered beam was defined by the Th strip and two slits in the magnetic field of the cyclotron. From a plot of the magnetic field along the path of the scattered protons, the mean energy was determined to be 18.00±0.02 Mev. By determining the thickness of Al that stopped half the incident beam, the mean range was found to be 447.0±0.5 mg/cm².

I. INTRODUCTION

THE range-energy curve for protons in Al has been determined experimentally by Parkinson, Herb, Bellamy, and Hudson[1] in the region below 2 Mev, by Bloembergen and van Heerden[2] in the region from 35 to 120 Mev, and by Mather and Segrè at 345 Mev.[3] The theoretical curve has been calculated by Livingston and Bethe[4] up to 13 Mev, and has been extended by Smith[5] up to 10 Bev. The ranges in material other than Al have been calculated by Aron, Hoffman, and Williams.[6] All calculated ranges are mean ranges.

The purpose of this investigation was to obtain an experimental point on the range-energy curve in the region of 18 Mev, the energy of the proton available from the UCLA 41-in. FM cyclotron. Since it is believed that the error in the range values calculated by Smith is about 0.1 percent in this region if the constants used are correct, this accuracy in the experimental measurements was desirable.

II. METHOD

To obtain a monoenergetic beam of protons, the circulating beam of the cyclotron was scattered by a narrow strip of Th suspended vertically inside the dee near the edge where the beam leaves it. The energy of the beam that was scattered upward was defined by the Th strip and two slits in the cyclotron magnetic field at 93 and 170 deg from the Th scatterer. Figure 1 is a plan view of the cyclotron tank showing the position of the Th strip and the slits. The second defining slit S_2 was mounted on the probe that contained the range measuring apparatus. The slits and the "end of the range probe" were located above the median plane of the cyclotron so that they did not interfere with the circulating beam. Approximate focusing of the particles scattered at different horizontal angles was obtained at the 170-deg slit.

Absolute measurements of the magnetic field at points along the path of the scattered protons were made with a nuclear radiofrequency magnetic resonance absorption probe. To determine the energy, an initial direction and energy of the protons leaving the Th strip were assumed, and the trajectory of these particles in the magnetic field was plotted to see if they went through the slits. By plotting trajectories for many energies and initial directions it was possible to determine the energy band that could get through the slits.

Inside the range measuring probe the beam passed through a thin Al foil and struck an Al plate. The thicknesses of the Al foil and plate were adjusted so that part of it penetrated the plate. The protons that penetrated the plate were collected by a second Al plate. The currents collected by either of the Al plates could be measured by an electrometer tube. The thickness of the Al foil could be changed, and the electrometer could be switched from one collecting plate to the other without turning off the cyclotron. The collector that was not being used was grounded. The current collected by each plate was determined for 10 foil thicknesses. A plot of these data gives the foil thickness for which the currents collected by the two plates were equal. This thickness plus the thickness of the first Al plate is the mean range.

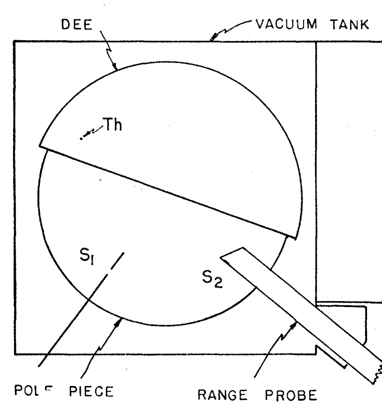

FIG. 1. Plan view of the cyclotron tank showing the location of the Th scatterer and the defining slits S_1 and S_2.

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[1] Parkinson, Herb, Bellamy, and Hudson, Phys. Rev. **52**, 75 (1937).

[2] N. Bloembergen and P. J. van Heerden, Phys. Rev. **83**, 561 (1951).

[3] K. B. Mather and E. Segrè, University of California Radiation Laboratory Report No. 1089 (1951).

[4] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 276 (1937).

[5] J. H. Smith, Phys. Rev. **71**, 32 (1947).

[6] Aron, Hoffman, and Williams, Report AECU-663 University of California Radiation Laboratory-121 (1949).

III. APPARATUS AND PROCEDURES

1. Multiple Scattering Deflector

The Th strip that scattered the circulating beam was mounted vertically inside the dee about 15 deg from the edge where the beam leaves it. The strip was 14 mils wide and 2 mils thick. A lead weight was attached to the lower end of the Th strip to make it hang vertically.

The Th strip was placed at a radius of 17.18 in. Because of the radial oscillations of the circulating beam and the loss of energy by multiple scattering in the Th, the deflected beam had an average radius of curvature of 15.8 in. The two defining slits therefore were at a considerably smaller radius than the Th strip.

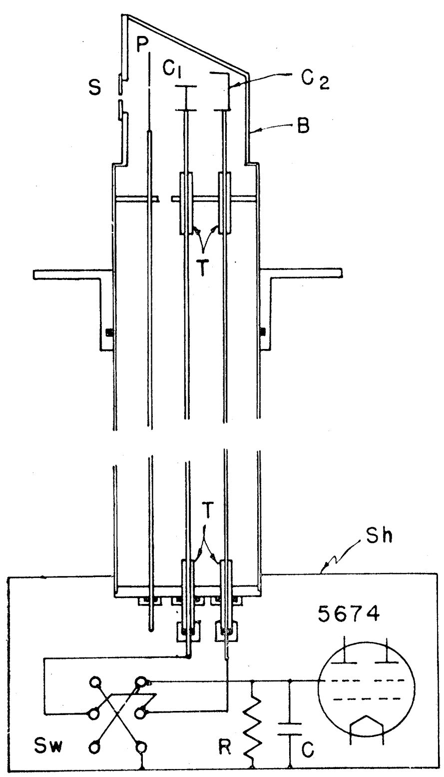

FIG. 2. Range probe and electrometer input circuit.

No appreciable beam was detected behind the last slit when the Th strip was moved out of the circulating beam.

2. First Defining Slit

The first defining slit was a $\frac{1}{8}$-in. vertical slot cut in a sheet of $\frac{1}{8}$-inch Al that was 6 in. long and 2 in. high. The lower edge was $\frac{1}{4}$ in. above the median plane. The outer edge of the slit was located at a radius of 15.74 in. and at 92.94 deg from the Th scatterer.

3. Range Probe

The Al plates (that collected the deflected beam) and the thin Al foils were supported by brass rods that were mounted in a brass tube 3 in. in diameter and 5 ft long. The tube was inserted into the cyclotron tank through a vacuum lock. The collectors and foils were inside a brass box that projected in from the end of the tube above the path of the circulating beam.

A schematic plan view of the range probe is shown in Fig. 2. The probe was mounted in the face plate F of the vacuum lock with a "O" ring seal so that its position could be changed without disturbing the cyclotron vacuum. C_1 and C_2 are the Al collecting plates with the shields that prevent the escape of secondary electrons. The brass rods supporting the collectors were insulated from their supports by Teflon tubes T. The thin foils were mounted on a paddle P. To minimize currents due to ionization of residual gas, the tube was evacuated to the cyclotron pressure through a baffle on the inside end. The rods and insulators were sealed at the outside end of the tube with "O" rings. The brass box B shielded the collectors from the rf, soft x-rays, and stray ions that are present in the tank.

The deflected beam entered the shield box B through a $\frac{1}{4}$-in. hole in the front side. The hole was covered with a 14-mil slit S made from two pieces of brass $\frac{1}{16}$-in. thick. The radius of the outside edge of the slit was 14.52 in. It was at 170.3 deg from the Th scatterer.

The 15,422-gauss magnetic field between the collectors caused some of the slowest protons that penetrated the first collector to miss the second collector. The radius of curvature of protons whose range is 0.1 percent of the range of 18-Mev protons is 2 in. The collectors were spaced $\frac{3}{8}$ in. apart so that the error due to this cause was negligible. The maximum radius of curvature of the secondary electrons knocked out of the collectors by the beam was 0.02 in. The collectors had 0.1-in. Cu shields around the edges to prevent their escape.

The first collecting plate was cut from an extruded rod of 99.995 percent pure Al. It was lapped until a dial indicator showed that the thickness of 66.2 mils was uniform to within 0.05 mil. The edges were made as square as possible and lapped until parallel and flat enough that they reflected light without distortion. The area of both sides was measured with a travelling microscope that could be read to 0.04 mil. The average width was 0.22568 in. It was measured by two observers who agreed to 0.14 mil. The average length measured perpendicular to the width was 0.50494 in. The weight was determined to be 0.3330 ± 0.0001 g with an analytical balance. These data give a thickness of 452.94 ± 0.34 mg/cm^2.

The paddle P contained Al foils of ten different thicknesses between 1 and 7 mils and could be quickly moved in front of the first collector. Using x-rays, Sachs[7] determined that the thickness of the foils was uniform to 1.5 percent. The foils were cut from triangles whose area and weight had been measured. The accuracy of

[7] Donald C. Sachs and J. Reginald Richardson, Phys. Rev. **83**, 834 (1951).

the thickness measurements was limited by the nonuniformity in the thickness of the foils. The estimated limit of error for the foils near the intersection of the straggling curves was 0.1 mg/cm^2.

4. Position Measurements and Magnetic Field Survey

The position of the slits was determined with an apparatus fitted with radial and azimuthal scales. The estimated rms error in the radius of curvature of the proton trajectories due to play in this apparatus is 0.05 percent. The magnetic field was measured to one part in 5000 along the path by a nuclear magnetic resonance probe using protons in a rubber sample.

The nuclear resonance probe could not be used when the cyclotron tank was evacuated. The magnet current was held constant by a regulator and slow drifts detected by a potentiometer and corrected manually. In this way the field could be held constant to two gauss during any one run. The magnitude of the field was monitored during a run by a pair of flip coils and a fluxmeter. This was necessary, as it was found that although the magnetic field was constant if the current was constant, the value of the field was different for the same magnet current each time the magnet was turned on. One of the flip coils was placed in the fringing field field of the cyclotron outside the vacuum tank. The other was in the field of a permanent Alnico magnet. The two coils were mounted on the same shaft so that they were flipped simultaneously through a definite angle. They were connected in series so that the emf's opposed each other and the fluxmeter read the difference in the number of maxwell turns. The coils and fluxmeter were calibrated with the nuclear absorption probe and could be read to within three gauss.

At four positions near the path, magnetic field readings were taken at several different vertical positions. The median plane field map was corrected to give the field strength at the average height of the deflected beam. The largest vertical correction required was -12 gauss. The magnetic field was three gauss higher when the tank was evacuated than when it was at atmospheric pressure. This correction was added to the field values obtained when the tank was down to air.

5. Determination of Proton Trajectories

The trajectories of the protons leaving the Th strip with a given momentum and initial direction were determined by a graphical method described by Parkins and Crittenden.[8] Points on the trajectory were computed at 10 deg intervals. To make sure that the 10 deg intervals were small enough, one of the trajectories was plotted using 5 deg intervals with no observable difference. The field values used were at the midpoints of the intervals. To further check the method, one trajectory was plotted in both directions and again there was no observable change in the trajectory. The estimated accuracy of the graphical method was 0.01 percent. Therefore the accuracy of the momentum determination was limited by the accuracy of the field values and the positions of the slits and the Th strip.

The lower limit of the momentum of the protons passing through the slits was determined by the trajectory that went through the inside of the Th strip and the second defining at 170 deg slit and the outside of the middle defining slit at 93 deg. The upper limit was determined by the trajectory that went through the outside of the Th strip and the second defining slit and the inside of the middle defining slit.

The trajectory plotting determined the energy of the beam due to the horizontal component of its velocity. The energy due to the vertical component of velocity was 0.011 Mev or 0.06 percent of that due to the horizontal component. The total energy was obtained by adding 0.011 Mev to the value determined graphically.

[8] W. E. Parkins and E. C. Crittenden, J. Appl. Phys. **17**, 447 (1946).

IV. RESULTS

1. Energy

The maximum and minimum values of the energy W of the protons passing through the slits was calculated from the maximum and minimum values of the momentum using the relativistic equation

$$W=-mc^2+[(mc^2)^2+(BRe)^2]^{\frac{1}{2}}, \qquad (1)$$

where m = rest mass of proton, c = velocity of light, B = magnetic field strength, R = radius of curvature, e = charge of proton, BR = momentum $\times c/e$. Equation (1) is expressed in gaussian units. The values of m, c, and e given by Birge[9] were used. The resulting maximum and minimum values for the energy were 18.037 Mev and 17.965 Mev. The difference between these values is 0.072 Mev or 0.4 percent. The mean value is 18.001 Mev.

Sachs[7] has determined the distribution in energy of the protons that pass through similar slits with an ionization chamber at 210 deg from the second defining slit. He obtained curves that were nearly symmetrical. The symmetry of these curves is consistent with the assumption that the mean energy of the protons was half-way between the extremes calculated from the slit geometry. The width of Sachs' curves at half-maximum was 48 percent of the total width so that 0.2 percent seems like a more reasonable value for the effective energy spread than 0.4 percent.

The total estimated error in the field measurements due to the centering of the pip, frequency measurements, field monitoring, and interpolation for the plotting of the trajectories is 5 gauss or 0.03 percent. The estimate of error in the radius measurement is 0.05 percent. The rms error in $(BR)^2$ or the energy is 0.13 percent or 0.023 Mev.

[9] R. T. Birge, Revs. Modern Phys. **13**, 233 (1941).

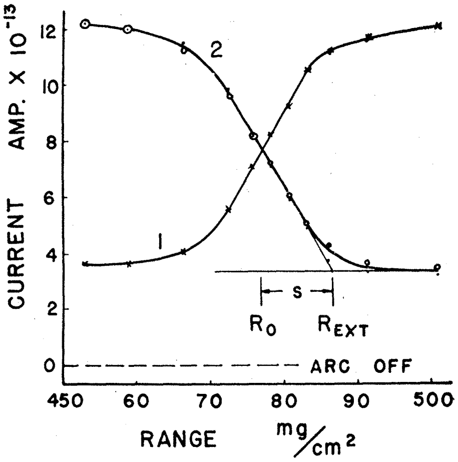

FIG. 3. Straggling curves. Curves 1 and 2 show the currents collected by the first and second Al plates, respectively. The intersection of the two curves determines the mean range R_0.

2. Range

The straggling curves obtained are shown in Fig. 3. The ordinates for curves 1 and 2 are the currents collected by the first and second Al plates, respectively. The abscissa is the thickness of the thin Al foil plus the thickness of the first Al plate. Experimental points on the curve for the second collector are given for two runs. Due to fluctuations in the beam intensity the 2 sets of points do not coincide exactly. The mean range determined by the intersection of the two curves is 476.9 mg/cm².

The current did not go to zero for thicknesses where the shape of the straggling curve indicates that no beam was being collected. Currents of about this magnitude were detected with the first defining slit covered with a $\frac{1}{16}$-inch brass sheet. Since these currents were independent of the Al foil thickness, it was assumed that they were not caused by the scattered beam hitting or entering the shield box around the collectors. Possible sources of this background are ionization of the residual gas in the tube and secondary emission from the collectors caused by general radiation from the circulating beam.

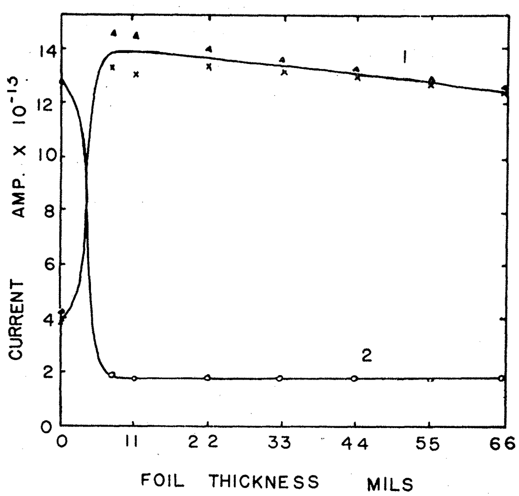

FIG. 4. Straggling curves showing the effect of the low energy component in the beam.

The background on the first collector was 1.5×10^{-13} amp higher than on the second. This difference was subtracted from the current readings on the first collector before plotting Fig. 3, but it is shown in Fig. 4. The extra current on the first collector was attributed to a low energy component in the beam. To show that the subtraction process was justified, a run was made, (Fig. 4) with the thin Al absorbers in front of the first collector replaced by thick absorbers. The first two thicknesses, 452.9 and 500.9 mg/cm², are the smallest and largest thicknesses in Fig. 3. The ratio of beam to background for this run was better than the runs shown in Fig. 3. It is seen in Fig. 4 that the current on the first collector fell off as thicker Al foils were put in front of it while the background on the second collector remained constant. This fall off indicates that there was a low energy component in the beam that should be subtracted from the current on the first collector. The magnitude of the fall off was about the same as the apparent difference in backgrounds on the two collectors. The low energy component in the beam was probably caused by scattering from the slit edges.

The biggest source of error in the range determination is the uncertainty in the amount subtracted from the currents of the first collector. The estimated limit of error due to the subtraction is 0.4 mg/cm² or 0.09 percent. When this error is combined with that of the thickness measurements, a total error of ±0.54 mg/cm² or 0.11 percent in the range measurement is obtained.

The mean square fluctuation of the range, $(R-R_0)_{\text{Av}}^2$, was determined from the difference s between the extrapolated range R_{ext} and the mean range R_0 by the equation

$$(R-R_0)_{\text{Av}}^2=(2/\pi)s^2. \quad (2)$$

The value obtained was 60.0 (mg/cm²)². The approximate expression

$$(R-R_0)/R\ \text{rms}=0.24W^{-0.1}E_0^{-\frac{1}{2}}, \quad (3)$$

where E_0 = rest energy of the proton, and W = ratio of kinetic energy to rest energy, was derived by Wilson[10] for protons in air. When the value given by Eq. (3) is increased by 5 percent to give the range fluctuation in Al, the result is 33.7 (mg/cm²)². If it is assumed that $R\propto E^{1.8}$, an energy spread of 0.2 percent gives a range fluctuation of 3.0 (mg/cm²)². A fluctuation of 23.3 (mg/cm²)² is left unaccounted for. A nonuniformity in the density of the first collector of 1.0 percent would account for this discrepancy. However, runs made with the first collector moved $\frac{1}{32}$ in. so that the beam hit a different part of it gave results identical with those obtained with the collector in its original position.

[10] R. R. Wilson, Phys. Rev. **71**, 385 (1947).

Some of the protons that penetrated the first collector captured an electron in it and emerged as neutral hydrogen atoms. These protons were detected as a positive current on the first collector although they were actually stopped in the second collector. Therefore the measured range was smaller than the actual range. To account for the neutralization effect, 0.1 mg/cm^2 or 0.02 percent was added to the measured range. This correction was calculated by H. N. Royden from the data of Hall.[11] The corrected mean range is 477.0 mg/cm^2.

The correction for multiple scattering has not been calculated exactly. If the individual angular deflections are assumed to be small, the measured range must be increased by about 0.2 percent.[2] The calculation is not valid for large deflections that occur near the end of the range.

3. Comparison with Theory

The theoretical curve calculated by Smith[5] and the experimental point with its limits of error are shown in Fig. 5. The experimental point gives a range of 477.0 $\pm$0.5 mg/cm^2 for a mean energy of 18.00$\pm$0.02 Mev. The theoretical curve gives 467.5 mg/cm^2 for the range of 18.00 Mev protons, differing from the experimental range by two percent. With corrections for multiple scattering the difference is about 2.2 percent.

In his range calculations Smith[5] used the value of 150 ev determined for the average ionization potential of Al by Wilson.[12] Sachs' experiments[7] on the absolute stopping power of Al give 156 ev for the average ionization potential.

Bloembergen and van Heerden[2] find a value of I of 164 volts at 35 Mev with some evidence that it is decreasing as the energy is raised. Mather and Segrè[3] find a value of I of 150$\pm$5 ev which agrees with Wilson. A value of 167 ev ($I=12.8Z$) would fit the present data for 18-Mev protons. This value can be obtained from

[11] T. Hall, Phys. Rev. **79**, 504 (1950).
[12] R. R. Wilson, Phys. Rev. **60**, 749 (1941).

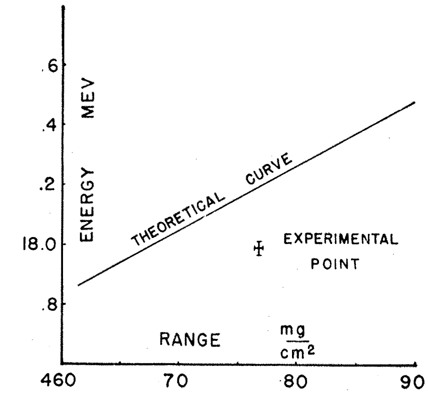

FIG. 5. Theoretical range-energy curve and experimental point.

Wilson's range relation[10]

$$R=\frac{10^{24}E_0W^{1.8}}{NZz^2\ln(4.14\times10^4/I)},$$

and for $I=11.5Z$ this agrees with Smith's calculations. For a given energy the variation of R with I is

$$\delta R/R=(\delta I/I)\ln(4\times10^4/I),$$

and for $\delta R/R=0.02$ (2 percent discrepancy) $\delta I=150\times5.7\times0.02=17$ ev. With corrections for multiple scattering the value of I would be about 170 volts, which is in fair agreement with Bloembergen and van Heerden but differs quite considerably from the values obtained by Sachs,[7] and Mather and Segrè.[3]

ACKNOWLEDGMENTS

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