The Absolute Energy Loss of 18-Mev Protons in Various Materials*†

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The absolute energy loss of 17.77±0.03-Mev protons upon passing through various materials was measured using the U.C.L.A. 41-inch FM cyclotron. A ribbon foil of thorium, mounted inside the dee, was used to deflect the circulating proton beam above the median plane of the cyclotron magnetic field. This scattered beam of protons, confined to a plane above the median plane, described a circular path in the magnetic field through a slit system. At the 180° point, the beam was made to pass through a thin metallic foil. The protons traveled an additional 210° to an ionization chamber detector. It was possible to move the detector to different cyclotron radii. The displacement of the proton intensity distribution caused by the presence of the metallic foil was a measure of the absolute energy loss in the foil. It was possible to calculate the stopping power and the mean excitation potential for each material investigated. The results for aluminum yield a value of 156±3 electron volts for the mean excitation potential. Other materials examined included Ni, Cu, Rh, Ag, Cd, Sn, Ta, Au, and Nylon.

Some information was obtained concerning the corrections to be applied to the stopping power formula; hence, the variation of these corrections with the atomic number of the stopping material was determined.

INTRODUCTION

IT is well known that the energy of a high speed charged particle is reduced upon passing through matter as a consequence of its many inelastic collisions with the atoms of the stopping material.

Bohr[1] was the first to develop a theory of stopping power $(-dE/dx)$ on the basis of classical mechanics. Subsequently, Bethe[2] and Bloch[3] applied the methods of quantum mechanics to the problem, the latter using the Fermi-Thomas statistical model of the atom. From the quantum statistical treatment, one derives the following relation for the stopping power:

$$-dE/dx=(4\pi e^4z^2/mv^2)NZ\ln(2mv^2/I), \quad (1)$$

where E is the energy, ez is the charge, and v is the velocity of the incident particle. The quantity x is the distance traveled by the particle through the stopping material. N is the number of atoms per cubic centimeter of the stopping material, Z is its atomic number, I is the mean excitation potential of the atom, and m is the electron mass. One condition for the validity of Eq. (1) is that the velocity of the incident particle be large compared with that of the electrons in the atoms of the stopping material. That is, in terms of energy,

$$E(\text{incident})\gg(M/m)E(\text{electron}), \quad (2)$$

where M is the mass of the incident particle and E (electron) is the ionization potential of the electron in the atom. When the inequality (2) is not satisfied for all electrons in the atom, then Eq. (1) is not valid as written and corrections must be applied.

These corrections have been calculated by Livingston and Bethe[4] for light elements where only the K electrons fail to satisfy condition (2). The corrected stopping power formula takes the form

$$-dE/dx=(4\pi e^4z^2/mv^2)N[Z\ln(2mv^2/I)-C], \quad (3)$$

where C is the total correction, including electrons in all the shells. Livingston and Bethe present a curve of the variation of C_k with $1/\eta$, which is a function of the energy of the incident particle. However, corrections for cases in which electrons of other shells do not satisfy the condition (2) have not yet been determined analytically or empirically.

It is difficult to determine the average excitation potential, I, purely theoretically with much accuracy; attempts in this direction[2] have met with little success. Therefore, I must be determined from the experimental data on stopping. Relative values of the mean excitation potentials have been obtained by Wilson,[5] Kelly,[6] Teasdale,[7] and by Bakker and Segrè.[8] Wilson determined the stopping power of aluminum relative to air for protons of energies to 4.0 Mev; the latter paper gives the stopping powers of various elements relative to Wilson's aluminum value for 340-Mev incident protons. The experiment described here is the first to measure absolute proton stopping powers.

THE DEFLECTION METHOD

Heretofore, in most cyclotron experiments which examined the stopping power of various materials, it has been necessary to use a beam of particles which was deflected so as to go outside the cyclotron tank. However, in the work described here, a unique method of deflection[9] was used and the experiment was carried on inside the tank of the U.C.L.A. 41-inch FM cyclo-

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[8] C. J. Bakker and E. Segrè, UCRL 850 (1950), unpublished (referred to here as BS).
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tron. The deflector took the form of a thorium foil (see Th in Fig. 1) mounted just inside the dee with its plane including a radial line and the vertical component of the magnetic field. When the circulating proton beam impinged upon the thorium foil, there was a slight decrease in the average energy coupled with a great deal of multiple scattering in the foil. The protons that were deflected upward were used in this experiment.

One can define the usual positive dimensionless quantity, n, as

$$n=-(r/H)\partial H/\partial r, \tag{4}$$

where r and H denote the cyclotron radius and magnetic field respectively. If one takes Z as the coordinate perpendicular to the cyclotron pole faces, it can be shown that the Z-component velocity of the particle away from the median plane due to scattering is opposed by the Z-component of force toward the median plane due to magnetic focussing forces. Considering the case of $Z=Z_0=0$ at zero time, i.e., a particle scattered at the median plane, one obtains

$$Z=(\phi r/n^{\frac{1}{2}})\sin(n^{\frac{1}{2}}\theta)=\phi s[\sin(n^{\frac{1}{2}}\theta)/n^{\frac{1}{2}}\theta], \tag{5}$$

where ϕ is the angle relative to the median plane through which the thorium foil deflects the particle and $s=r\theta$ is the particle path length. For a given scattering angle, ϕ, and for the value of n corresponding to the cyclotron radius used, the product $s[\sin(n^{\frac{1}{2}}\theta)/n^{\frac{1}{2}}\theta]$ remains relatively constant for values of θ between 180° and 390°. The explanation lies in the fact that the wavelength of the harmonic motion is long compared with the particle path length in this interval. If one considers the more general case where a particle off the median plane is deflected but where $Z_0 \ll \phi r/n^{\frac{1}{2}}$, one obtains an equation similar to Eq. (5) above. From this analysis it was computed that protons scattered from the thorium as much as one-fourth inch from the median plane will travel around the vacuum tank without hitting the dee or upper pole face. This conclusion was verified by experiment.

APPARATUS

A schematic drawing of the geometry of the experiment is shown in Fig. 1. The slit, S_1, was the "defining" or central slit and it took the form of an aluminum plate with a slot cut out of it. The slit, S_2, was the "foil" slit and it was equipped with copper out-rigger fins to stop those deflected protons which missed the slit. The ionization chamber, C, which moved on a radial track, T, was located in a plane above the dee structure and thorium foil as indicated in the end view of the cyclotron tank shown in Fig. 1. The slit, S_3, was the chamber slit and was mounted in front of the aluminum window of the ionization chamber.

The positions of the thorium, the slits, and the motion of the ionization chamber along its track were measured with a special precision-built measuring device. With the aid of a magnifying glass, one could read the scales to an accuracy of ±0.1 mm. The procedure was to measure the positions of the thorium, slits, and chamber motion both before and after a series of runs. There were two different sets of slit widths used in this experiment; the first (Geometry I) produced a well-defined proton beam that was adapted to the investigation of the thin aluminum foils, while the second (Geometry II) provided the larger beam intensity necessary for testing the thicker foils and heavier elements.

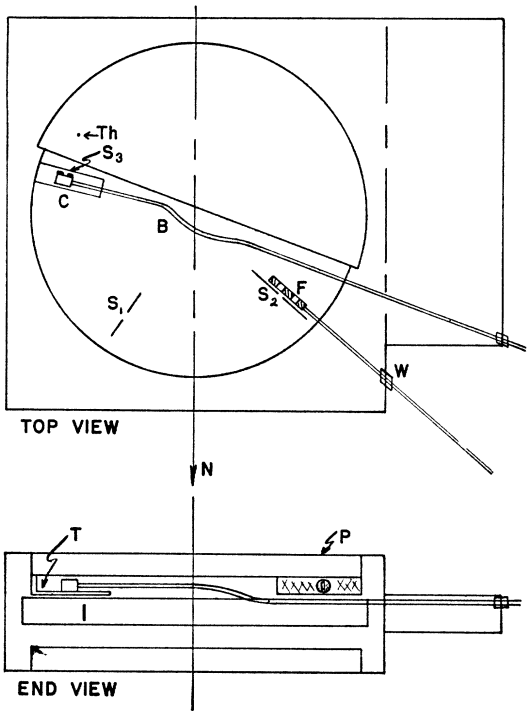

FIG. 1. A schematic drawing of the geometry of the absolute energy loss experiment.

So that it would be possible to investigate more than one material or thickness during a cyclotron run, a foil frame (see F in Fig. 1) was built to hold the foils and was fastened to a rod which passed into the cyclotron tank through a Wilson seal.

The ionization chamber was of the parallel-plate type, it was filled with air at atmospheric pressure, and was operated at saturation. The ionization current was measured by means of a conventional electrometer tube circuit.

To be certain that the intensity distribution of the deflected proton beam was obtained with constant cyclotron operating conditions, a means for moving the chamber during cyclotron operation was devised. It was arranged so that an observer outside the cyclotron building could both change and read the position of the chamber.

The circulating proton beam was monitored using a Beckman radiation meter located near the vacuum tank and connected to a 0–100 microampere meter in the control room. The magnetic field of the cyclotron

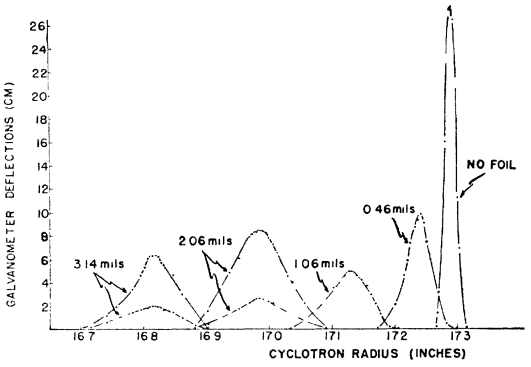

FIG. 2. A plot of a typical energy loss run. This shows the displacements of the proton momentum distributions after the beam has been made to pass through thin aluminum foils (Geometry I).

was monitored with a special flip coil and fluxmeter arrangement. The magnetic field could be maintained constant to ±4 parts in 15,000.

In addition to the usual determination of the surface density of the foils, the thickness variations of each foil were measured. These measurements were made with a copper target x-ray beam and a thin window electron counter. Only those foils whose thickness variations (rms deviation) was less than one percent were selected for the energy loss experiment. The foils were considered chemically pure, since the largest total impurity was 0.2 percent, while the aluminum foils were 99.9 percent aluminum.

The energy of the incident protons and the energies lost in the foils were determined by measuring the magnetic field values along the proton paths. With this information, it was possible to plot the proton trajectories graphically. The magnetic field was measured with a nuclear resonance absorption device similar to the one described by Hopkins.[10] It was possible to reproduce resonance absorption readings to ±7 gauss or ±0.05 percent. The proton energy determination method that was employed is described by Parkins and Crittenden.[11]

TABLE I. Mean excitation potential of aluminum.

Surface density (mg/cm²)	Most probable energy loss (Mev)	Most probable energy loss (10^4) g/cm² (with probable error)	Mean excitation potential (ev) (with probable error)
7.153[a]	0.153	0.3422±0.0085	168.3±20.2
14.054[a]	0.301	0.3432±0.0050	168.4±12.6
21.432	0.465	0.3476±0.0037	160.6±8.0
21.532[a]	0.470	0.3497±0.0040	155.6±8.9
33.875	0.737	0.3485±0.0028	162.8±6.5
38.395	0.839	0.3500±0.0020	162.0±4.7
47.457	1.048	0.3538±0.0017	156.7±7.7
57.493	1.276	0.3555±0.0025	157.1±5.5
67.294	1.515	0.3607±0.0024	150.0±5.0
76.849	1.737	0.3621±0.0018	150.8±3.8

[a] These measurements were made with Geometry I; the remaining measurements were made using Geometry II.

[10] N. J. Hopkins, Rev. Sci. Instr. **20**, 401 (1949).
[11] W. E. Parkins and R. Crittenden, J. Appl. Phys. **17**, 447 (1946).

RESULTS

Energy

The incident or "no foil" energy was determined to be 17.77 Mev with an energy spread of ±0.15 percent. From the accuracy of the energy loss measurements and the energy calibration (i.e., the change in energy corresponding to a certain change in cyclotron radius), the probable error in the energy loss determination was fixed at ±0.004 Mev. It must be noted that, since the mean excitation potential, I, appears in the argument of the logarithm in Eq. (3), its value will be sensitive to small changes in (dE/dx). A one percent probable error in (dE/dx) will be magnified to almost 6 percent in I.

Aluminum

Figure 2 shows a plot of a typical aluminum foil run. The displacement of the foil intensity distribution maxima from the "no foil" maximum represents the magnitude of the most probable energy loss in the foil. The two curves for the 2.06- and 3.14-mil foils correspond to different electrometer sensitivity settings. In both cases, the data for the lower curves were taken with the same setting as used for the "no foil" data. However, the sensitivity was later increased and the higher distribution curves resulted. The results of the aluminum runs are shown in Table I. The values of C_k from Livingston and Bethe[4] corresponding to the average energy were used in the calculation of the mean excitation potential. Consideration of all ten values in Table I gives a weighted average for the mean excitation potential of 156.2±2.0 electron volts. The first two values correspond to fairly thin foils and have a relatively large associated error. If these are thrown out, the weighted average is changed to 155.8±1.8 electron volts. Using the standard error, we then state our result as 156±3 electron volts. This result must be compared with the value of 150 electron volts determined by Wilson.[5] Since Wilson's standard error in the stopping power seems to have been about 3 percent, his standard error in the mean excitation potential was approximately 15 percent.

TABLE II. Weighted averages of the uncorrected mean excitation potentials.

Element	Weighted average uncorrected mean excitation potential (ev)	Root mean square deviation (ev)	Percent rms deviation
Al	161.4	2.0	1.2
Ni	375	19	5.1
Cu	412	6.3	1.5
Rh	760	17	2.2
Ag	766	21	2.7
Cd	766	32	4.2
Sn	831	47	5.6
Ta	1092	25	2.3
Au	1290	40	3.1

Corrections in Stopping Formula

The uncorrected mean excitation potentials of the elements other than aluminum which were investigated can be found in Table II. These results were computed using Eq. (1), and are not corrected for nonparticipating electrons.

It was thought that further use could be made of these data in the following way: BS,[8] using 340-Mev protons, were working with a $(m/M)E(\text{incident})=185$ kev, and thus one could assume that the condition of Eq. (2) would be met for all the electronic shells of the elements which they investigated. Hence, one could compare the BS results for the relative mean excitation potentials with the uncorrected results of the present investigation, and thereby obtain the corrections to the stopping formula corresponding to each element. The second column of Table III shows the BS results referred to the I_{AL} of the present investigation. One of

TABLE III. Corrections to be applied to the stopping power formula.

Element	Mean excitation Potential (ev) (from BS)	C/Z
Al	155.8[a]	0.037
Ni	270	0.328
Cu	290	0.351
Rh	425	0.579
Ag	438	0.560
Cd	454	0.526
Sn	470	0.574
Ta	690	0.460
	567[b]	(0.668)
Au	747	0.546
	594[b]	(0.771)

[a] Normalized to present results.
[b] C_k correction equal to 0.30 applied; value taken from Livingston and Bethe curve.

the features of the BS results was that for elements between $Z=47$ and $Z=92$ the quantity I/Z was essentially constant. This fact was used in determining the approximate corrected potentials of nickel, rhodium, cadmium, tantalum, and gold. The results of the correction determinations are listed for each element as C/Z, the total correction divided by the atomic number, in the third column of Table III. A plot of this quantity *vs* the atomic number is shown in Fig. 3. It is evident from this plot that the curve begins to bend over after rising steadily to about $Z=40$. Before proceeding, however, one had to be sure this bending over of the curve was not a function of the method of analysis.

When the energies of the K electrons of tantalum and gold were calculated from x-ray absorption edge data, it became evident that even at the very high incident energy of 340 Mev one had to considered C_k corrections in these high Z elements. Nevertheless, this

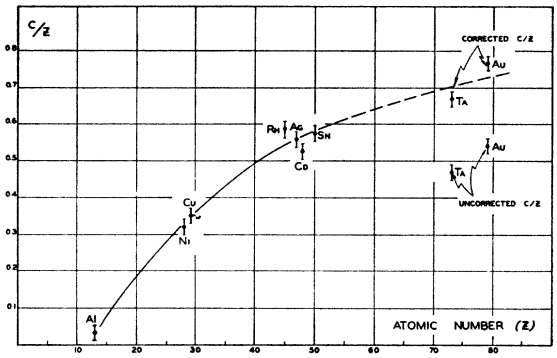

FIG. 3. A plot of the correction quantity C/Z for 18-Mev protons *vs* the atomic number of the stopping substance.

C_k correction could not change the nonlinearity of the curve in Fig. 3, since this would require that C_k/Z be comparable to C/Z, which in turn would change I by about a factor of three. As an approximation for tantalum and gold, it is possible to use the C_k as read off the Livingston and Bethe curve. These corrected C/Z points are shown in Fig. 3 and the dotted portion of the curve indicates the approximate plot.

For a given particle velocity, the value of C/Z increases with increasing atomic number since more electrons become ineffective in stopping at higher Z. However, Fig. 3 indicates that after $Z=40$, the fractional increase in the number of ineffective electrons is comparable to the fractional increase in the total number of electrons. The reason for this is found in the fact that the electrons in outer shells are more effective in the stopping process than those in the inner shells. Thus, an added electron in tantalum or gold will not increase the fractional number of ineffective electrons as much as the addition of an electron to nickel or copper.

Nylon

Since Nylon[12] is a material used widely for counter windows and as a target in scattering experiments, it was included in this investigation of absolute energy loss. Because the stopping number was very large, the calculation of the mean excitation potential was insensitive to the addition of the C_k correction. The calculated weighted average of I_{Nylon} was 38.5 ± 0.5 electron volts. No effort was made to determine the individual excitation potentials of the component atoms. For equal energy losses in the Nylon and aluminum, the mass stopping power relative to aluminum was computed to be 1.21 ± 0.02.

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[12] The sample used was supplied by the Goodyear Tire and Rubber Company.