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STOPPING POWER AND ENERGY FOR ION PAIR PRODUCTION FOR 340 MEV PROTONS

C. J. Bakker and E. Segrè

August 3, 1950

Berkeley, California

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August 3, 1950

Summary

The relative stopping powers for 300 Mev protons of H, Li, Be, C, Al, Fe, Cu, Ag, Sn, W, Pb, and U have been measured. The results are shown in Table I. The energy spent per ion-pair production in the gases H_2, He, N_2, O_2, and A at 340 Mev proton energy has also been measured. The results are shown in Table II.

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Introduction

The average rate of energy loss of fast particles due to ionization only is given by the well-known Bethe formula[1]

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} N Z \left[\ln \frac{2mv^2}{I} - \ln(1 - \beta^2) - \beta^2 \right] \qquad (1)$$

in which e and m are the electronic charge and mass, ez is the charge of the incident particle, NZ is the number of electrons per unit volume of stopping material, $\beta = \frac{v}{c}$ and I is the mean excitation potential of the atoms in the stopping material.

This formula holds when $v \gg u_k$ where u_k is the velocity of the orbital electrons in the K-shell of the atoms in the stopping material. Effects such as radiation, nuclear interactions and so on are not taken into account in formula (1); they may play an increasingly important part at higher energies.

Extensive tables based on formula (1) have been computed by Aron, Hoffman and Williams[2] of the Radiation Laboratory of the University of California. In these tables the mean excitation potential I was chosen proportional to Z, in accordance with Bloch's theory[3] developed on the basis of the Thomas-Fermi model of the atom. The value of the Bloch constant I/Z was chosen to be 11.5 ev in accordance with measurements by R. R. Wilson.[4] In cases where the condition $v \gg u_k$ was not fulfilled correction terms were added to formula (1) given by Livingston and Bethe.[1]

Experimental

Since the 340 Mev protons of the Berkeley cyclotron afford a good opportunity of checking the semi-empirical part of the stopping power calculation and the result is of practical importance, we decided, using these particles, to measure the stopping power of various elements spread over the periodic system.

The high energy protons of the 184-inch cyclotron are stopped by 93.7 g/cm^2 of copper (ionization extrapolated range) as measured from the Bragg curve at the end of the range (see below). In the experiments approximately 30 g/cm^2 of copper were replaced by the material to be investigated. By again measuring the Bragg curve at the end of the range the mass stopping power of the various materials relative to copper could be determined. At the initial energy of the protons (measured as 340 Mev from the radius of the orbit and magnetic field in the cyclotron) the energy loss induced by 30 g/cm^2 of copper amounts to about 75 Mev. The mean energy of the protons in the absorbing material is therefore about 300 Mev. The experimental arrangement may be essentially seen from Fig. 1. The fast protons emerged from the concrete wall surrounding the 184-inch cyclotron through a collimator of 1/2 inch inner diameter at the exit, passed successively through the material to be investigated, through 56.70 g/cm^2 of copper and then, in order to measure the Bragg curve, through layers of copper that could be varied from 0 to 11 times 0.72 g/cm^2. The latter were mounted in 2 inch holes arranged near the circumference of a large wheel which could be rotated from a distance. The measurements of all 12 positions could be made in about 10 minutes. As a measuring instrument for the protons we used an ionization chamber filled with argon to atmospheric pressure (Chamber C in Fig. 1). A similar chamber served as a monitor for the proton beam (Chamber B in Fig. 1).

In order to compare the absorption in the various materials we had to choose a reference point in the various Bragg curves measured (Fig. 2b). Either the range at the maximum of the specific ionization, or the range at the intersection of the steepest tangent with the abscissa, or the range at half maximum could be taken for this. After considering the three possibilities carefully we arrived at the conclusion that they were all about equally accurate. In agreement with common practice we chose as a reference the range given by the intersection of the steepest tangent with the abscissa, usually referred to as the ionization extrapolated range.

As the absorption in copper was used as a standard, in the course of the run of the measurements the Bragg curve of the copper absorber was intermittently measured. The result was always the same within the experimental errors, which indeed is an excellent proof of the constancy of the energy of the proton beam of the 184-inch cyclotron. This may be seen from Fig. 2b where the circles and crosses denote different measurements.

Results

By dividing the number of g/cm^2 of copper by the equivalent number of g/cm^2 of the element under investigation one obtains the mass stopping power relative to copper. Table I, column 2, shows the results of the measurements. The mean experimental error of these numbers, except for hydrogen, is about 2 percent. The value for hydrogen was obtained by subtracting the carbon figure from the measurement of polyethylene, which consists of long chain molecules and has a chemical composition CH_2. The error in the hydrogen figure is about 10 percent. Moreover it must be remembered that the chemical binding

Table I

Element		Mass stopping power Cu = 1	Mass stopping power Al = 1	q = Stopping power per electron Al = 1	I_{ev}	I/Z ev
1	H_2(in CH_2)	3.010	2.634	1.280	15.5	15.5
3	Li	1.214	1.062	1.184	34.0	11.3
4	Be	1.171	1.024	1.113	60.4	15.1
6	C	1.285	1.124	1.084	76.4	12.7
13	Al	1.143	1.000*	1.000*	150*	11.5*
26	Fe	1.036	.906	.941	243	9.3
29	Cu	1.000*	.875	.924	279	9.6
47	Ag	.902	.789	.873	422	9.0
50	Sn	.858	.751	.859	453	9.1
74	W	.777	.680	.814	680	9.2
82	Pb	.754	.660	.804	737	9.0
92	U	.720	.630	.786	853	9.3

In each column the reference value is marked by an * .

of the hydrogen in polyethylene may have considerable influence. (Experiments on the effect of chemical binding in stopping power will be carried out in the near future in this Laboratory.)

As it is common practice to tabulate the mass stopping power relative to aluminum, we also calculated this quantity from our measurements. The data are shown in column 3 of Table I.

It is of interest to determine from our data the stopping power per electron. According to formula (1) this quantity is

$$- \frac{dE}{dx} \Big/ _{NZ} = \frac{4\pi e^4 z^2}{mv^2} \left[\ell n \frac{2mv^2}{I} - \ell n \, (1 - \beta^2) - \beta^2 \right] \qquad (2)$$

The stopping power per electron relative to aluminum is

$$q = \frac{- \ell n \, I + \left[\ell n \, 2 \, mv^2 - \ell n \, (1 - \beta^2) - \beta^2 \right]}{- \ell n \, I_{Al} + \left[\ell n \, 2 \, mv^2 - \ell n \, (1 - \beta^2) - \beta^2 \right]} \qquad (3)$$

which was calculated from our data by multiplying the figures of Table I, column 3 by $A/A_{Al} \cdot Z_{Al}/Z$, in which A and Z are the atomic weight and the atomic number of the element under investigation, and $A_{Al} = 26.97$, $Z_{Al} = 13$, the corresponding numbers for aluminum. Column 4 of Table I shows the result.

Dr. H. A. Bethe has kindly pointed out to us that the most favorable method for further analyzing our results is to use formula (3) to calculate the mean excitation potentials I. The absolute value of I can be based on Wilson's determination of 150 ev as the mean excitation potential for aluminum which is accurate to ± 3 percent. Wilson's measurement, however, does not give a satisfactory value for the Bloch constant I/Z as aluminum is too light an element for the Bloch theory to be valid.

Introducing in formula (3) I_{Al} = 150 ev and β = 0.65, so that $\left[\ln 2\, mv^2 - \ln (1 - \beta^2) - \beta^2\right]$ = 13.112, it follows that

$$\ln I = 13.112 - 8.096 \cdot q$$

The values of I and I/Z are tabulated in columns 5 and 6 of Table I.

It is seen from the last column that the Bloch "constant" is nearly constant between Z = 46 and Z = 92. The average value is 9.1 ev. This value is somewhat lower than the value Bethe derived in a similar way from Stephan and Thornton's[5] total range measurements of 194 Mev deuterons, namely slightly over 10 ev. Our value should be considered as more accurate.

As also pointed out to us by Dr. Bethe a satisfactory result confirming the analysis is the average potential for beryllium, which comes out to be 60.4 ev. Madsen and Venkateswarlu[6] have determined this value by a direct and absolute experiment and found it to be 64 ± 5 ev. This result is not as accurate as Wilson's but has the advantage of being a direct absolute determination in which, unlike Wilson, they did not make use of the stopping power for air. The agreement within experimental errors serves to confirm Wilson's values for aluminum to some extent.

<u>Analysis of straggling</u>

Formula (1) gives the average energy loss suffered by a charged particle in traversing some stopping material. Actually the number of collisions, which reduces the energy, is finite, and a statistical fluctuation in the amount of energy lost can be expected ("straggling").

Starting with particles of the same initial energy E_o and R_o being the average range, the probability for a particle to have a range R is given by the Gaussian

$$P(R) = \frac{1}{2\pi\ \overline{(R - R_o)^2_{av}}} \ \exp - \frac{(R - R_o)^2}{2(R - R_o)^2_{av}}$$

It has been shown by Bohr[7] and by Livingston and Bethe[8] that for protons of high initial energy the mean square fluctuation in the range is

$$(R - R_o)^2_{av} = 4\pi e^4 NZ \int_o^{E_o} \left(\frac{dE}{dx}\right)^{-3} dE$$

We calculated $(R - R_o)^2_{av}$ for 340 Mev protons stopped in copper. The values of dE/dx as a function of E were taken from the list in the tables of Aron et al.[2] The result is

$$(R - R_o)^2_{av} = 0.67\ (g/cm^2\ Cu)^2$$

In order to compare this theoretical value of straggling in copper with the experimental Bragg curve we "folded" the one particle ionization curve in argon* into a Gaussian. It was found that satisfactory agreement with the experimental Bragg curve was obtained if we chose

$$(R - R_o)^2_{av} = 1.3\ (g/cm^2\ Cu)^2$$

The difference between the experimental and theoretical value of the straggling constant must be ascribed to inhomogeneities in the absorbing layer, which for copper are small, and to the spread in energy of the initial protons. If we suppose the latter to be the main effect it follows that the spread in initial energy of the 340 Mev proton beam gives rise to an additional straggling with $(R - R_o)^2_{av} = 0.63\ (g/cm^2\ Cu)^2$ which denotes an average energy spread of the proton beam of about 1/2 percent. This value is in satisfactory agreement

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*The range-energy curves of Aron et al. (ref. 2) were used to determine this curve.

with what one expects from the geometrical arrangement of the collimators and the small magnet which bends the proton beam into the exit hole in the concrete wall surrounding the 184-inch cyclotron. Moreover, a similar result follows from the study of the threshold range of the reaction $C^{12}(p,pn)C^{11}$ by Peterson, Aamodt, and Phillips[9] of this Laboratory.

From our analysis we derive that the mean range R_o of the protons is 92.4 g/cm^2 Cu, which according to the table of Aron et al. corresponds with 334.7 Mev initial proton energy. It should be remarked however that Aron et al. used for copper the value of I = 333.5 ev whereas according to the present paper I_{Cu} = 279 ev. This increases the value of the initial proton energy by 2 percent to 341 Mev.*

Energy for ion pair production

The energy for ion pair production by the 340 Mev protons of the 184-inch cyclotron was measured for the gases hydrogen, helium, nitrogen, oxygen and argon. The proton beam was allowed to cross two identical ionization chambers. One, filled with argon at atmospheric pressure, served as a monitor. The other was successively filled with the gases to be investigated. In order to compare the results corrections were made for differences in temperature and filling pressure. The energy per ion production W follows from

$$W = \frac{\text{energy loss}}{\text{number of ion pairs produced}}$$

In this relation the numerator is the rate of energy loss $-\frac{dE}{dx}$ which for the various gases is to be found in the tables of Aron;[2] the denominator is

*An entirely independent measurement of the energy of the beam made by Mr. Mather using the properties of the Cerenkov radiation gives 345 Mev. However the two results are not comparable because they were obtained with the beam deflected in slightly different ways and this change is enough to justify the slight discrepancy.

proportional to the ionization measured in the ionization chamber.

The second column of Table II lists the values of $-\frac{dE}{dx}$ used to derive from our measurements the values of W relative to argon, which is shown in column 3.

Recently Chamberlain, Segrè and Wiegand measured the number of ion pairs produced by one 340 Mev proton crossing 1 cm of argon at atmospheric pressure and 0° C; this number is 169 and was obtained by combining the ionization measurement with an absolute current measurement by means of a Faraday cage. It agrees with results independently obtained by V. Z. Peterson. This result is of practical importance because it can be used to measure beam currents in a simple way avoiding the somewhat tedious use of a Faraday cage.

Combining the last number with the theoretical value of $-\frac{dE}{dx}$ for argon we find $W_A = 24.84$ electron volts per ion pair. This allows the determination of the W's of the other gases. The result is shown in column 4 of Table II. For comparing we added in column 5 of Table II the values of W measured at low energy(Po - α-particles) by Alder, Huber and Metzger.[10]

We wish to thank Dr. Karl Strauch and Mr. T. Thompson for their help during the measurements.

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Table II

Gas	$-\frac{dE}{dx}$ (Mev/cm) 340 Mev p	W/W_A 340 Mev p	W(ev) 340 Mev p	W(ev) Po - α-particles
hydrogen	5.84×10^{-4}	1.40^5	34.9	35.1
helium	5.34×10^{-4}	1.02	25.3	30.2
nitrogen	3.49×10^{-3}	1.31^5	32.7	36.3
oxygen	3.92×10^{-3}	1.23	30.6	34.5
argon	4.02×10^{-3}	1.00	24.84	27.6
air (calculated)			32.2	35.8

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Figure Captions

Fig. 1 The experimental arrangement A is the concrete wall surrounding the 184-inch cyclotron. The 340 Mev protons pass through a collimator with 1/2 inch diameter exit hole. B and C are ionization chambers. X is the material under investigation, with stopping power equivalent to about 30 g/cm^2 of copper. Cu is 56.70 g/cm^2 of copper absorber. D is a wheel, by which different thicknesses of copper absorber could be inserted.

Fig. 2 a) shows the complete experimental Bragg curve for 340 Mev protons stopped by copper.

b) gives the end of the Bragg curve on an enlarged scale. The crosses and circles denote measurements at different times. The steepest tangent has been drawn in.

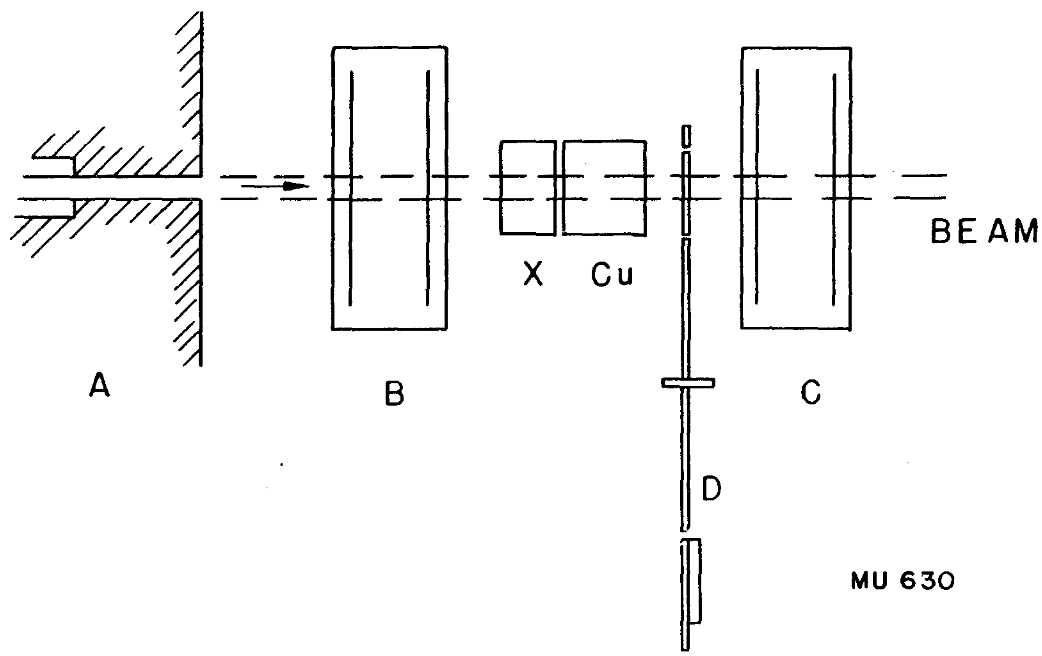


FIG. 1

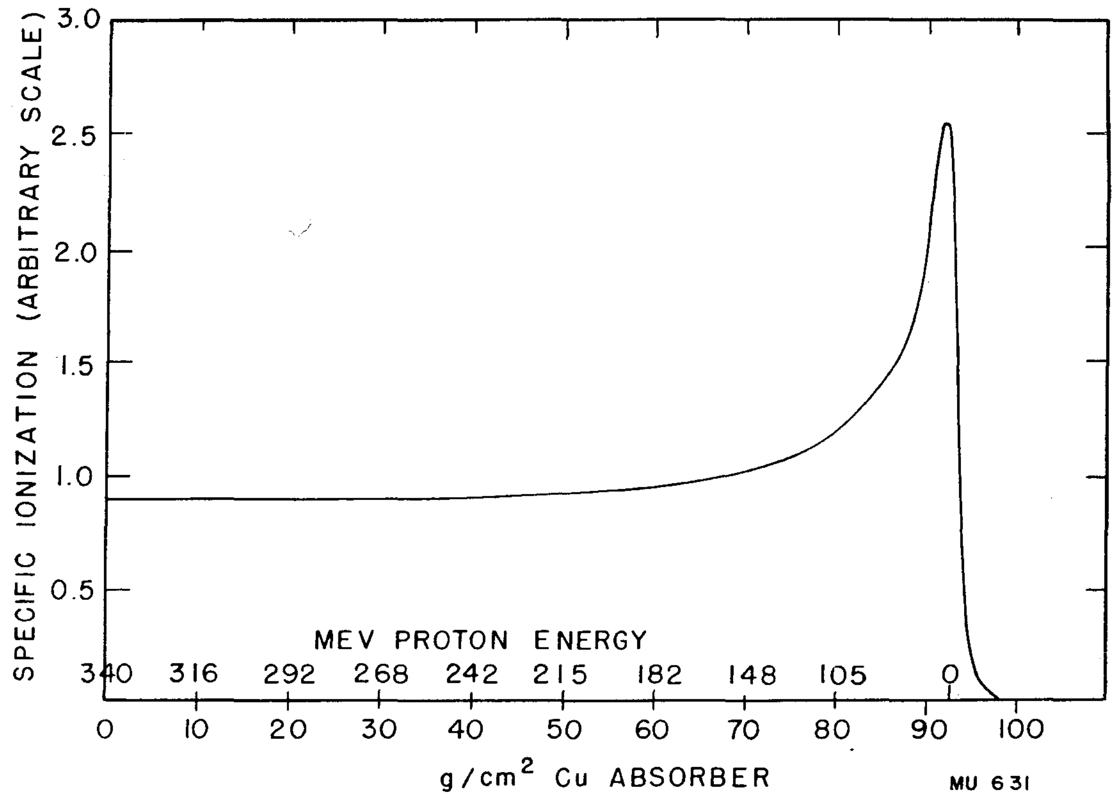
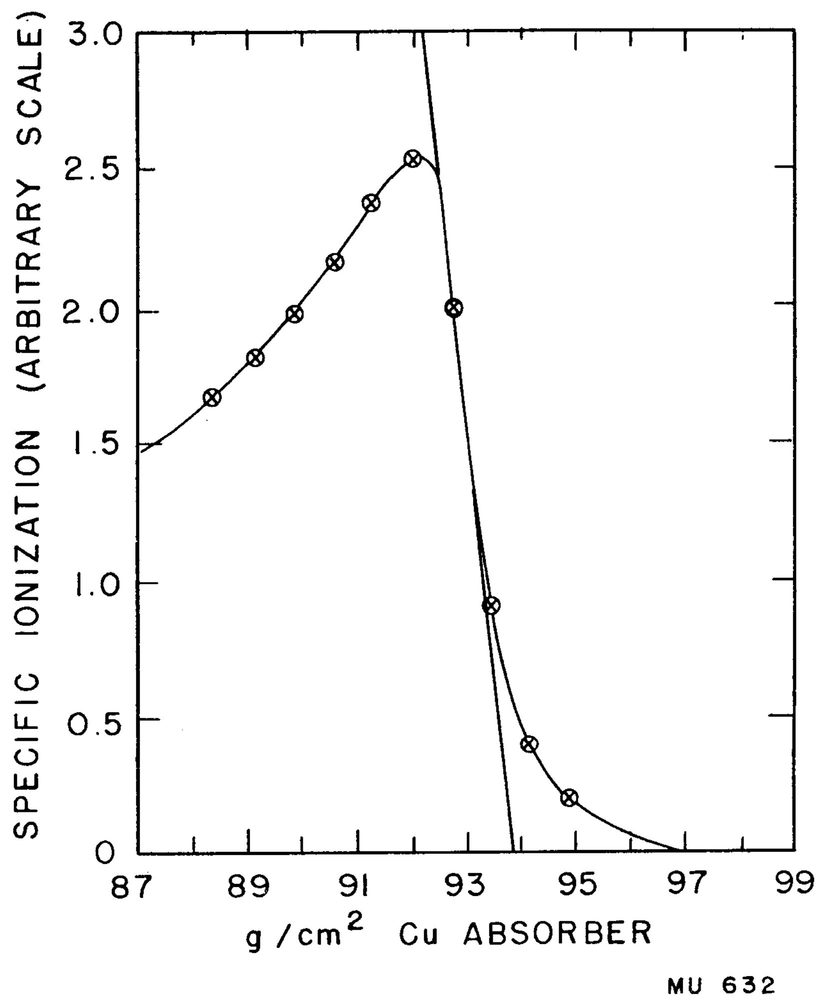

SPECIFIC IONIZATION (ARBITRARY SCALE)
3.0
2.5
2.0
1.5
1.0
0.5
MEV PROTON ENERGY
340 316 292 268 242 215 182 148 105 0
0 10 20 30 40 50 60 70 80 90 100
g/cm^2 Cu ABSORBER
MU 631

FIG. 2a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2.0
1.5
1.0
0.5
0
87
89
91
93
95
97
99
g /cm^2 Cu ABSORBER
MU 632

FIG. 2b