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Experimental Range of Protons in Al†

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The ranges of protons of 1 to 6 Mev in Al have been determined experimentally. Combining these results with earlier experimental data, the range can be represented by the following analytic functions: for $1<E<2.7$ Mev, $R=3.837E^{1.5874}$; for $2.7<E<20$ Mev, $R=2.837E^2/(0.68+\log_{10}E)$, with E in Mev and R in mg/cm^2. A tentative comparison with the theory of stopping power was made. The neutron thresholds for proton bombardment of C^{13}, F^{19}, and Na^{23} were obtained as an incidental result.

I. INTRODUCTION

A RANGE-ENERGY table for protons from 1 to 20 Mev in Al was obtained from the results of experimental range measurements at Princeton.[1] The region from 1 to 6 Mev had to be covered by extrapolation with the aid of the theory of stopping power,[2] which requires the knowledge of the shell corrections c_K and c_L. Both of these corrections have been derived theoretically by Walske,[3] but the L-shell corrections are reliable only for elements with $Z>30$. In view of this situation it seems desirable to actually measure proton ranges at low energies, and this in turn would allow a determination of the L-shell corrections, which are largest at these energies. The Rice Institute electrostatic generator covers the desired energy region, and the analyzing magnet allows the accurate determination of proton energies. The close spacing of experimental measurements makes possible an accurate analytic representation of the results. Difficulties in the evaluation of multiple scattering allow only a preliminary comparison with Bethe's theory.[2]

II. MEASUREMENTS

Range and Line-Up

For the range measurements the Princeton counter was available,[4] and the methods used were the same as described in the earlier paper.[1] Great care was taken in the machining of the relatively thin foils. A more accurate, automatic balance[5] was available for the weighing of the foils and an accuracy of ± 0.03 mg was achieved. Estimates of the errors in the surface densities will be given later on.

The procedure for the line-up of the counter with respect to the proton beam was greatly simplified through the adjustable regulating slits of the beam-analyzing system of the accelerator: the slits were kept wider than the entrance hole of the counter (2 mm in diameter). Then the shadow of the entrance hole would be observed on a quartz plate at the wall of the last counter through a hole of 3-mm diameter, concentric with the counter axis. The counter axis was moved until the shadow of the entrance hole was concentric with the hole at the back end of the counter. Then the regulating slits were closed to approximately 1 mm^2. It was necessary to remove stopping foil and entrance foil of the counter for this line up.

Energy

The analyzing magnet of the accelerator deflects the proton beam by 90°. Through the use of two slits about 1 mm wide both before and after the magnet a well-defined proton energy was obtained. For the calibration of the magnet the proton beam was directed upon a lithium target. The threshold for the $Li^7(p,n)$ reaction (at 1.8810 Mev) was then determined in terms of the magnetic field at a point near the proton path.[6] The field was measured with a proton magnetic resonance probe. In order to eliminate hysteresis effects of the iron, care was taken to always approach the threshold from low proton energies, and the magnet was always brought close to saturation (18 000 gauss) before the current was turned off.

In principle it would be possible to determine other proton energies from the relation[7]

$$\frac{E}{1+E/2Mc^2}=kf^2,$$

where E is the kinetic energy of the particle, Mc^2 its rest energy, f the Larmor frequency of the proton in the magnetic field, and k a constant. Saturation effects will tend to reduce k for higher fields. To determine the magnitude of this effect k was measured for the $Li(p,n)$ threshold mentioned above and then at about twice the frequency for the same threshold, measured by bom-

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[1] Bichsel, Mozley, and Aron, Phys. Rev. **105**, 1788 (1957).
[2] See e.g. E. Segrè, *Experimental Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Vol. I, Part 2.
[3] M. C. Walske, Phys. Rev. **88**, 1283 (1952), and **101**, 940 (1956).
[4] I am grateful to Princeton University for the loan of the equipment.
[5] Distributed by Mettler Instrument Corporation, Hightstown, New Jersey.
[6] Bonner, Kraus, Marion, and Schiffer, Phys. Rev. **102**, 1348 (1956).
[7] Kington, Bair, Cohn, and Willard, Phys. Rev. **99**, 1393 (1955).

TABLE I. Neutron thresholds (Mev).

Reaction	Present data	Kington *et al.*
C^{13} (p,n)	3.241±0.006	3.236±0.006
F^{19} (p,n)	4.242±0.005	4.240±0.008
Na^{23} (p,n)	5.051±0.006	5.053±0.010

bardment with a molecular beam HH^+. The ratio of the two constants was 1.0042. A linear interpolation was used to obtain k for other energies between 1.88 and 7.5 Mev; and below 1.88 Mev k was assumed to be constant. As a control for the interpolation the thresholds for the following reactions were determined: $C^{13}(p,n)$, $F^{19}(p,n)$, and $Na^{23}(p,n)$. Table I shows a comparison with the results of Kington *et al.*[7]

While for the present measurement new Li and Na targets were prepared for each run by evaporation in place and new F^{19} targets were used, the C^{13} targets had been used before, and therefore may have been covered with pump oil, requiring a somewhat higher proton energy. The errors in the thresholds were estimated to be smaller than Kington's because the saturation effects were smaller.

For the range measurements it was necessary to decrease the proton beam current considerably. This was achieved by putting a thin Al foil (~2 mg cm^{-2}) before the first slit of the analyzing system. It was then necessary to regulate the Van de Graaff voltage manually. Elastic deformations of the slit system upon interchange of lithium target and range counter were checked with dial gauges and, if necessary, corrected.

III. EXPERIMENTAL RESULTS

The transmission curves obtained for the present experiment are similar to the ones obtained at Princeton. The energy for which 50% transmission is achieved is used as the energy belonging to the mean range given by the thickness of stopping material. Maximum transmissions between 98% and 99% were reached except for proton energies below 2 Mev. Multiple scattering in the entrance foil became important there. A total of 16 runs of range measurements were made. In each of the first eight runs, at least one of the threshold measurements mentioned above was made together with measurements in the 2-, 3-, 4-, and 5-Mev Al foils. Later on these measurements were used as standards for the energy calibration of all the other foils. The energies corresponding to the 50% transmission point for these four foils were reproduced to ±0.06% rms.

An accurate experimental determination of the effects of the counter filling was necessary, because its contribution to the energy loss was relatively large (about 10% at 1 Mev, about 1% at 5 Mev). The counter was filled with pressures of 25, 50, 100, 150, and 200 torr (≡mm Hg) of argon at several different proton energies. For each pressure the energy for 50% transmission was determined, then the energy for 0 pressure was found through extrapolation.

The energies thus determined agreed within the experimental error of about 4 kev with the calculated energies, using the known stopping power of argon, and the thickness of the counter; except for proton energies below 2 Mev, where unexplainable differences of up to 15 kev appeared. The experimental extrapolated values have been used in this energy region. For 0 pressure, the range R (which is equal to the absorber thickness) is given by (a) the thickness of the entrance foil and (b) the thickness of the stopping foil.

Entrance Foils

Commerical, pure aluminum foil of 3.5×10^{-4}-in. thickness was used for the entrance foils. The average surface density of 10 samples measured was 2.37±0.03 mg cm^{-2}. The homogeneity of the foil thickness could not be determined, but the use of a new foil for each run should give a fair average for this effect. In addition,

TABLE II. Experimental results.[a]

E (Mev)	R (mg cm^{-2})	R^* (mg cm^{-2})
1.130	4.66	4.66
1.352	6.19	6.19
1.599	8.10	8.08
1.623	8.27	8.28
1.911	10.68	10.73
2.114	12.64	12.59
2.114	12.64	12.59
2.677	18.31	18.32
3.062	22.85	22.81
4.023	35.74	35.74
5.038	52.31	52.09
5.504	60.51	60.50
6.150	73.01	73.05
11.820	226.33	226.15
14.971	342.63	342.74
17.836	466.92	467.31

[a] R is the range measured experimentally for a proton of energy E. The Princeton values are added as a convenience. No correction for multiple scattering is included in R. R^* is computed from E with the interpolation formulas given in the text.

a piece of this foil was used as a stopping foil for $E_p=1.13$ Mev. It showed less than 0.2% variation in thickness over the surface area.

Stopping Foils

The 2.1-, 3-, 4-, and 5-Mev foils were weighed three times, and their areas measured as often. The other foils were measured once or twice. The errors of the surface densities are about ±0.06 mg cm^{-2}. The homogeneity in the thickness of the foils was measured experimentally, and corresponding corrections applied. The corrections never exceeded 0.4%.

The experimental results are given in Table II. The error for the range is estimated to be ±0.07 mg cm^{-2}, the error for the energy was produced by (a) absolute error in energy due to uncertainty in thresholds, and magnet calibration, about ±0.12%, and (b) error due to pressure extrapolation, about ±4 kev.

IV. EVALUATION

It is not possible to find one relatively simple analytic function for the experimental range covering energies between 1 and 20 Mev.

For $1.13<E_p<2.677$ Mev a least squares fit for the logarithms gives $R=3.837E^{1.5874}$ within $\pm 0.4\%$. For $2.677<E_p<18$ Mev the experimental ranges can be expressed with

$$R=2.837E^2/(0.68+\log_{10}E),$$

within $\pm 0.2\%$ except the point at 5.038 Mev (with a difference of 0.4%), with E in Mev and R in mg cm^{-2}. A list of ranges computed from these formulas is presented in Table III. It can be used for the determination of proton energies from range measurements with apparatus similar to the Princeton equipment. For comparison the values obtained by Whaling[8] and Smith[9] are also listed. Whaling's data are obtained from the integration of stopping power values which are based on a theoretical extrapolation of experimental values measured below 1 Mev. These experiments are accurate to only about $\pm 5\%$. Therefore the ranges will show an error of about this magnitude. In addition a systematic error of several percent is introduced by the neglect of the shell corrections in the theoretical formula used.

Smith uses an I value of 150 ev for his computations. It is derived from Wilson's experiments[10] which have an accuracy of about 2%. Therefore Smith's calculations cannot be expected to be more accurate than 3% around 4 Mev. Many of the later tabulations have used Smith's values.[11]

A comparison of the data with Bethe's theory[2] was made. The main difficulty in the evaluation lies in the uncertainty of the multiple scattering correction. Preliminary values for it have been computed; more reliable calculations are under way.

If Walske's corrections for the K shell[3] are used, it is possible to fit the theory to the experimental data corrected for multiple scattering by choosing an I value of 164 ev, and using L-shell corrections which are within a factor of two of the corrections suggested by Walske. More detailed theoretical considerations will be published at a later date.

Straggling has not been investigated because the effects of microscopic scratches on the foils might contribute considerably to the straggling. No excessive straggling was observed though (at $E=3$ Mev, $\Delta R/R=2\%$, at $E=1.2$ Mev, $\Delta R/R=5\%$).

TABLE III. Range-energy table for Al.[a]

E (Mev)	R (mg cm^{-2})	Whaling	Smith
1	3.84	3.89	3.45
1.2	5.12		
1.4	6.55		
1.5	7.30	7.14	6.69
1.6	8.09		
1.8	9.76		
2	11.53	11.2	10.8
2.5	16.43	16.1	15.6
3	22.07	21.7	21.0
3.5	28.39	27.9	27.3
4	35.40	34.9	34.5
5	51.43	51.1	50.3
6	70.04	70.0	69.1
7	91.15	91.5	90.0
8	114.7	115	113.2
9	140.6	142	138.8
10	168.9±0.2%	171±5%	166.7±3%
11	199.4		196.6
12	232.2		229.0
13	267.3		263.7
14	304.5		300.6
15	343.9		339.3
16	385.5		
17	429.2		422.8
18	475.0		
19	522.9		514.6
20	572.8		
22	678.9		
24	793.2		
26	915.4		
28	1045.6		
30	1183.7		1157

[a] R is the experimental range. Smith and Whaling give path length.

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[8] W. Whaling, *Encyclopedia of Physics* (Springer-Verlag, Berlin, 1958), Vol. 34, p. 208.
[9] J. H. Smith, Phys. Rev. **71**, 32 (1947).
[10] R. R. Wilson, Phys. Rev. **60**, 749 (1941).
[11] M. Rich and R. Madey, University of California, Radiation Laboratory, UCRL-2301 (unpublished), may be consulted for further references.