JULY 15, 1937 PHYSICAL REVIEW VOLUME 52

The Range of Protons in Aluminum and in Air

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(Received May 10, 1937)

By the use of the two million volt generator developed at this laboratory the range of protons in air and in aluminum has been measured as a function of proton energy up to about 2 Mev energy. The range in air data are in good agreement with the theoretical values of Mano at high energies but diverge considerably at energies below 0.7 Mev. The ratio of the range in air to the range in aluminum has been found to increase from a value of approximately 1000 at 200 kv to a value of 1550 at 1200 kv. From 1200 kv up to the maximum voltage available the ratio is shown to remain nearly constant.

Introduction

The measurement of the range of protons in aluminum and in air was undertaken at this laboratory both because of the importance of the data in the interpretation of the results of nuclear disintegration experiments and to get reliable information on the energy absorption in the aluminum foil windows used in our proton-proton scattering apparatus. Blackett and Lees[1] have published data obtained from cloud chamber measurements, but these are for only lower energy protons. Blackett[2] gives range values for fast protons in air by using a theoretical expression with empirically determined constants to extrapolate alpha-particle range curves. Mano[3] has published a table giving proton ranges in air as a function of energy up to an energy of 19 Mev. These are theoretical values, obtained by integrating an equation from the work of Bethe and Bloch after making certain approximations and then applying corrections. These values of range are consistently higher than Blackett's by a few percent.

The only direct experimental data obtained under conditions comparable to ours are a curve given by Tuve, Heydenburg and Hafstad[4] showing the visually estimated range of protons in air up to about 1.2 Mev energy. It was therefore thought advisable to make a careful determination of the range curves using protons from the two million volt electrostatic generator for the purpose.

Range of Protons in Aluminum

Fig. 1 shows the apparatus used to determine the range of protons in aluminum. This was a short cylindrical brass box, 9.5 cm in diameter, mounted with an insulating bushing on the magnetic analyzer of the two million volt generator. A brass disk having twelve holes equally spaced near its circumference was mounted inside the box as shown and could be rotated by turning the ground brass plug. In this way the various aluminum foils mounted over the holes in the disk could be brought one after another into the proton beam which was defined by the slits at the front part of the box. A Faraday cage, mounted directly behind the holes in the wheel served to detect the transmitted protons. A magnetic field across the entrance of the Faraday cage eliminated any trouble from secondary electrons at that point and the whole box was put at a negative potential of 45 volts to prevent secondaries from the defining slits from interfering with current measurement.

The aluminum foils, ranging in thickness from 0.979×10^{-4} cm to 37.6×10^{-4} cm were obtained from the Aluminum Company of America and from the American Platinum Works. The foil thickness was determined as follows. With the edge of an accurately ground quartz crystal as a straight edge, triangles about 3 cm on a side were cut from the foils with a razor blade. The lengths of the sides of these triangles were then measured with a micrometer microscope and the areas computed. The triangles were then weighed on a micro balance, the weight of the lightest being of the order of two milligrams, and the thickness computed using 2.699 g per cc as the density

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[1] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. **134**, 658 (1931).

[2] P. M. S. Blackett, Proc. Roy. Soc. **135**, 132 (1932).

[3] G. Mano, J. de phys. et rad. **5**, 628 (1934).

[4] M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

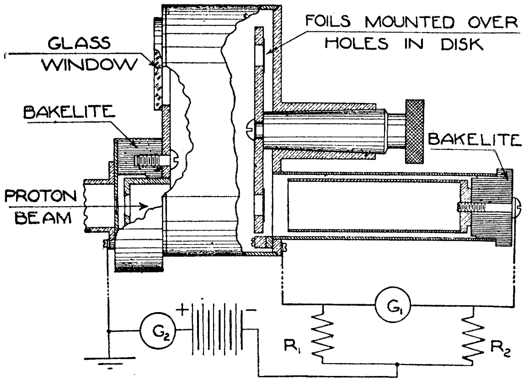

FIG. 1. Apparatus and electrical circuit used to measure the range of protons in aluminum.

of aluminum. In many cases two determinations were made with separate triangles cut from the same sheet of aluminum. The results of these checks will be discussed later.

In order to plot a range curve it was necessary to determine the minimum energy at which protons were able to penetrate each of the various thicknesses of foil. This was done by measuring the current due to protons incident on the foil, and the current to the Faraday cage due to those that penetrated the foil and plotting the ratio of these two currents as a function of proton energy for each of the various thicknesses. Trouble due to continuous small fluctuations of the current was eliminated by using the null method electrical circuit indicated in Fig. 1. When the voltage of the generator and consequently the energy of the protons was such that the galvanometer G_1 read zero, the fraction of protons transmitted was equal to the predetermined ratio R_1/R_1+R_2. The galvanometer G_2 merely served to indicate the order of magnitude of the total current. A series of curves was taken in this way and appear in Fig. 2. Curves III, IV, V, and VI of this group are of particular interest. The circles of curve III are experimental points taken with a foil that was determined to have a thickness of 2.51×10^{-4} cm while the crosses are experimental points taken with another foil measured by a second person to have a thickness of 2.47×10^{-4} cm. The two foils were cut from separate triangles which came from the same sheet of aluminum foil. The same conditions hold for curve IV, the circles representing data taken with a foil determined to be 3.46×10^{-4} cm thick and the crosses representing data taken with a different foil measured to be 3.49×10^{-4} cm thick. Curve V is for a foil which measured 4.67×10^{-4} cm in thickness and curve VI is for a foil taken from a different part of the same sheet and having an apparent thickness of 5.39×10^{-4} cm. This proved to be no error in thickness determinations for the two foils yielded different cut-off curves (Fig. 2) and furnish points that lie very closely on the smooth range curve of Fig. 3. The range curve is constructed by extrapolating the curves of Fig. 2 down to a ratio of zero and plotting the value of energy so obtained against the foil thickness.

RANGE OF PROTONS IN AIR

The apparatus used to measure the range of protons in air is shown in Fig. 4. An aluminum foil, A, 1.44×10^{-4} cm thick was mounted over an aperture 1.0 mm in diameter and served as a window to conduct the protons out of the vacuum system. The proton beam was defined by an aperture 0.8 mm in diameter placed immediately ahead of A. After leaving the foil A the protons traversed a predetermined thickness of air and then entered a thin ionization chamber by penetrating the aluminum foil B, thickness 0.979×10^{-4} cm. In this work the ratio of ion current to incident proton current at suitable values of proton energy was determined for various thicknesses of air gap between the ionization chamber and the foil A, the air gap being measured with a micrometer microscope. Again a balancing method was employed for measuring the current ratios, the circuit being indicated in Fig. 4. As in the arrangement for measuring the range in aluminum it was found most convenient to first adjust the ratio of the resistances R_1 and R_2 to some con-

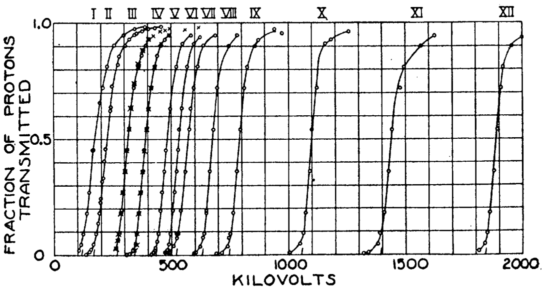

FIG. 2. Curves showing the apparent fraction of incident protons transmitted by various thicknesses of aluminum foil as a function of proton energy.

venient value and then vary the energy of the protons to obtain a balance. Secondary electrons from the slits near *A* were prevented from interfering with the current measurements by the field of a small electromagnet placed across the ion path.

Curves obtained by this method for various distances traversed in air are shown in Fig. 5. The ionization chamber was kept at a depth of 0.4 mm throughout the experiments. Various clearing potentials were tried but the ratio of ion current to proton current seemed to be independent of clearing potential, provided 180 volts or more were applied, and provided the air path was greater than about 10 mm. All the curves shown were obtained using a potential of 270 volts so that for the majority of them recombination should not have entered in to any great extent. It is probable, however, that the reduced height of the curves taken with the ionization chamber very near *A* was caused by recombination, since the proton beam was concentrated near *A* and at high ratios the ion density in the center of the ionization chamber was very great. The curves taken with the longer air paths also show a decrease in the apparent maximum number of ions per proton, probably due to the fact that after having traversed 4 or more cm of air a fair proportion of the protons was scattered through a sufficiently large angle to miss the rather small window in the ionization chamber. The shape of the specific ionization curve at higher energies was determined by continuing curve VI out to the highest obtainable voltage.

The straight sections of the curves of Fig. 5 were extrapolated down to a zero ratio as indicated, thus obtaining values for the energy loss of the protons in the two aluminum foils *A* and *B* and the measured thickness of air. The energy loss in the foil *A* for each of the extrapolated values was easily obtained from the range in aluminum curve. The energy loss in *B* was a constant, 117 kv, but in order to plot the range in air curve it was necessary to know in addition to this the air equivalent of foil *B* for incident protons of 117 kv energy. This was determined by placing a duplicate foil in the air path close against *B*, where it proved to be equivalent to 1.0±0.1 mm of air for 215 kv protons. The same foil placed close to *A* where the protons had an energy of 1550 kv was equivalent to an air path increase of 1.6±0.12 mm. Since the air equivalent of the foil obviously decreased with decreasing proton energy it seemed probable that a value of 0.90 mm would not be greatly in error for protons of 117 kv and consequently this value was used

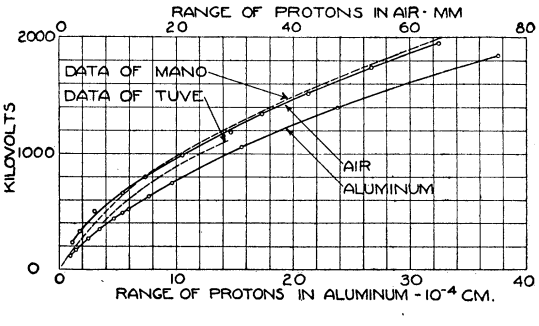

FIG. 3. The range of protons in air and in aluminum. The long dotted line shows Mano's theoretical values for the range in air. The short dotted curve is Tuve's visually estimated range curve.

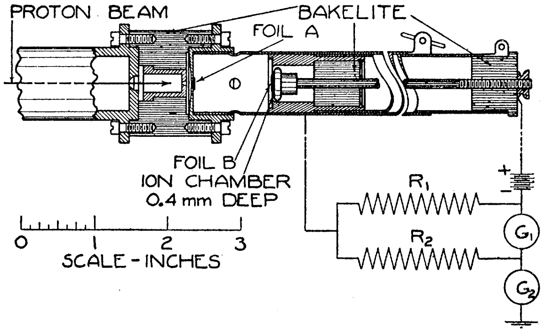

FIG. 4. Apparatus and electrical circuit used to measure the range of protons in air.

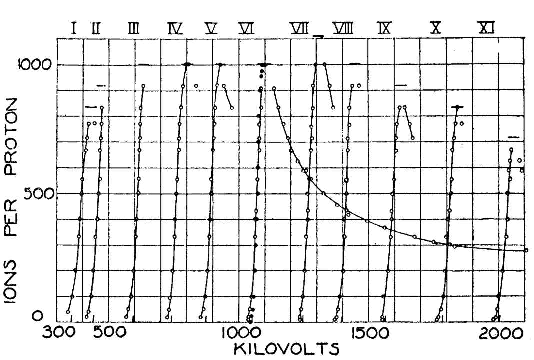

FIG. 5. Curves showing the experimental data taken to determine the range of protons in air. Each curve gives the variation with proton energy of the ratio of current in the ionization chamber to incident proton current for a particular air path. The straggling expected on the basis of Bohr's theory is indicated by the heavy black dots.

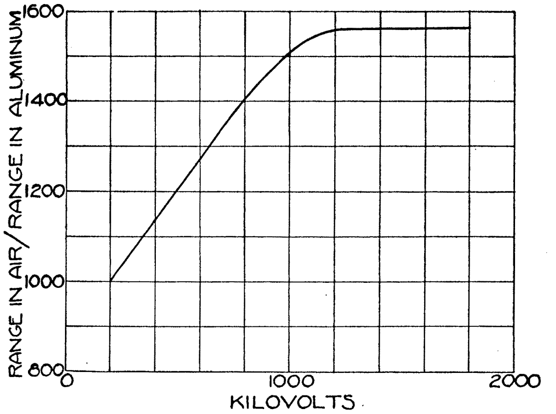

FIG. 6. Ratio of the range of protons in air to the range in aluminum as a function of energy.

in plotting the range in air curve. The curve showing the ratio of the range in air to the range in aluminum as given in Fig. 6 was constructed from values read from this range in air curve and from the range in aluminum curve. A careful study of the shape of the curve of Fig. 6 will show that the value of 0.9 mm as the air equivalent of foil *B* is probably accurate within 3 or 4 percent, which is entirely satisfactory, since even a large error in this correction is of minor importance over the greater part of the range in air curve.

The data on the range of protons in air were taken under laboratory conditions of temperature and pressure and then reduced to corresponding values at 0°C and 760 mm Hg. The temperature of the air through which the protons were passing was taken to be the temperature of the brass tube supporting the ionization chamber, measured to within about 2°C. It is possible however that the effective temperature of the column of air through which the concentrated proton beam was passing may have been considerably higher and that the ranges as given are somewhat greater than would be expected from cloud chamber measurements. The uncertainty of the temperature is probably responsible for most of the spread of the experimental points on the range in air curve.

DISCUSSION

Several factors contribute to the slope of the curves of Fig. 5, namely: the natural shape of the specific ionization curve of protons, straggling of the protons, inhomogeneity of the proton energies, nonuniformity of the foils and the depth of the ionization chamber. As it would be of interest to know something about the relative magnitudes of some of these contributions the expected straggling of the protons under conditions as of curve VI, Fig. 5, was computed using the theory developed by Bohr[5] for the straggling of alpha-particles. By making the proper substitutions the equations were made to apply to protons, and yielded the points shown by the heavy black dots in Fig. 5. The energy spread of this theoretical curve is about 40 kv. The depth of the ionization chamber, 0.40 mm, could account for about 10 kv, making for these two factors a total of about 50 kv spread which is as nearly as can be determined the spread of the experimental data. Thus if the straggling theory is correct, nonuniformity of the foils, inhomogeneity of the proton beam and slope of the specific ionization curve must be of negligible importance.

The shape of the tops of the curves could not be determined due to a lack of sensitivity of the measuring instruments. The bars over the curves are at ratios of R_1 and R_2 at which it was either just possible or impossible to obtain a balance and are consequently equal to or greater than the maximum height of the curves.

The comparatively wide spread in energy of the curves taken with the aluminum foils and Faraday cage is a matter of some interest. When a proton is leaving a foil with low energy there is a certain probability that it will capture an electron and leave as a neutral atom, and consequently not register in the Faraday cage. The probability that this will occur is a function of the energy with which the proton emerges, increasing as the proton energy decreases. The difference in slopes of the curves of Figs. 2 and 5 is thought to be due entirely to this effect since the loss due to wide angle scattering was shown experimentally to be negligible. As a result the range curve was plotted using the extrapolated values of energy which would probably be only slightly influenced by the neutralization effect if influenced at all.

That the curve obtained in this way is not greatly in error was checked by modifying the range in air apparatus to accommodate the foils and mountings used in the aluminum range measurements and determining the absorption of

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[5] N. Bohr, Phil. Mag. **30**, 581 (1915).

the same foils by means of the ionization chamber, foils being inserted one after another in the air path. The check was not completely satisfactory since the energy losses so determined involved taking the small difference of two large numbers read off the range in air curve, and this small difference could not be determined better than about 8 percent. With this limitation the values determined in the two ways agree. The data taken when testing the air equivalence of foil *B* constitute a better check on this point and indicate that the aluminum values are reliable.

Since the data presented here depend for their accuracy on the calibration of the voltmeter, its reliability, and its linearity over wide ranges it is of interest to note here the checks that were made in these respects. It was found that the cut-off curves for the aluminum foils could be repeated from day to day and would give the same experimental points within less than 2 percent. The absolute value of the voltage was determined as described in an earlier publication[6] and was rechecked shortly before this work was started. An excellent check on the linearity was provided by the range in aluminum apparatus. In energy ranges where it was possible, after a cut-off curve for a given foil had been taken with protons, some of the experimental points were rechecked using the diatomic ion beam. This would necessitate increasing the generator voltage by a factor of exactly two, and it was found that within 1 percent the voltmeter reading would also increase by a factor of two. Additional checks, made from time to time, showed that within less than 1 percent, the voltage indicated was independent of the pressure in the tank.

TABLE I. *Range of protons in air and in aluminum.*

kv	RANGE IN Al (cm)	kv	RANGE IN AIR (cm)
117	0.979×10^{-4}	232	0.226
166	1.44	329	0.345
267	2.51	500	0.600
342	3.46	657	1.09
433	4.67	798	1.49
486	5.39	983	2.11
520	5.93	1184	2.93
630	7.69	1339	3.47
745	9.65	1514	4.26
1055	15.6	1739	5.34
1393	23.8	1950	6.50
1842	37.6		

For convenience of comparison, Mano's range in air data, reduced to 0°C, are shown by the long dotted curve of Fig. 3. Mano's values are for mean range, and the two curves would probably agree well at high energies if we had plotted mean values instead of extrapolated values of energy. Disagreement at lower energies is very marked. The short dotted curve is the visual range curve of Tuve, Heydenburg, and Hafstad.

For convenience in using these data the experimental points from which our two range curves are plotted are given in Table I.

We wish to express our appreciation to Professor G. Breit, Professor H. B. Wahlin, and Professor L. R. Ingersoll for their generous support in this research. We are also indebted to D. W. Kerst for valuable help and to the Wisconsin Alumni Research Foundation for generous financial assistance.

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[6] R. G. Herb, D. B. Parkinson and D. W. Kerst, Phys. Rev. **51**, 75 (1937).