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The Disintegration of Li^7 Bombarded by Slow Protons

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The number of Li^7 atoms disintegrated by protons of energies from 23.6 to 72.5 electron kilovolts has been determined. Oppenheimer's integration of Gamow's equation giving the probability of the lithium-proton disintegration as $n=bVe^{-a/V^{\frac{1}{2}}}$ has been compared with the experimental data by plotting $\log n-\log V$ against $1/V^{\frac{1}{2}}$. The agreement is within the experimental error. The results of the present experiment have been compared with other observer's data taken at higher voltages; the slopes of the lines have been found to vary somewhat. No indications of resonance nor of a minimum voltage required for disintegration were observed. Considerable difficulty was encountered as regards surface contamination of the target and also the formation of a highly insulating layer of lithium oxide. The latter effect made necessary the frequent use of a Faraday chamber for recording the proton current. An FP-54 pliotron in a modified form of the DuBridge-Brown balanced circuit was used in photographic recording of the alpha-particles.

SEVERAL studies have already been made of the disintegration of lithium bombarded by slow protons.[1] Much of this work was done without magnetic analysis of the proton beam, and often scintillation screens were used for counting the alpha-particles. Very few observations have been made of the absolute yield of the long range particles below 60 kilovolts. Diebner and Hoffman[1] working in this region have reported some indication of resonance. The minimum voltage required for disintegration has been given at anywhere from 10 to 30 kilovolts. Considerable discussion also has arisen concerning the yield as a function of the surface of the target. It is the purpose of this paper to attempt to answer these questions, in part at least, and to continue the yield curve to as low proton energies as possible.

APPARATUS AND METHOD

A. Discharge tube and high voltage

At first an ordinary Wien type discharge tube was tried with a mechanically rectified high voltage. Although this discharge current could be run as high as 50 milliamperes, it was not possible to get a sufficiently intense beam of protons of a narrow energy range. This tube was then set up at high potential and an additional accelerating field over a distance of 5/16 of an inch was applied to the protons emerging from the canal of the Wien tube, Fig. 1. With this arrangement up to 2.5 microamperes could be recorded in a Faraday chamber after bending the beam through 90° and selecting the desired energy with a $\frac{1}{8}$-inch slit, where the separation of the pole faces was $\frac{1}{4}$ inch. The total ion current without magnetic bending was about 25 micro-

[1] F. Kirchner, Physik. Zeits. **34**, 777 (1933); Naturwiss. **21**, 473 (1933); Traubenberg, Eckardt and Gebauer, Naturwiss. **21**, 26 (1933); Zeits. f. Physik **80**, 557 (1933); Rutherford, Nature **131**, 388 (1933); Oliphant and Rutherford, Proc. Roy. Soc. **A141**, 259 (1933); Döpel, Zeits. f. Physik **81**, 821 (1933); Diebner and Hoffman, Naturwiss. **22**, 119 (1934); Jakowlew, Zeits. f. Physik **93**, 644 (1935).

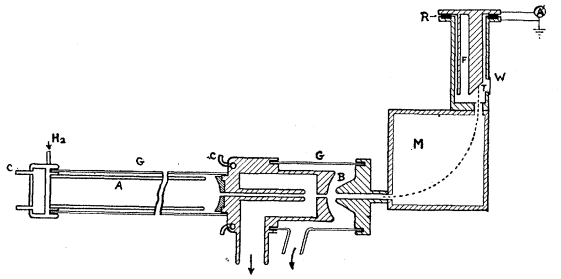

FIG. 1. The discharge tube and the target. A, steel tube; B, accelerating chamber; CC, oil cooling; GG, glass tubes; M, magnetic field; W, mica window; F, Faraday chamber; A', microammeter; T, target; R, rubber gasket.

amperes. In order to keep the pressure sufficiently low in the accelerating chamber a system of double differential pumping was used as shown in Fig. 1. This made possible a pressure of from 2 to 4×10^{-5} mm of Hg in the accelerating chamber, B. The hydrogen was admitted to the discharge tube through a palladium valve; this intake as well as the pump connections were protected from sparking back by the use of wire grid electrodes. The metal tube, A, which was about 2 feet long served to prevent local heating of the glass due to electron bombardment. When the discharge tube was properly outgassed, it could be run very steadily at anything from 10 to 30 milliamperes discharge current. The voltage supplied to this tube came from a 25-kilovolt transformer whose 110-volt primary was fed by the generator of a motor generator set. The motor and generator were connected by a 3-foot Bakelite shaft and were mounted on kiln-dried and paraffined oak planking. A kenetron rectified the voltage for the discharge tube, but no condensor was used here. The accelerating potential was supplied by another transformer with full wave rectification and condensors. With this arrangement it was possible to get from 10 to 72 kilovolt protons. At 72 kilovolts the tube broke down by sparking in the chamber B.

B. Counter, target and measurement of proton current

An FP-54 pliotron in a slight modification of the DuBridge-Brown[2] balanced circuit together with a camera was used to record the alpha-particles. The circuit as given by DuBridge and Brown gave too great a drift at the maximum sensitivity used (2×10^{-16} amp./mm with an input resistance of 8.6×10^{10} ohms). It was found that the plate currents of three different pliotrons changed very rapidly during the first three weeks of continuous operation. It was then necessary to make the resistance, R_a,[2] about 10,000 ohms to secure a balance with proper voltages on the elements. The circuit kept balancing at higher and higher filament current, necessitating frequent changes of R_1 and R_2. After nearly a month of continuous running one tube settled down to steady conditions with 97 milliamperes through the filament and within five percent of the rated voltages elsewhere. It was necessary, however, to put an Edison cell in series with the lead batteries as described by Hafstad.[3] With this arrangement the drift was made as low as 1.5 cm in 36 hours with a galvanometer of 5×10^{-10} amp./mm sensitivity. Since the drift depends upon the change in plate current with the time and since the over-all sensitivity depends upon the input resistance together with the galvanometer sensitivity, the best arrangement for minimum of drift is to use as low a sensitivity galvanometer and as high an input resistance as is possible without making the product of R times C too great.

The protons after emerging from the accelerating field were bent through 90° in the arc of a circle of 9.2 cm radius. The $\frac{1}{8}$-inch slit selected the beam which fell on the lithium target, T, at an angle of 45°. The target was insulated by the rubber gasket, R, and by rotating the whole through 180° could be replaced by the Faraday chamber, F. The alpha-particles emitted passed through a mica window, W, of about 3.5 cm stopping power into the ionization chamber connected to the pliotron. The mica window was waxed over a round hole of 9/16 inch diameter. The aperture of the ionization chamber determined the solid angle over which the particles were counted. This solid angle was 0.276 for most of the counting, although a solid angle of half this value was used as a check and for the higher voltages, where the counting rate would have been too great for sufficient resolution.

The ionization chamber was of the conical type 15 mm deep. An alpha-particle entering the

[2] DuBridge and Brown, Rev. Sci. Inst. **4**, 532 (1933).

[3] Hafstad, Phys. Rev. **44**, 201 (1933).

chamber gave a deflection of the galvanometer of about 16 mm at maximum sensitivity. The fluctuations were cut down to ± 2 mm by taking the usual precautions and evacuating the case containing the pliotron. In general the circuit was used at one-half the maximum sensitivity. The ionization chamber was of steel which gave about one-half the residual count given by a similar chamber of copper. No attempt was made to pass "dead" gas through the chamber or to clean it other than by polishing it with steel wool. The residual count was 7.3 alpha-particles per hour. The circuit was sufficiently shielded so that no amount of sparking or other electrical disturbances due to the high voltage altered the background count.

The Li^7 target was made by hammering a piece of pure lithium into a depression in a brass holder. Since the surface was soon covered by a layer of hydroxide the bombarded target was lithium hydroxide. The proton current falling on this target was measured by a sensitive microammeter, A'. The stray magnetic field was sufficiently great to hold back secondary electrons. This was verified for every target used by rotating the target holder through 180°; this replaced the target with the Faraday chamber, F. Occasionally a disagreement was observed; this was found to be due to a layer of oxide forming between the brass and the metallic lithium, and such targets were discarded since a more accurate control of the proton current could be kept with a new target. A target of Li_2O formed by burning pure lithium in air and condensing the smoke on a brass plate gave yields identical with the lithium hydroxide target, provided the proton current was measured by the Faraday chamber. The current to the Li_2O seemed to be a function of the thickness of the film, and in the case of the thicker films (about 0.1 mm) no current could be detected at all. A study of this discrepancy showed that the protons collected on the surface of the highly insulating Li_2O, building up a charge. As the gas surrounding the target was sufficiently ionized partly to neutralize this charge, an equilibrium was probably set up so that little current reached the target holder. That there was enough gas present to provide sufficient ions to neutralize such a charge was shown by the fact that the current to a brass target depended very markedly upon the potential to which the target was raised.

Unfortunately the area of the target intercepted by the proton beam gradually collected a brown deposit such as has been discussed by Stewart.[4] In most cases no appreciable difference in the counting rate could be detected between the first two fifteen-minute intervals. The third fifteen-minute interval showed a slight decrease at the lowest voltages. At 28 kilovolts the sixth interval showed the count had dropped to nearly half that of the first interval. At higher voltages the effect was not so serious. The yield may thus be slightly higher than the values given, but every effort was made to avoid this source of error and in no case was the count included after a consistent decrease in yield appeared. The uniformity of the results for many targets at a given voltage indicates strongly that little error arises from their method of preparation.

TABLE I. *The number of Li^7-proton disintegrations at low voltage.*

$n \times 10^{12}$	$1/V^{\frac{1}{2}} \times 10^5$	V
0.032	650	23,600
.080	598	28,000
.42	527	36,000
1.08	487	42,000
2.30	452	49,000
5.80	423	56,000
9.60	400	62,500
14.6	383	68,000
22.4	371	72,500

Results and Discussion

The number, n, of Li^7 atoms disintegrated per proton from a thick target of pure lithium at the bombarding energies used is given in Table I. n is equal to one-half the total yield of alpha-particles, since each disintegration gives rise to two long range particles. The numbers deduced from the experiments have been multiplied by a factor of 4 owing to the fact that pure lithium would give four times the yield of the lithium hydroxide target used. V is expressed in volts.

From 900 to 1500 particles were counted for each proton energy used. The errors due to measuring the energy of the protons from the value of their $H\rho$, and the uncertainty in the solid angle were slightly larger than the proba-

[4] R. L. Stewart, Phys. Rev. **45**, 488 (1934).

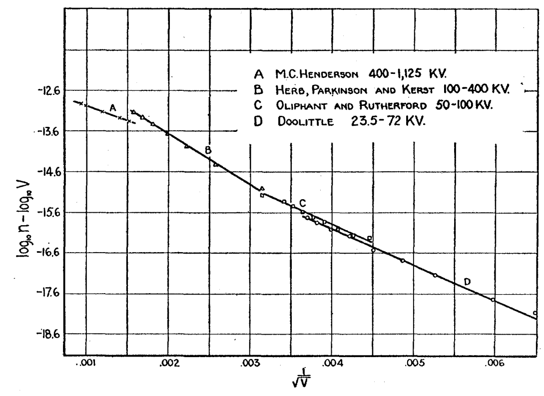

FIG. 2. A comparison of the results of several observers on the disintegration function of Li^7.

bility errors in counting. Taking the relative error for probability fluctuations as $A^{\frac{1}{2}}/A$, where A is the number of atoms breaking up in a given time interval, the error from this source is a little less than $\pm$ three percent. In all cases allowance was made for the residual count. For the lowest point, corresponding to 23.6 kilovolt protons, only about 150 particles above the background were counted; consequently the error in this reading may be quite large. Nevertheless the certainty of disintegrations at this voltage is established. A brass target gave no increase over the usual background count. These data further verified the fact that the pliotron was sufficiently shielded.

The probability of disintegration has been derived by Gamow[5] and the value for thick targets has been derived by Oppenheimer[6] by integrating Gamow's formula assuming the range to be proportional to $V^{1.5}$. The number of disintegrations is found to be proportional to $Ve^{-a/\sqrt{V}}$. Henderson compared this value with his observations at high potentials and found very good agreement. Bearing in mind the analogy with Richardson's thermionic equation, $\log n - \log V$ is plotted against $1/V^{\frac{1}{2}}$. The author's results are shown in Fig. 2 together with those of several other observers which were taken at higher voltages. The curve A represents Henderson's[6] data for very high energy protons. Curve B gives the observations of Herb, Parkinson and Kerst[7] for the range from 100 to 400 kilovolts. Curve C is a portion of the curve taken from the graph of Oliphant and Rutherford.[8] The results of the present paper are given in curve D. The slope of curve A is slightly less than C or D, whereas curve B has a distinctly greater slope than C or D. Curve C has the same slope as D but the values of n are slightly higher. This would indicate a constant factor such as might arise in the measurement of the proton currents, the velocity or the solid angle used. In all cases the data of the various observers have been altered where necessary to agree with the definition of n given at the beginning of this section. From the general form of the disintegration curve (Fig. 2) no signs of resonance are evident, nor does there appear any discontinuity in the lower end of the curve such as would suggest a low voltage limit. By using a more intense proton beam or increasing the efficiency of the detecting apparatus this curve might well be continued to lower voltages.

The yield from a thin film of lithium was calculated from the thick film data after the manner described by Herb, Parkinson and Kerst.[7] However, the theoretical data of Mano[9] indicate that the range of the protons is more nearly given by $R = kV^{1.2}$ rather than $kV^{1.5}$ in the range from 80 to 300 kilovolts. From 80 kilovolts down the departure from the $V^{1.2}$ relation is greater, and it is doubtful if such a curve would have much additional significance. Assuming $R = kV^{1.2}$ a curve similar to the one given by Herb, Parkinson and Kerst[7] is obtained. The assumption of the relation $R = kV^{1.2}$ would alter the theory of the curves of Fig. 2 slightly.

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[5] G. Gamow, *Nuclear Structure and Radioactivity*, pp. 49, 97.
[6] M. C. Henderson, Phys. Rev. **43**, 98 (1933).
[7] Herb, Parkinson and Kerst, Phys. Rev. **48**, 118 (1935).
[8] J. D. Cockcroft, "Noyaux Atomique," Institute de Physique Solvay, 7e Conseil de Physique, p. 35.
[9] G. Mano, J. de phys. rad. **5**, 628 (1934).