# The Disintegration of Lithium by Protons of High Energy

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The results recently obtained by Lawrence, Livingston and White have been extended to protons having an energy up to 1,125,000 electron-volts. After the rapid increase found by Cockroft and Walton at lower voltages the number of disintegrations per proton increases above 400,000 electron-volts proportionally to the 3/2 power of the energy. The range of the proton is known to be proportional to the same power of the energy. These facts indicate that the probability of disintegration of the individual lithium nucleus is independent of the energy of the proton above 400,000 volts. The relative number of disintegrations over the whole range from zero to 1,125,000 electron-volts is given quite exactly by $N=k'Ve^{-a/V^{\frac{1}{2}}}$ where $V$ is the energy of the protons and $k'$ and $a$ are constants. From 400,000 to the upper limit reached this formula is practically indistinguishable from $N=k(V^{3/2}-V_0^{3/2})$ when the experimentally determined values of the constants are used. The more complex formula has theoretical justification and the radius of the lithium nucleus as calculated from the experimental value of $a$ is about $4\times10^{-13}$ cm. The cross section effective for disintegration seems to be much smaller, with a radius of $1.4\times10^{-14}$ cm. The actual number of disintegrations is half the number of alpha-particles emitted and is equal to 2.0 disintegrations per $10^9$ protons at 250,000 electron-volts; 10.2 disintegrations per $10^9$ protons at 500,000 electron-volts; 40 disintegrations per $10^9$ protons at 1,000,000 electron-volts. The results at 500,000 volts are in excellent agreement with those of Cockroft and Walton. The form of the curve differs slightly and the probable causes of this difference are discussed.

## INTRODUCTION

COCKROFT and Walton[1] first showed that the nuclei of many elements can be disintegrated by protons having energies in some cases as low as 100,000 electron-volts. Working with lithium 7 they found that two alpha-particles with a range of 8.5 cm were the product of the disintegration of a single nucleus. The mechanism of the disintegration apparently involves the capture of the proton. Lawrence, Livingston and White[2] were at once able to confirm the fact of disintegration in the case of lithium and to extend the data up to protons with 710,000 volts energy. The method used by them to produce the high energy protons has been described in this journal.[3] Through the courtesy of Professor Lawrence in placing the apparatus at my disposal I have been able to extend the results practically to the limit of energy attainable with it and to determine more accurately the rate of disintegration at all energies.

[1] Cockroft and Walton, Proc. Roy. Soc. **A137**, 229 (1932).

[2] Lawrence, Livingston and White, Phys. Rev. **42**, 150 (1932).

[3] Lawrence and Livingston, Phys. Rev. **40**, 19 (1932).

## APPARATUS AND METHOD OF EXPERIMENT

The apparatus devised by Lawrence and Livingston[3] produces the high-speed proton or other ion by the repeated acceleration of the ion through a relatively small potential drop. The proton is produced in a high-frequency alternating electric field which has at right angles to it a strong magnetic field. The magnetic field bends the path of the proton into a circle and, if the frequency and magnetic field bear the correct relationship, the proton returns to the accelerating electrodes one-half cycle later and receives another impulse. The time taken by a particle of given $e/m$ to describe a semicircle in a constant magnetic field is independent of the radius of the semicircle. Consequently the proton continues to describe larger and larger semicircles in phase with the electric field and may receive as many as 300 impulses before passing into the collector. The limit of energy attainable with the apparatus used in this work is 1,230,000 electron-volts, corresponding to a field of 14,000 gauss, a wavelength of 14 meters and a final radius of 11.5 cm. For further details of the method the original paper should be consulted. The only changes needed to adapt the apparatus to measure atomic disintegrations are some modifications of the Faraday collector and the addition of a Geiger counter or other detector for the products of disintegration.

Fig. 1 shows the plan of the accelerating system and proton generator. $A$ is the accelerating electrode, shaped like an enlarged "duant" or half pill box, the potential of which oscillates at

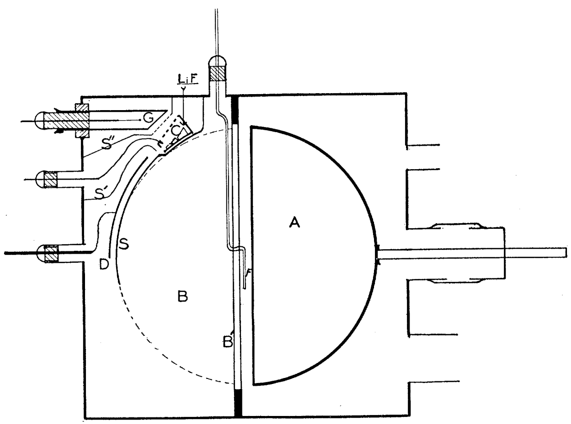


FIG. 1. Showing the arrangement of the proton generator, Geiger counter, etc.

high frequency. $B$ is the grounded half of the accelerating system. The brass dividing wall $B'$ and the opening of the electrode $A$ are the two planes between which the protons are accelerated. The filament for producing electrons which in turn ionize the hydrogen to form protons is shown at $F$. The magnetic field is perpendicular to the plane of the diagram. At $D$ is the deflecting electrode which draws the protons out on a circular path of larger radius into the Faraday box $C$. The Faraday box is screened from the parts at high potential by the screens $S$, $S'$, $S''$. At $G$ is the tube containing the Geiger point.

Two sides of the brass Faraday box have been removed and in their place mounted a thin aluminum foil, shown dashed in the diagram. This foil has a stopping power equivalent to 1.5 mm of air. Protons entering the box will therefore lose from 35 to 75 kilovolts of energy depending on their initial energy.[4] This loss must be applied as a correction to the energy of the proton as measured by the wave-length or magnetic field.

Mounted in the Faraday box are three crystals of lithium fluoride, so placed that they intercept the whole of the beam of protons. The cross section of the beam is quite small, about 1 $mm^2$.

The products of disintegration, shown by Cockroft and Walton to be alpha-particles, were recorded by the Geiger point counter, which was placed as shown in the diagram. A small platinum ball fused on the end of a 0.001 inch platinum wire served as "point." The counter was used at atmospheric pressure. Its threshold for gamma-rays was about 1500 volts. Counting was in all cases carried out at a fixed voltage above this threshold. The natural background of the counter was about one-half a discharge per minute. The same point that Lawrence, Livingston and White used was employed throughout the entire work, and its characteristics remained constant. No counts were obtained more than the natural background unless protons were entering the Faraday box and the number of counts per minute was proportional to the proton current at any given energy. The disintegrations were observed with proton current ranging up to half a millimicroampere at the lowest voltage. At higher voltages the yield of alpha-particles was too large to be counted unless the current was reduced to a tenth or twentieth of that amount.

The discharges caused by the alpha-particles were recorded on a three stage amplifier connected to a telegraph relay and a Cenco impulse counter. The amplifier needed to be well shielded from the strong high-frequency radiation of the oscillator. Pick-up through the wire leading from the counter to the amplifier was most troublesome. It was finally eliminated entirely by putting the wire inside a grounded copper braid and by placing a five megohm resistance in series between the lead wire and the grid of the first tube. The high frequency was by-passed to ground by the capacity of the braid and the impulses at the relay were scarcely reduced at all by the five megohms.

The end of the Geiger counter was closed by a brass plate perforated by 24 holes 0.1 inch in diameter. The average distance of these holes from the lithium fluoride was 2.0 cm. Thus the effective solid angle subtended by the counter is about 1/40 of the total. The holes in the plate were covered internally by a sheet of mica having

[4] Blackett and Lees, Proc. Roy. Soc. **A134**, 658 (1932).

a stopping power of 2.12 cm of air. At the opening in $S''$ was another mica screen with a stopping power of 3.2 cm. Thus any particle reaching the interior of the counter from the lithium must have a range of at least 5.32 cm in air, which corresponds, for protons, to an energy of 1,600,000 volts. As the maximum that this apparatus can produce is 1,200,000 volts, none of the counts can have been due to primary protons. Cockroft and Walton found that the range of the alpha-particles emitted by fluorine is only 2.8 cm, so they could not reach the counter.

To make certain that gamma-rays were not causing the counts a check run with protons of 600,000 volts was made, during which the screen in $S''$ was replaced by a sheet of aluminum 0.002 inch thick. This thickness is equivalent to 9.4 cm of air, which, plus the mica in the counter, makes 11.6 cm in the path of any particles. No counts were observed at the highest protons currents obtainable. It was calculated from this experiment that if gamma-rays are produced they cause less than five counts per minute per millimicroampere, not more than 2 percent of the whole effect.

In taking a measurement the proton current to the Faraday box, which was measured on an electrometer by the method of constant deflection, was kept as steady as possible by adjusting the magnetic field to compensate for variations in the line voltage and by varying the filament emission. At the same time there was noted the number of counts recorded by the amplifier in a convenient interval. From the proton current, the solid angle of the counter and the yield of alpha-particles, is readily calculated the number of protons required per disintegration.

## Results

In Fig. 2 are plotted all the available data on the disintegration of lithium by protons. The ordinates are the numbers of alpha-particles counted by the Geiger counter per minute per millimicroampere of proton current. The total yield of alpha-particles in all directions is 40 times as much. All points have been determined by counting at least 400 particles. The abscissa shows the effective energy of the protons, that is the energy as calculated from the wave-length

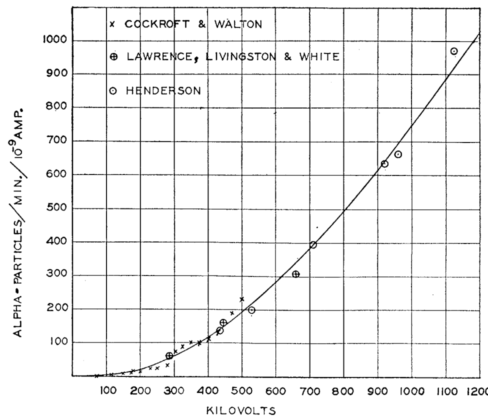


FIG. 2. Showing the number of alpha-particles received by the Geiger counter per minute per millimicroampere of proton current, plotted against the energy of the protons in electron kilovolts. The total production of alpha-particles may be obtained by multiplying by 40. The theoretical curve is a plot of $N=0.0037\ Ve^{-1600/V^{\frac{1}{2}}}$, $V$ in volts. Cockroft and Walton's figures have been multiplied by a constant factor to fit this curve.

or the magnetic field minus the appropriate correction for absorption in the aluminum foil on the Faraday box. This correction for absorption was not made by Lawrence, Livingston and White, so the plotted values differ from their published figures. After their work was published it was found that the resistance used in the electrometer circuit had a considerably higher value than that assumed, and their yields were therefore higher. This correction has also been made.

For comparison the points obtained by Cockroft and Walton[1] are shown. They have been multiplied by a constant factor to make them fall approximately on the curve drawn through the data taken in this laboratory.

The absolute yields,[5] or the number of disintegrations per $10^9$ protons, are: 2.0 per $10^9$ protons at 250,000 electron-volts; 10.2 per $10^9$ protons at 500,000 electron-volts; 40 per $10^9$ protons at 1,000,000 electron-volts.

Cockroft and Walton's yields are in excellent agreement with these results at 500,000 volts. There is a difference at lower voltages but it probably lies within experimental error. For

[5] Because of a slip in calculation, Lawrence, Livingston and White's estimated number of disintegrations is too high by a factor of 60.

several reasons the agreement is surprising. Cockroft and Walton's proton currents were in part made up of the hydrogen molecular ion, $H_2^+$. They estimate that half their current was carried by these ions. They assumed that the molecular ion played no part in the disintegration. As a matter of fact a 500,000 volt $H_2^+$ ion is certainly the same for the purposes of these experiments as two 250,000 volt protons. So it would be expected that the points obtained by Cockroft and Walton at higher voltages should show a more rapid rise than those found in this work, which were obtained with protons only. As may be seen from Fig. 2, or their Fig. 4, this expectation is fulfilled.

The fact that they used lithium metal instead of the fluoride would at first sight lead one to expect that they should find a higher yield, for the following reason. In lithium fluoride there are 12 external electrons per lithium nucleus. In pure lithium there are but 3. Since the external electrons are the only important means for absorbing the energy of the protons, a proton in its path through a lithium fluoride crystal will approach only one quarter as many lithium nuclei before being stopped as it would in pure lithium. Thus from lithium fluoride there should be one quarter as many disintegrations per proton.

It is probable however that the lithium used by Cockroft and Walton had absorbed enough moisture to turn the surface into lithium hydroxide. A film 0.002 inch thick would be ample to absorb the protons. As lithium hydroxide and lithium fluoride have almost exactly the same number of electrons per gram, the yields found by Cockroft and Walton and those found in this laboratory should therefore not differ, although apparently different substances were used.

If the surface of the lithium used by them were much rougher than the crystal faces used here there should be a difference on yield in the direction actually found.

## Discussion

The new determinations show that the increase in the number of disintegrations per proton is always more rapid than would correspond to a linear function of the energy of the protons. Since it is well known that the range of a proton in any substance is proportional to the 3/2 power of its energy, a curve of the form $k(V^{3/2}-V_0^{3/2})$ was fitted to the data by least squares. The values found were $k=0.86\times10^{-6}$, $V_0=256{,}000$ electron-volts. The fit is excellent above about 400,000 electron-volts, but as this formula gives values from 400,000 to 1,200,000 that are practically indistinguishable from those given by another one, which will be discussed below, it is not plotted separately.

This excellent fit to a 3/2 power law shows that the increase in the yield of disintegrations above 400,000 volts may be attributed simply to the increased range of the protons. In a thick target the number of lithium atoms exposed to the protons is of course exactly proportional to the distance the protons travel in the target. Apparently therefore a proton has just as good a chance of disintegrating a particular lithium atom when it has 400,000 volts of energy as when it has 1,000,000. This conclusion could of course be better substantiated by experiments with a thin target. Work with a larger apparatus is in progress in this laboratory to extend the curve to still higher energies.

I am greatly indebted to Professor J. R. Oppenheimer for working out from Gamow's theory an approximate formula for the number of disintegrations in a thick target as a function of $V$. This formula has the form $N=k'Ve^{-a/V^{\frac{1}{2}}}$ where $k'$ and $a$ are constants.

The value of $k'$ that is obtained theoretically can only give a rough estimate of the maximum number of disintegrations possible. It is obtained by assuming that every particle that penetrates the nucleus produces a disintegration. The experimental yields are lower than the theoretical maximum by a factor between ten and one hundred.

The value of $a$ can be more accurately estimated. It is a function of the radius $r$ of the potential "trough" inside the nucleus.[6] It is given approximately by $a=(2400-1.44\times10^{40}r^3)$, in units of (electron-volts)$^{\frac{1}{2}}$. When $r=4\times10^{-13}$, $a=1500$.

[6] A proton with an energy of 1,000,000 electron-volts should be able to penetrate the nucleus even according to classical theory, since the total height of the barrier is only about 1,000,000 volts.

In Fig. 2 the curve drawn through the experimental points is a plot of the theoretical formula with $a$ taken as 1600 and $k'$ as 0.0037. These values of the constants were determined by trial, but a least squares solution gave essentially the same values. The corresponding value of the radius of the potential trough is about $4\times10^{-13}$ cm. Greater accuracy than this is not justified by the present state of the theory. This value is in good accord with the determination from scattering experiments of the "radius" of the helium nucleus, that is the distance within which the inverse square law of repulsion no longer holds.

It happens that, for the numerical values of the constants that best fit the data, the curves plotted from the two theoretical formulas practically coincide over the range from 400,000 to 1,200,000 electron-volts. The exponential form of course fits better from zero to 400,000.

In physical terms we can explain the dependence of the yield of disintegrations on the energy of the proton in terms of two things: an effectively constant cross section of the nucleus and a probability that the proton will enter the nucleus if it hits within that area. The product of the cross section and the probability of entrance should be proportional to the probability of disintegration. If the probability of entering the nucleus increases from zero to approximately unity in the region from 100,000 to 400,000 electron-volts, this increase would account for the initial rise in the curve. After reaching unity the probability can increase no more and the observed increase in the number of disintegrations is simply due to the larger number of lithium atoms that are exposed to bombardment.

The effective cross section just discussed can be readily calculated from the existing experimental data. A 1,000,000 volt proton travels 1.56 cm in air at N.T.P. in losing 500,000 electron volts.[4] Converted to terms of lithium fluoride this corresponds to passage through a layer containing $5\times10^{19}$ atoms of lithium per square centimeter. From this datum and the experimental fact that from such a layer 30 disintegrations are observed per $10^9$ protons, may be calculated the cross section: $6\times10^{-28}$ cm$^2$, or a radius of $1.4\times10^{-14}$ cm. Since the radius of the potential trough is about $4\times10^{-13}$ cm, it appears that very few of the protons that penetrate the nucleus produce disintegration.

I am greatly indebted to Professor E. O. Lawrence for placing the apparatus at my disposal and for many valuable discussions. Professor J. R. Oppenheimer provided the theoretical formula and has been most helpful. My predecessors in work with the same apparatus have each contributed something and I desire to thank them collectively.