A Photographic Investigation of the Transmutation of Lithium and Boron by Protons and of Lithium by Ions of the Heavy Isotope of Hydrogen

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Transmutation of Lithium and Boron by Protons and Ions.

which is complex and consists of particles of all ranges from about 1·0 cm. up to 7·8 ± 0·2 cm., i.e., with all energies from 1·7 to 8·3 million $e$ volts.

(4) It is shown that the particles are probably helium nuclei and that the 13·0 cm. group arises from the reaction

$$3\text{Li}^6 + 1\text{H}^2 \rightarrow 2\text{He}^4 + \text{He}^4,$$

while the complex group is a result of the three-body nuclear reaction

$$3\text{Li}^7 + 1\text{H}^2 \rightarrow 2\text{He}^4 + \alpha \text{n}^1.$$

The masses and energies check within the experimental error.

A Photographic Investigation of the Transmutation of Lithium and Boron by Protons and of Lithium by Ions of the Heavy Isotope of Hydrogen.


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[Plates 14–17.]

1. Introduction.

In the preceding paper, p. 722, Oliphant, Kinsey and Rutherford have given an account of the examination of the disintegration of lithium by protons and by ions of the heavy isotope of hydrogen, using electrical counting methods, and have shown that the results of their experiments lend strong support to the views of the modes of disintegration which they there suggest. Certain of these conclusions may be more completely examined by photographing the tracks of the disintegration particles in an expansion chamber and with that object we have made the experiments described below. In the course of this work a great amount of experimental data has been collected which will require a more detailed analysis; in the present paper the photographs described have been selected with the object of testing the above-mentioned theories. It is possible that the photographs show evidence of other modes of disintegration, but in view of the time required for a full analysis, we publish here only an account of the more obvious phenomena.

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2. Experimental Arrangement.

The apparatus used for the production of the high voltage and its application to the tubes used for accelerating the bombarding particles was that described by Cockcroft and Walton,* and potentials up to about 400 kilovolts were used. The first attempts to work an expansion chamber in conjunction with that apparatus showed that the maximum number of disintegrations produced per second was much too small, and considerable time was spent in attempting to obtain a more intense beam of protons. The form of discharge tube finally adopted was that described by Oliphant and Rutherford.† This has been found much more definite in behaviour than the glass discharge tube used in the early work of Cockcroft and Walton. The total positive ion current measured at the target is at least ten times greater than could be obtained from the latter tube, and the number of disintegrations produced per second has been increased by an even larger factor. It is probable that the new type of tube gives a larger ratio of protons to molecular ions in the beam—this ratio being more liable to fluctuation with the glass discharge tubes. With the present arrangement, using the maximum output of current and voltage, it is possible to obtain over 100 tracks per expansion from a lithium target a few square millimetres in area.

The expansion chamber was of the standard Wilson type 15 cm. in diameter and 5 cm. deep. This type of chamber is not the most suitable for the purpose in hand and it is intended to erect later a completely sealed chamber which can be operated at any pressure. The expansion chamber, cameras, and mechanism requiring attention during use were mounted in a compact manner upon a framework which could be accommodated together with the operator in the lead-lined observation cubicle at the foot of the proton tube. Photographs were taken through the glass roof of the chamber with two cameras mounted together on a board such that the angle made with the vertical by the axis of each camera lens was 30°, the angle between the two optic axes being 20°. The backs of the cameras were tilted relative to the lens axes in the normal manner, the object plane being horizontal and passing through the centre of the chamber. Photographs were taken at a reduction of 1 : 3·5, the lenses being of focal length 3½ inches. This camera board could be removed as a unit and the plates reinserted in the cameras after development. Measurements were

then made upon images of the tracks which were reproduced in space in the relative positions in which they actually occurred.

In these experiments, the proton beam fell upon the target contained in a small tube which passed through the top of the chamber as illustrated in fig. 1. The target was a few square millimetres in area and had a small stopping power. It was inclined to the incoming beam at an angle of 30° and was surrounded by a window system (usually of mica) which had to withstand atmospheric pressure and at the same time admit the products of disintegration into the expansion chamber. Owing to the large proton currents now obtainable it was possible to make these tubes only 1 cm. in diameter and thus very little of the expansion chamber was obscured from the view of the cameras.

To study products of different ranges, grids of various types were inserted in the central hole in the glass roof of the chamber. Connection was made to the end of the main proton tube by a piece of "tombac" tubing held in such compression that although evacuated, its tendency was to expand, and hence any vibration of the chamber during expansion did not impair the vacuum seals. A change of windows or target could be made without admitting air to the whole of the accelerating tubes, by closing a flap in the main proton tube and removing the tombac. The proton beam was shielded from the
target by a light shutter which was held closed by an electromagnet inside the proton tube. It was opened at the desired instant relative to the expansion by short circuiting the electromagnet by a thyratron. The grid was charged to the striking voltage through a capacity resistance circuit, variation of the resistance giving the required control over this instant. The striking of the thyratron was also arranged to operate a light relay which produced the illumination, the timing of which was effected by the variation of the resistance in a second circuit which contained some inductance. The use of this electric timing has the advantage of compactness and has been found to be very reproducible in behaviour.

3. The Disintegration of Lithium by Protons.

Cockcroft and Walton first showed that the disintegration of lithium under proton bombardment gave rise to particles of 8·4 cm. range,* and to a shorter group of less than 2·0 cm. range† They showed that the assumed reaction

\[ ^7\text{Li} + ^1\text{H} \rightarrow ^2\text{He} + ^2\text{He} \tag{1} \]

gave good agreement with the 8·4 cm. range, and also showed by scintillation counting that there was evidence of the simultaneous emission of two particles. Kirchner‡ has published photographs obtained in an expansion chamber of the emission of two particles in nearly opposite directions, and has shown that the observed angle between the tracks is in approximate agreement with that calculated from the energy and momenta relations. Kirchner did not arrange for the tracks to end in the expansion chamber, and thus a simultaneous measurement of the ranges of pairs of particles emitted in opposite directions could not be made. In our experiments, four windows of 5·1 cm. stopping power were used mounted upon grid (a) of fig. 2. With this arrangement the tracks were a convenient length for measurement.

The constancy of range in this type of disintegration is shown by fig. 3, Plate 14. The difference in range on the two sides of the target is due to the fact that particles emerging on the right have to pass through a piece of mica of 6 mm. stopping power on which was deposited the layer of lithium oxide of 2 mm. stopping power. Figs. 5, 6 and 7, Plate 15, show four disintegrations of this type. In all cases, tests were made as to whether the two tracks passed

through a point. The plane containing the two tracks was usually vertical—any departure could be attributed to a scattering from its original vertical direction of the proton responsible for the disintegration.

The mean value of the sum of lengths of pairs of tracks taken from a number of such photographs was $16.6$ cm. The differences in the lengths of each pair in the actual expansion chamber was in agreement with the air equivalent of the path of the right-hand member in the mica used to support the lithium oxide. The average range of the particles emitted in opposite directions was therefore $8.3$ cm, which is in good agreement with the value $8.4$ cm. deduced from the absorption curves, and with the theoretical value of $8.25$ cm. obtained by substituting the latest data for the masses of the nuclei concerned in re-

\[ \text{Fast protons} \quad \text{Fast protons} \quad \text{Fast protons} \]

**Fig. 2.**

action (1). This would seem to furnish complete confirmation of this mode of disintegration. In many experiments tracks appeared without the presence of a related opposite track; this is most probably due to inefficiency of the windows. A further study would be required to be able to affirm that the above reaction occurs in all experiments where the $8.4$ cm. particles are produced. Kirchner found no evidence of the short range (less than $2$ cm.) group reported by Cockcroft and Walton, this being probably due to the windows used having too great a stopping power. Oliphant, Kinsey and Rutherford, p. 723, have examined this region more fully and report two ranges of about $0.7$ and $1.2$ cm.

In order to photograph such short ranges satisfactorily, it is essential to use windows of less than $4$ mm. air equivalent, this necessitating very close spacing of the supporting grid, and consequently a high inefficiency for penetration by incident particles. A mixture of $90\%$ hydrogen and $10\%$ air was used in the
chamber in order to increase the lengths of the tracks. An attempt to examine this mode of disintegration was made with the grid shown in fig. 2 (c), the slits being 0·3 mm. wide. On the sloping side of the target the particles emitted from the lithium oxide have an unobstructed solid angle for emergence of nearly $2\pi$ while particles passing through the opposite vertical face have to pass through the supporting grids. Although these grids had an efficiency of more than 50% for normally incident particles, their finite thickness prevented emergence of particles which fell obliquely upon them. Fig. 8, Plate 15, taken under these conditions, shows clearly the presence of the 12 mm. range and suggests the existence of a group of still shorter range. A number of these longer tracks was measured and gave an average range of 11 mm. The few tracks of still shorter range which were photographed had a length of about 6 mm. In a short run, taken under these conditions, we only obtained one track emerging from the vertical face, and this was the companion to the long range track visible on the other side, both passing obliquely out of the chamber. It is intended to investigate this problem in detail by passing the proton beam into the expansion chamber upon a target suspended in the gas.

4. The Disintegration of Lithium by Ions of the Heavy Isotope of Hydrogen.

Lewis, Livingston and Lawrence* have reported the existence of particles of ranges 14·5 cm. and 35·0 cm. when lithium is bombarded by ions of the heavy isotope of hydrogen. Oliphant, Kinsey and Rutherford, p. 727, have described the absorption curve of these particles and have concluded that there is a continuous range distribution up to 7·8 cm. with a homogeneous group of 13·2 cm. range. Lewis, Livingston and Lawrence have suggested the possible reaction

$$^3\text{Li}^6 + ^1\text{H}^2 \rightarrow ^2\text{He}^4 + ^2\text{He}^4$$  \hspace{1cm} (2)$$
to account for the 13·2 cm. group. The value calculated from equation (2) using Bainbridge's results is in very close agreement with the observed range.

Lord Rutherford kindly gave us a sample of the heavy isotope of hydrogen which had been presented to him by Professor G. N. Lewis, and this was passed into the discharge tube for the following experiments, the bombarded element being lithium as before. Fig. 4, Plate 14, shows the general type of events obtained under these conditions, the windows having the same stopping power

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as for fig. 3, Plate 14, which was for proton bombardment. The existence of a group with all ranges up to about 8 cm. is clearly shown, together with particles which passed out to the walls of the chamber and had therefore a range of more than 10 cm.

Figs. 9, 10 and 11, Plate 16, show examples with smaller ion currents and strongly suggest the emission of pairs of long range particles in opposite directions as is required by the conservation of momentum in reaction (2). About 100 similar photographs have been taken and the number of such opposite pairs is far greater than could be attributed to chance. Thicker windows of 10·4 cm. stopping power were then used on a more efficient grid system, and figs. 12 and 13, Plate 17, show a pair of stereoscopic photographs of a disintegration obtained under these conditions. The tracks then ended in the gas and permitted measurement of ranges. The reduced range of each of this particular pair of particles was 13·4 cm., in good agreement with the value of 13·2 obtained by Oliphant, Kinsey and Rutherford, and with the value obtained from equation (2). This particular mode of disintegration would thus seem to be definitely confirmed. Fig. 14, Plate 17, shows another pair of particles of this range, together with a track which passes out to the wall of the chamber and has therefore a range of at least 16 cm. Many other similar tracks were obtained, and the smaller ionization along them would suggest that they may constitute the 35 cm. group reported by Lawrence, Livingston and Lewis (loc. cit.). In a brief examination of these tracks, no obvious correlation has been noticed between their direction of emission and those of other particles. Among the tracks of about 8 cm. range, we have observed a few forks which were measured, and gave approximate values of the ratio of the masses of the colliding particles in agreement with the ratios He to O or He to N.

5. Disintegration of Boron by Proton Bombardment.

Cockcroft and Walton showed that boron under proton bombardment emitted particles of ranges up to about 5 cm. and suggested that three \(3^1\) particles were produced in the disintegration according to the equation

\[ ^5\text{B}^{11} + ^1\text{H}^1 \rightarrow ^2\text{He}^4 + ^2\text{He}^4 + ^2\text{He}^4 \] (3)

Oliphan and Rutherford* showed that a careful examination of the absorption curve gave strong support to this hypothesis and Kirchner (loc. cit.) has

published a photograph of three particles emitted at approximately 120°, but does not state the ranges of the particles or whether the three tracks show conservation of momentum.

Using a thin piece of pyrex glass (which contains boron) of 2.5 mm. stopping power as target and a mica window of 6.4 mm. stopping power mounted on the grid shown in fig. 2 (b), we have taken over 100 photographs. In order to make the average track a suitable length, a mixture of 80% hydrogen and 20% air was used in the chamber. The slots of this grid were 0.4 mm. wide and the efficiency of the grid for normally incident particles was about 70%.

Fig. 15, Plate 17, is typical of this run. On these plates there were many cases of groups of three particles which appeared to be due to simultaneous emission of three particles, but after careful measurement on the tracks reproduced in space it was found that although there were cases of three tracks lying in the same plane and passing through a point, the majority of these did not satisfy the momentum relations as accurately as could be reasonably expected. The possibility of slight deflections in the mica windows of particles of such small residual range must not be overlooked. For the study of a three-body emission, it is essential to reduce the inefficiency of the windows to a further extent and a full discussion of this disintegration is therefore postponed to a later date.

This research was carried out with the high voltage installation set up by Cockcroft and Walton and we are much indebted to Dr. Cockcroft for use of this apparatus and for valuable suggestions. We wish to express our gratitude to Lord Rutherford for his interest in the work, and for the benefit we have derived from many helpful discussions. One of us (E. T. S. W.) wishes to acknowledge a grant from the Department of Scientific and Industrial Research. Our thanks are also due to Mr. W. Birtwhistle for much technical assistance.

Summary.

Photographs have been taken, using an expansion chamber and double camera, of the tracks emitted in the transmutations of lithium and boron by protons and of lithium by ions of the heavy isotope of hydrogen. By measurement of the tracks reproduced in space from the photographs taken, the modes of disintegration

\[
^3\text{Li}^7 + ^1\text{H}^1 \rightarrow ^2\text{He}^4 + ^2\text{He}^4
\]

and

\[
^3\text{Li}^6 + ^2\text{H}^2 \rightarrow ^2\text{He}^4 + ^2\text{He}^4
\]

have been definitely confirmed.
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DESCRIPTION OF PLATES.

At the centre of each photograph the window system surrounding the target can be seen, and above this the tube down which passes the stream of fast ions. The emergent tracks are produced by the particles emitted in the disintegrations. Except where otherwise stated the stopping power of the windows used was 5.1 cm. of air.

Figs. 3-14 are reproduced three-quarter natural size, figs. 15 and 16 at half natural size. Tracks are referred to by letters at the margin in their direction from the target. The white patch on each photograph is the image in the floor of the chamber of the target tube.

PLATE 14.

Fig. 3.—Protons incident on thin lithium target, the a-particles emitted showing a constant range of 8.4 cm. The particular fan shape is due to oblique passage of the a-particles through the mica windows and interception by the supporting grid. The particles on the right have shorter length in the chamber as they have to pass through the mica which carries the lithium oxide.

Fig. 4.—Ions of the heavy isotope of hydrogen incident upon thin lithium target. This photograph was taken under the same conditions as fig. 3 and shows the existence of particles which pass out to the walls of the chamber and have therefore a range greater than 10 cm. The continuous range of less than 8 cm. is also obvious. Some of the thinner tracks may be due to fast protons, but the density of the track under these conditions of photography is not a certain guide as to the nature of the ionizing particle.

PLATE 15.

Figs. 5 and 6.—A stereoscopic pair showing the disintegration of lithium by proton bombardment with the emission of pairs of a-particles in opposite directions. Tracks a1, a2 belong to one disintegration, b1, b2 to another. These tracks occupy the positions a1', a2' and b1', b2' in the other photograph, illustrating the manner in which the pair of photographs taken from different positions shows that the tracks are colinear and not merely coplanar.

Fig. 7.—Another photograph showing two separate disintegrations of lithium by protons. The tracks c1, c2, d1, d2 being the opposite pairs.

Fig. 8.—The short range group from lithium under proton bombardment photographed in a mixture 90 % hydrogen and 10 % air, the particles passing through mica windows of 4 mm. stopping power. An opposite pair of long range particles is also present which pass obliquely out of the illumination. The length of the short range tracks reduced to standard air is 11 mm.

PLATE 16.

Fig. 9.—Disintegration of lithium by ions of the heavy isotope of hydrogen, showing the emission of two particles (a1, a2) in opposite directions passing out of the expansion chamber and with ranges therefore greater than 10 cm. (Li9 + H2 → 2He4). The thin long track (b) is probably a fast proton.

Fig. 10.—This photograph shows the type of disintegration described above, fig. 9, and also a disintegration with the emission of a pair of opposite 8·4 cm. particles (b1, b2), probably due to the presence of protons in the positive ion beam.

Fig. 11.—This shows several cases of particles with range greater than 10 cm. lying in opposite directions. There are also particles with different ranges less than 8 cm. ending in the chamber.
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Plate 17.

Figs. 12 and 13.—This pair of photographs was taken with ions of the heavy isotope of hydrogen incident upon thin lithium, the windows having a stopping power of 10 cm. which made the particles end in the chamber. The ranges of this opposite pair are 13.4 cm. corresponding to the transmutation of Li\(^6\) + H\(^2\) into two helium atoms.

Fig. 14.—This was taken under the same conditions as the preceding but showing a fine track, probably due to a proton, passing out of the chamber and with range therefore greater than 16 cm. This photograph also shows another pair of particles of 13 cm. range emitted in opposite directions.

Fig. 15.—This is a typical photograph of the tracks produced by the bombardment of boron by protons. Three of the tracks lie in a plane and pass through a point, but measurement shows that conservation of momentum does not hold and hence the tracks probably come from different disintegrations.

Fig. 16.—This shows a pair of oppositely directed particles from boron under proton bombardment and may illustrate one of the cases discussed by Rutherford and Oliphant where two particles come out in nearly opposite directions and the third receives very little energy.

Figs. 15 and 16.—These were taken in a mixture of 80% hydrogen and 20% air; stopping power of windows = 6.4 mm.