equality of the total separations and the relatively inverted positions of the levels due to the two isotopes 199 and 201. The structure now proposed shows that the anomaly noted by Schüler and Keyston regarding the magnitudes of the isotope displacements and the fine intervals does not exist in the $6\,^1P_1$ level.

In conclusion, we should like to record our deepest thanks to Professor Venkatesachar for his guidance and encouragement throughout this work. One of us is indebted to the University of Mysore for the award of a scholarship.

Experiments with High Velocity Positive Ions. II.—*The Disintegration of Elements by High Velocity Protons.*

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(Communicated by Lord Rutherford, O.M., F.R.S.—Received June 15, 1932.)

[Plate 12.]

1. *Introduction.*

In a previous paper* we have described a method of producing high velocity positive ions having energies up to 700,000 electron volts. We first used this method to determine the range of high-speed protons in air and hydrogen and the results obtained will be described in a subsequent paper. In the present communication we describe experiments which show that protons having energies above 150,000 volts are capable of disintegrating a considerable number of elements.

Experiments in artificial disintegration have in the past been carried out with streams of α-particles as the bombarding particles; the resulting transmutations have in general been accompanied by the emission of a proton and in some cases γ-radiation.† The present experiments show that under the bombardment of protons, α-particles are emitted from many elements; the disintegration process is thus in a sense the reverse process to the α-particle transformation.

* 'Proc. Roy. Soc.,' A, vol. 136, p. 619 (1932) denoted as (I) hereafter.

† Rutherford, Chadwick and Ellis, "Radioactive Substances."

2. *The Experimental Method.*

Positive ions of hydrogen obtained from a hydrogen canal ray tube are accelerated by voltages up to 600 kilovolts in the experimental tube described in (I) and emerge through a 3-inch diameter brass tube into a chamber well shielded by lead and screened from electrostatic fields. To this brass tube is attached by a flat joint and plasticene seal the apparatus shown in fig. 1. A target, A, of the metal to be investigated is placed at an angle of 45 degrees to the direction of the proton stream. Opposite the centre of the target is a side tube across which is sealed at B either a zinc sulphide screen or a mica window.

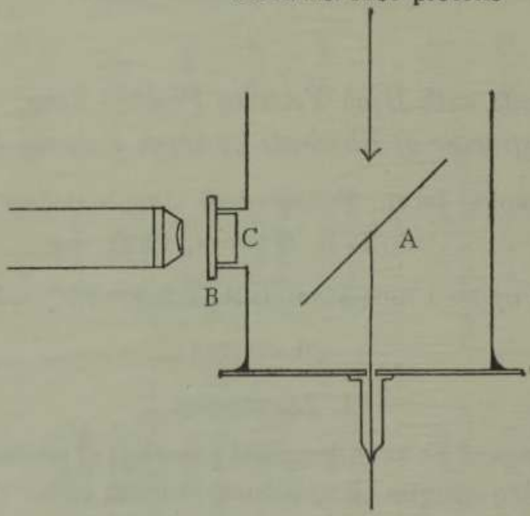


Fig. 1.

In our first experiments we used a round target of lithium 5 cm. in diameter and sealed the side tube with a zinc sulphide screen, the sensitive surface being towards the target. The distance from the centre of the target to the screen was 5 cm. A sheet of mica, C, of stopping power 1·4 cm. was placed between the screen and target and was more than adequate to prevent any scattered protons reaching the screen, since our range determinations* and the experiments of Blackett† have shown that the maximum range of protons accelerated by 600 kilovolts is of the order of 10 mm. in air. The screen is observed with a microscope having a numerical aperture of 0·6, the area of screen covered being 12 sq. mm. This arrangement with the fluorescent surface inside the vacuum is generally used in the preliminary investigations

* In course of publication.

† 'Proc. Roy. Soc.' A, vol. 134, p. 658 (1931).

of elements and when it is necessary to detect the presence of particles of short range.

The current to the target is measured by a galvanometer and controlled by varying the speed of the motor used for driving the alternator exciting the discharge tube (see Paper I). Currents of up to 5 microamperes can be obtained. Since metals bombarded by high-speed positive ions emit large numbers of secondary electrons for each incident ion, it is necessary to prevent the emission of these electrons if an accurate determination of the number of incident ions is required. This has been effected by applying a magnetic field of the order of 700 gauss to the target. Since it is well known that the majority of the secondary electrons have energies below 20 volts, such a field should be adequate to prevent secondary electron emission being a serious source of error.

An accurate determination of the exact composition of the beam of ions has not yet been made, but deflection experiments with a magnetic field in a subsidiary apparatus have shown that approximately half the current is carried by protons and half by H_2^+ ions. The number of neutral atoms appears to be small.

The accelerating voltage used in the experiments is controlled by varying the field of the alternator exciting the main high tension transformer. The secondary voltage of this transformer is measured by the method described in an earlier paper,* which rectifies the current passing through a condenser. A microammeter on the control table allows a continuous reading of this voltage to be obtained. The value of the steady potential produced by the rectifier system varies between 3 and 3·5 times the maximum of the transformer voltage according to the brightness of the rectifier filaments. The actual value of the voltage is determined by using a sphere gap consisting of two 75-cm. diameter aluminium spheres, one of which is earthed. In each experiment the multiplication factor of the rectifier system is determined for several voltages and intermediate points obtained by interpolation. The accuracy of the determination of the voltage by the sphere gaps has been checked by measuring the deflection of the protons in a magnetic field. It has been found that corrections of the order of 15 per cent. may be required as a result of the proximity of neighbouring objects or unfavourable arrangements of the connecting leads. The voltages given in this paper have all been corrected by reference to the magnetic deflection experiments.

* 'Proc. Roy. Soc.' A, vol. 129, p. 477 (1930).

3. *The Disintegration of Lithium.*

When the current passing to the target was of the order of 1 microampere and the accelerating potential was increased to 125 kilovolts, a number of bright scintillations were observed on the screen, the numbers being proportional to the current collected and of the order of 5 per minute per microampere at 125 kilovolts.

No scintillations were observed when the proton current was cut off by shutting off the discharge tube excitation or by interposing a brass flap between the beam and the target. Since the scintillations were very similar in appearance and brightness to α-particle scintillations, the apparatus was now changed to allow a determination of their range to be made. For this purpose a mica window having a stopping power of 2 cm. was sealed to the side tube in place of the fluorescent screen, which was now placed outside the window. It was then possible to insert mica screens of known stopping power between the window and the screen. In this way it became apparent that the scintillations were produced by particles having a well-defined range of about 8 cm. Variations of voltage between 250 and 500 kilovolts did not appear to alter the range appreciably.

In order to check this conclusion, the particles were now passed into a Shimizu expansion chamber, through a mica window in the side of the chamber having a stopping power of 3·6 cm. When the accelerating voltage was applied to the tube a number of discrete tracks were at once observed in the chamber whose lengths agreed closely with the first range determinations. From the appearance of the tracks and the brightness of the scintillations it seemed now fairly clear that we were observing α-particles ejected from the lithium nuclei under the proton bombardment, and that the lithium isotope of mass 7 was breaking up into two α-particles.

In order to obtain a further proof of the nature of the particles the experiments were repeated with an ionisation chamber, amplifier and oscillograph of the type described by Wynn Williams and Ward.* The mica window on the side tube was reduced to a thickness corresponding to a stopping power of 1·2 mm. with an area of about 1 sq. cm., the mica being supported on a grid structure. The lithium target was at the same time reduced in size to a circle of 1 cm. diameter in order to reduce the angular spread of the particles entering the counter. The ionisation chamber was of the parallel plane type having a total depth of 3 mm. and was sealed by an aluminium window having a stopping

* 'Proc. Roy. Soc.,' A, vol. 132, p. 391 (1931).

power of 5 mm. The degree of resolution of the amplifier and oscillograph was such that it was possible to record accurately up to 2000 particles per minute. With the full potential applied to the apparatus but with no proton current, the number of spurious deflections in the oscillograph was of the order of 2 per minute, whilst with an accelerating potential of 500 kilovolts and a current of 0·3 microamperes the number of particles entering the ionisation chamber per minute was of the order of 700.

In figs. 8, 9, 10 and 11, Plate 12, are shown the oscillograph records obtained as additional mica absorbers are inserted. It will be seen that the size of the deflections increases as additional mica is inserted, whilst the numbers fall off rapidly when the total absorber thickness is increased beyond 7 cm. In fig. 2 is plotted the number of particles entering the chamber per minute per micro-ampere for increasing absorber thickness and for accelerating potentials of 270 kilovolts and 450 kilovolts. The stopping power of the mica screens of windows has been checked and the final range determination made by a comparison with the α-particles from thorium C. We find that the range is 8·4 cm. Preliminary observations showed that between the lowest and highest voltages used, the range remained approximately constant. It is, however, of great interest to test whether the whole of the energy of the proton is communicated to the α-particles, and it is intended at a later date to examine this point more carefully. The general shape of the range curve, together with the evidence from the size of the oscillograph deflections, suggests that the great majority of the particles have initially a uniform velocity, but further investigation will be required with lower total absorption to exclude the possibility of the existence of particles of short range.

As is well known, the size of the oscillograph kicks are a measure of the ionisation produced by the particles. At the beginning of the range the size of the kicks observed was very uniform, whilst the average size varied with the range of the particle corresponding to the ionisation given by the Bragg curve. Fig. 3 shows the variation of the ionisation of the most numerous particles with range.

The sizes of the deflections were now compared with the deflections produced in the same ionisation chamber by α-particles from a polonium source, these deflections being recorded in fig. 12, Plate 12, for comparison. It has been shown in this way that the maximum deflection for the two types of particle is the same. This result, together with the uniformity of the ionisation produced by the particles, is sufficient to exclude the possibility of some of the particles being protons, since the maximum ionisation produced by a

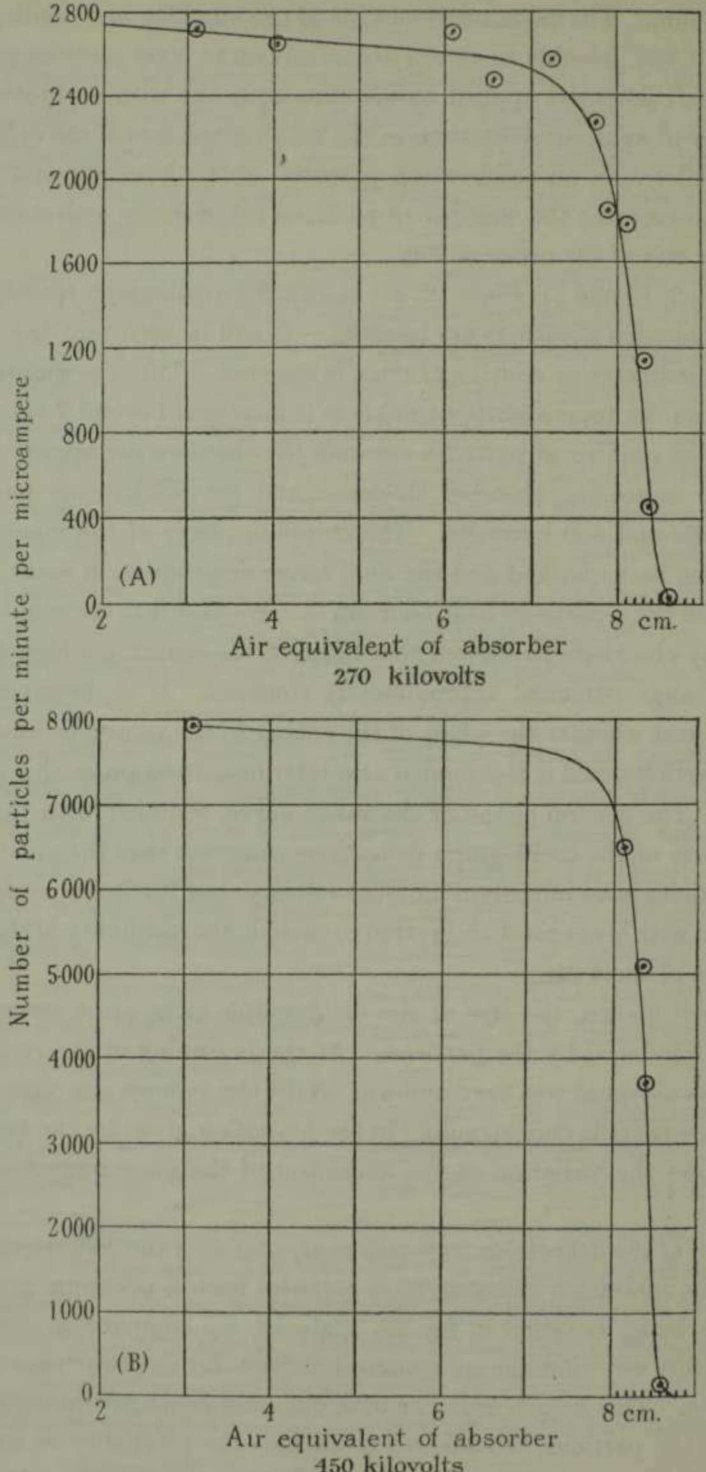

2800
2400
2000
1600
1200
800
400
0
(A)
2
4
6
8 cm.
Air equivalent of absorber
270 kilovolts
Number of particles per minute per microampere
8000
7000
6000
5000
4000
3000
2000
1000
0
(B)
2
4
6
8 cm.
Air equivalent of absorber
450 kilovolts

Fig. 2.

proton is less than 40 per cent. of the maximum ionisation produced by an α-particle.

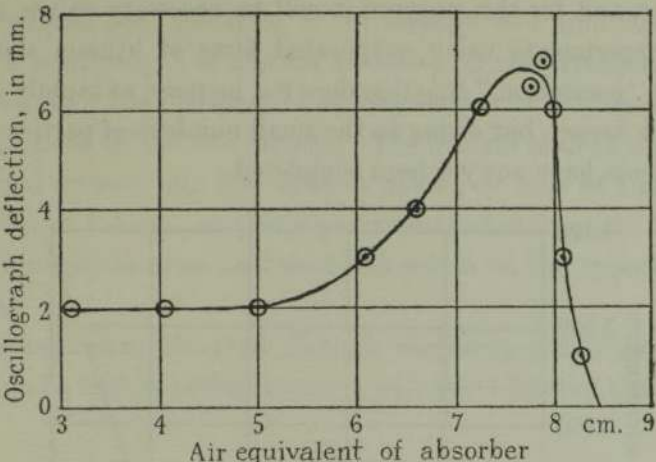


Fig. 3.

The variation of the numbers of particles with accelerating voltage was determined from the oscillograph records between 200 kilovolts and 500 kilovolts, the change in numbers being clear from the records, figs. 13, 14, 15, Plate 12. For voltages between 70 kilovolts and 250 kilovolts, the numbers of particles entering the ionisation chamber were counted by a single stage thyratron counter of the type described by Wynn Williams and Ward.* The results are plotted in fig. 4. The numbers increase roughly exponentially with the voltage at the lower voltages and linearly with voltage above 300 kilovolts.†

It is of great interest to estimate the number of particles produced by the bombardment of a thick layer of lithium by a fixed number of protons. In making this estimate we have assumed that the particles are emitted uniformly in all directions and that the molecular ions produce no effect. With these assumptions the number of disintegrations for a voltage of 250 kilovolts is 1 per 10^9 protons, and for a voltage of 500 kilovolts is 10 per 10^9 protons.

In considering the variation in numbers of particles with voltage it has, of course, to be borne in mind that with a thick target the effects are due to

* 'Proc. Roy. Soc.,' A, vol. 131, p. 191 (1931).

† All the measurements in a single run, in which more than 2000 particles were counted, are included in the figure. The spread of the points in the centre part of the curve is probably due to variations in the vacuum and therefore in the voltage applied during the experiment. In other runs no evidence was obtained for such a variation.

protons of all energies from the maximum to zero energy. It will be very important to determine the probability of disintegration for protons of one definite energy, and for this purpose it will be necessary to use thin targets. Preliminary experiments using evaporated films of lithium show that the probability or " excitation " function does not increase so rapidly with voltage as for the thick target, but owing to the small numbers of particles obtainable these experiments have not yet been completed.

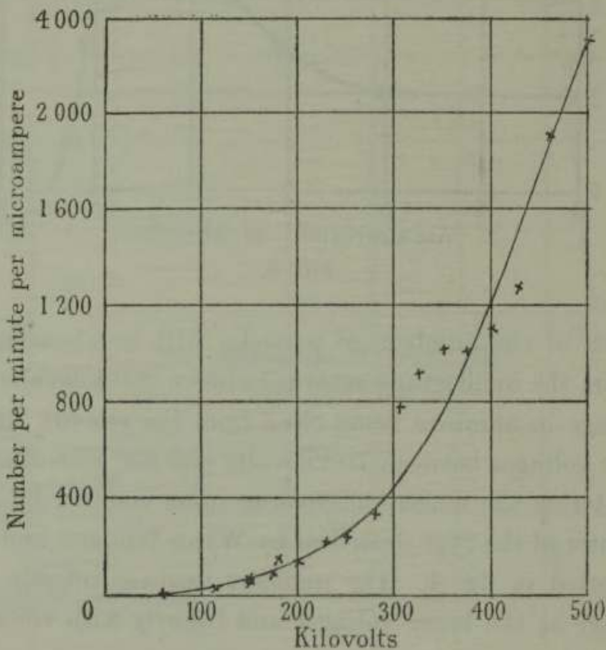


Fig. 4.

4. *The Interpretation of Results.*

We have already stated that the obvious interpretation of our results is to assume that the lithium isotope of mass 7 captures a proton and that the resulting nucleus of mass 8 breaks up into two α-particles. If momentum is conserved in the process, then each of the α-particles must take up equal amounts of energy, and from the observed range of the α-particles we conclude that an energy of 17·2 million volts would be liberated in this disintegration process. The mass of the Li_7 nucleus from Costa's determination is 7·0104 with a probable error of 0·003. The decrease of mass in the disintegration process is therefore $7 \cdot 0104 + 1 \cdot 0072 - 8 \cdot 0022 = 0 \cdot 0154 \pm 0 \cdot 003$. This is equivalent to an energy liberation of $(14 \cdot 3 \pm 2 \cdot 7) \times 10^6$ volts. We conclude, therefore, that the observed energies of the α-particles are consistent with our hypothesis. An additional test can, however, be applied. If momentum is conserved in the disintegration, the two α-particles must be ejected in practically opposite directions and, therefore, if we arrange two zinc sulphide screens opposite to a small target of lithium as shown in the arrangement of fig. 5, we should observe a large proportion of coincidences in the time of appearance of the scintillations on the two screens. The lithium used in the experiments was evaporated on to a thin film of mica having an area of 1 sq. mm. and a stopping power of 1·1 cm., so that α-particles ejected from the lithium would pass easily through the mica and reach the screen on the opposite side of the lithium layer.

The two screens were observed through microscopes each covering an area of 7 sq. mm. and a tape recording machine was used to record the scintillations,

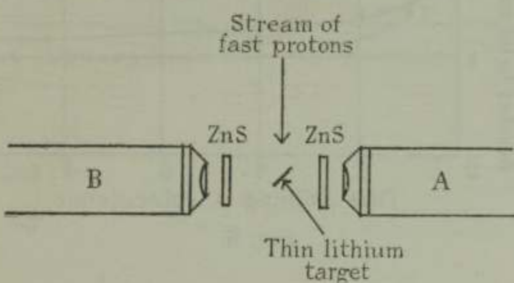


Fig. 5.

a buzzer being installed in the observation chamber to prevent the noise of the recording keys being audible to the observers. Five hundred and sixty-five scintillations were observed in microscope A and 288 scintillations in microscope B, the former being nearer the target. Analysis of the records showed that the results are consistent with the assumption that about 25 per cent. of the scintillations recorded in B have a corresponding scintillation in A. If we calculate the chance of a scintillation being recorded by B within x seconds of the record of a scintillation in A, assuming a perfectly random distribution of scintillations, and compare this with the observed record, the curve shown in fig. 6 is obtained. It will be seen that as the interval x is made less, the ratio of the observed to the random coincidences increases. We also plot for comparison the theoretical curve (shown by broken line) which would be obtained if there were 25 per cent. of coincidences. It will be seen that the two curves are in good accord. The number of coincidences observed is about that to be expected on our theory of the disintegration process, when we take into account the geometry of the experimental arrangement and the efficiency of the zinc sulphide screens. It is clear that there is strong evidence supporting the hypothesis that the α-particles are emitted in pairs. A more complete investigation will be made later, using larger areas for the counting device, when it is to be expected that the fraction of coincidences should increase.

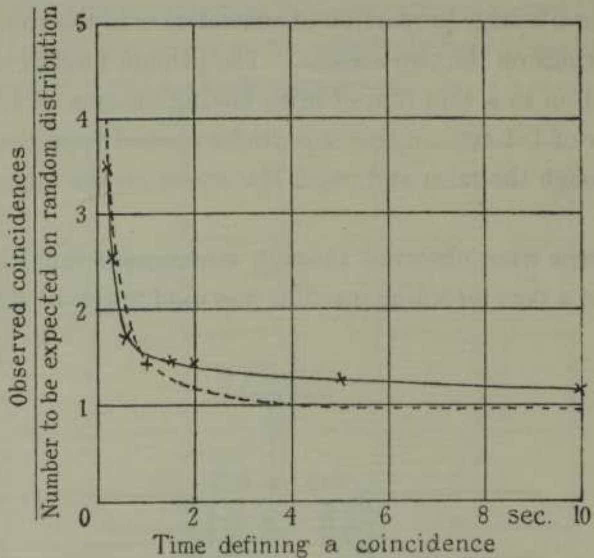


FIG. 6.

5. *Comparison with the Gamow Theory.*

In a paper which was largely responsible for stimulating the present investigation, Gamow† has calculated the probability W_1^* of a particle of charge Ze, mass m and energy E, entering a nucleus of charge $Z'e$. Gamow's formula is

$$W_1^* = e^{\frac{-4\pi\sqrt{(2m)}}{h}\cdot\frac{ZZ'e^2}{\sqrt{(E)}}\cdot J_k},$$

where J_k is a function varying slowly with E and Z. Using this formula, we have calculated W_1^*, the probability of a proton entering a lithium nucleus, for 600, 300 and 100 kilovolts, and find the values $0\cdot187$, $2\cdot75 \times 10^{-2}$ and $1\cdot78 \times 10^{-4}$. Using these figures, our observed variation of proton range with velocity for a thick target, and assuming a target area of 10^{-25} cm.^{2}, the number of protons N required to produce one disintegration may be calculated. For 600 kilovolts we find N to be of the order of 10^6, and for 300 kilovolts of the order of 2×10^7.

The order of magnitude of the numbers observed is thus smaller than the

† 'Z. Physik,' vol. 52, p. 510 (1928).

number predicted by the Gamow theory, but a closer comparison must be deferred until the results for a thin target are available.

6. *The Disintegration of other Elements.*

Preliminary investigations have been made to determine whether any evidence of disintegration under proton bombardment could be obtained for the following elements : Be, B, C, O, F, Na, Al, K, Ca, Fe, Co, Ni, Cu, Ag, Pb, U. Using the fluorescent screen as a detector we have observed some bright scintillations from all these elements, the numbers varying markedly from element to element, the relative orders of magnitude being indicated by fig. 7 for 300 kilovolts. The results of the scintillation method have been confirmed by the electrical counter for Ca, K, Ni, Fe and Co, and the size of the oscillograph kicks suggests that the majority of the particles ejected are α-particles.

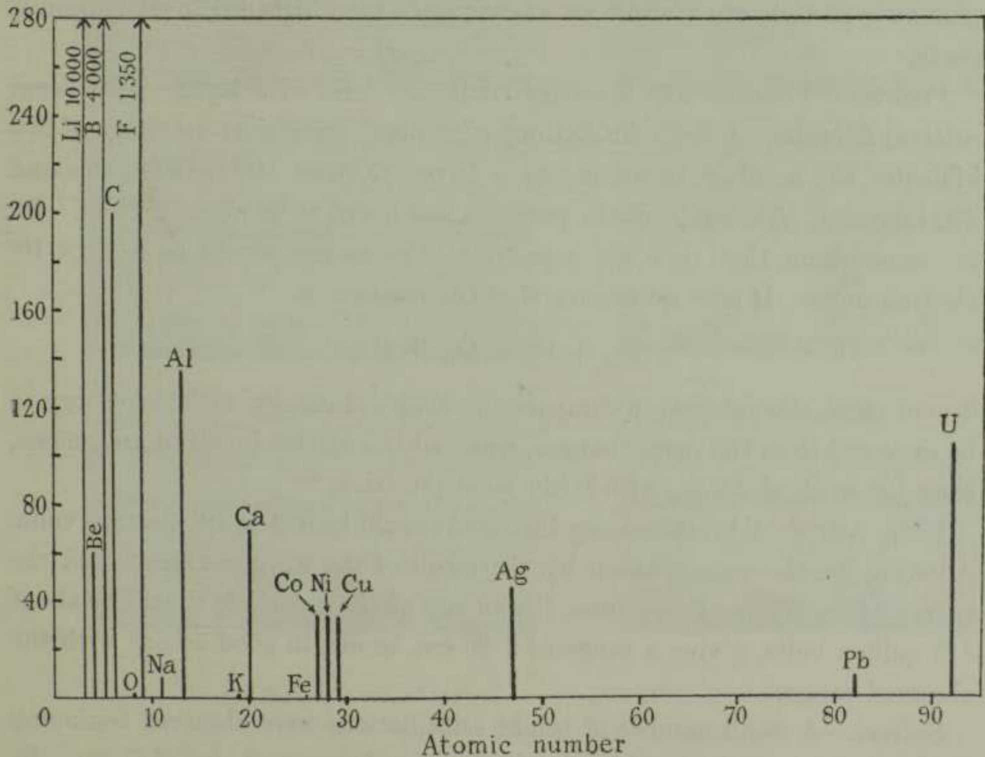


FIG. 7.

The numbers of particles counted have up to the present not been sufficient to enable these figures to be taken as anything other than an order of magnitude. In particular, the possibility must be borne in mind that some of the particles observed may be due to impurities. It may, however, be of some interest to describe briefly the general character of the effects observed in some of the more interesting cases.

Beryllium.—Two types of scintillation were observed with beryllium, a few bright scintillations having the appearance of α-particle scintillations together with a much greater number of faint scintillations appearing at about 500 kilovolts, the numbers increasing rapidly with voltage. We were not able to observe the faint scintillations outside the vacuum chamber, so that they are presumably due to particles of short range.

Boron.—Next to lithium, boron gave the greatest number of scintillations, most of the particles having a range of about 3·5 cm. Scintillations were first observed at voltages of the order of 115 kilovolts, the numbers increasing by more than 100 between this voltage and 375 kilovolts. The interesting problem as to whether the boron splits up into three α-particles or into Be_8 plus an α-particle must await an answer until more detailed investigation is made.

Fluorine.—Fluorine was investigated in the form of a layer of powdered calcium fluoride. A few scintillations were first observed at a voltage of 200 kilovolts, the numbers increasing by a factor of about 100 between this and 450 kilovolts. The range of the particles was found to be about 2·8 cm. On the assumption that they are α-particles, the energy would be $4 \cdot 15 \times 10^6$ electron volts. If now we assume that the reaction is

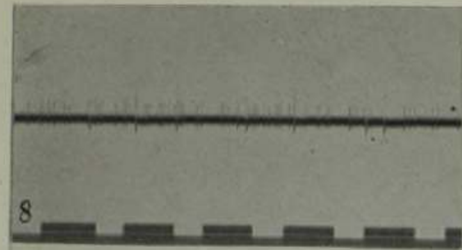
$$F_{19} + H_1 = O_{16} + He_4$$

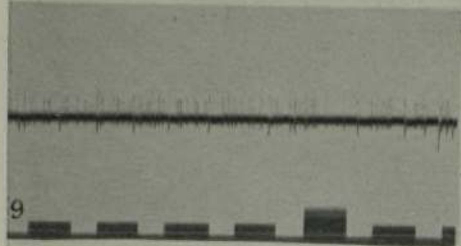
it is of particular interest to compare the observed energy with the energy to be expected from the mass changes, since all the masses involved are known, from the work of Aston, with fairly good precision.

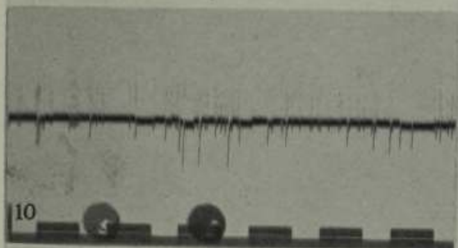
Using Aston's data, the energy liberated should be $5 \cdot 2 \times 10^6$ electron volts. Allowing for the energy taken by the recoil of the oxygen nucleus and the energy of the bombarding proton, the energy of the α-particle should be about 4·3 million volts, giving a range of 2·95 cm. in air, in good accord with the observed ranges.

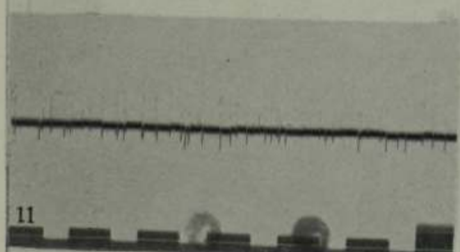
Sodium.—A small number of bright scintillations were observed beginning at 300 kilovolts, the particles having ranges between 2 and 3·5 cm. In addition to the bright scintillations, a number of faint scintillations were observed similar to those seen in the case of beryllium. The faint scintillations are again presumably due to particles of short range since they could not be observed outside the tube. The probable α-particle transition would be

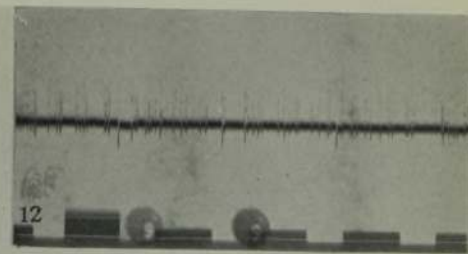
$$Na_{23} + H_1 = Ne_{20} + He_4.$$

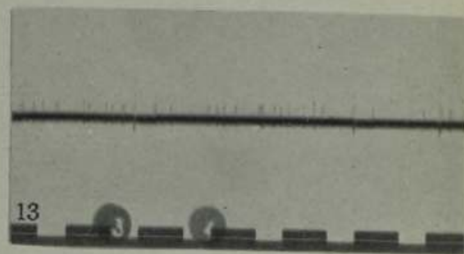


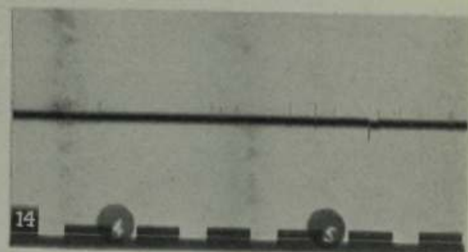












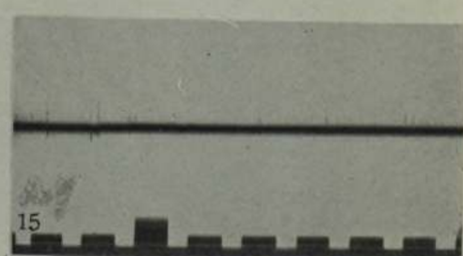


Fig. 8.—270 Kv. 4·0 cm. absorber.

Fig. 9.—270 Kv. 5·0 cm. absorber.

Fig. 10.—270 Kv. 6·6 cm. absorber.

Fig. 11.—270 Kv. 7·9 cm. absorber.

Fig. 12.—Polonium α-particles 2 cm. absorber.

Fig. 13.—250 Kv. 3·1 cm. absorber.

Fig. 14.—210 Kv. 3·1 cm. absorber.

Fig. 15.—175 Kv. 3·1 cm. absorber.

(*Facing p.* 240.)

Potassium.—Potassium is of special interest on account of its radioactivity. The very small effects observed may easily be due to an impurity. The most likely reaction to occur

$$K_{39} + H_1 = A_{36} + He_4,$$

would probably have a negative energy balance.

Iron, Nickel, Cobalt, Copper.—These elements follow each other in the periodic table, so that the small result obtained for iron compared with that for the following three elements is of special interest. The effect for iron is of the same order as that for potassium, and again may be due to impurity. For these elements most of the particles had a range of about 2·5 cm., but a few particles were present having a slightly longer range.

Uranium.—Using potentials of up to 600 kilovolts and strong proton currents, the number of scintillations observed was about four times the natural radioactive effect, and the artificially produced particles appeared to have a longer range than the natural ones. The numbers obtained did not appear to vary markedly with voltage.

We hope in the near future to investigate the above and other elements in much greater detail and in particular to determine whether any of the effects described are due to impurities. There seems to be little doubt, however, that most of the effects are due to transformations giving rise to an α-particle emission. In view of the very small probability of a proton of 500 kilovolts energy penetrating the potential barrier of the heavier nuclei by any process other than a resonance process, it would appear most likely that such processes are responsible for the effects observed with the heavier elements.

We have seen that the three elements, lithium, boron and fluorine give the largest emission of particles, the emission varying similarly with rise of voltage. These elements are all of the $4n + 3$ type, and presumably the nuclei are made up of α-particles with the addition of three protons and two electrons. It is natural to suppose that the addition of a captured proton leads to the formation of a new α-particle inside the nucleus. In the case of lithium, it seems probable that the capture of the proton, the formation of the α-particle and the disintegration of the resulting nucleus into two α-particles must at this stage be regarded as a single process, the excess energy appearing in the form of kinetic energy of the expelled α-particles.* Until further and more accurate data are available it is not desirable to discuss at this stage the possible bearing of

* Such a view does not preclude the possibility that sometimes part of the energy may appear in another form, for example, as γ-radiation.

these new observations on the problems of astrophysics and on the question of the abundance of the elements.

In conclusion, we wish to express our thanks to Lord Rutherford for his constant encouragement and advice. We are indebted to Dr. Wynn Williams for considerable assistance with the electrical recording apparatus, and to members of the research staff of Metropolitan-Vickers Electrical Company for their assistance in supplying much of the apparatus used in this work. One of us (E.T.S.W.) has been in receipt of a senior research award from the Department of Scientific and Industrial Research.