The Transmutation of Potassium, Chlorine and Phosphorus by Th C′ Alpha-Particles

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The transmutation of the three similar $(4n+3)$ type elements K, Cl, P under alpha-particle bombardment has been studied by observing the energy distribution of emitted protons. These are found to occur in groups corresponding to discrete values of the nuclear energy changes which have been determined and tabulated. A general similarity between the behavior of the three elements is observed: They each give groups with energy changes differing by 1.5 Mev on the average, which fit in with the groups from the similar type elements F, Na, Al as found by May and Vaidyanathan. The values 33.9799 ($\pm$0.0015) and 37.9753 ($\pm$0.0016) for the masses of S^{34} and A^{38} are deduced.

RECENT experiments by Haxel[1] and by May and Vaidyanathan[2] on the transmutation of elements differing in nuclear structure by the equivalent of an alpha-particle have shown that for reactions in which an alpha-particle enters and a proton is ejected, the excited states of the product nucleus are similar. Haxel's experiments were performed on the $4n$-type elements Mg^{24}, Si^{28} and S^{32} while May and Vaidyanathan worked with F^{19}, Na^{23}, Al^{27} and P^{31} of the type $4n+3$. The similarity of the proton groups emitted by the $4n$-type elements is quite striking: the groups occur in sets of three with separations of a little under a million electron volts. The three elements F^{19}, Na^{23} and Al^{27} give four groups with an average separation of a million and a half electron volts. Phosphorus has been found to give three groups by both May and Vaidyanathan[2] and Paton,[3] having a mean separation roughly the same as the three previous elements, but with the longest range group absent. We considered it of interest to examine the elements chlorine ($Cl^{35, 37}$) and potassium (K^{39}) which have not been investigated since the early scintillation experiments of Rutherford and Chadwick,[4] as well as phosphorus to see whether the similarity between elements of the $4n+3$ type continues.

The masses of chlorine and phosphorus are known and the transmutation of these elements therefore should enable the masses of argon and sulphur isotopes to be determined by measuring the limiting energy of the proton groups.

APPARATUS

The essential features of the apparatus have been described in a previous paper.[5] In the experiments here reported we have made two important changes. The first was an improvement in the counter which was designed to permit evacuation of the outer grounded case, thus eliminating the need for an insulating mica foil over the counter itself. For the foil covering the counter opening (1.8 cm diameter) we used aluminum of 4.1 cm air equivalent. The axial wire was of tungsten, 0.013 cm diameter. The major improvement was in the use of argon instead of air in the counter: This operates at a lower case voltage and permits higher gas pressures with higher ionization per proton and also gives much more uniform multiplication over the counter opening. With argon at atmospheric pressure the potential of the case of the counter is -2000 while with air at 50 cm, -4000 is needed. The lower voltage renders operation simpler and the counter has given no trouble in five months of steady operation.

The second improvement, made possible by the trouble-free operation of the detection apparatus, was an automatic screen-changing device which interposed successively, between target and counter, ten different sets of absorption screens at regular intervals. The protons are recorded by a thyratron circuit actuating a magnet which deflects a metal point running on waxed (Stylograph) paper.

The targets we used were as follows. Potassium was bombarded as KOH melted on gold foil or

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[3] R. F. Paton, Zeits. f. Physik **90**, 586 (1934).

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copper according to whether the layer was required to transmit protons or not. Chlorine was used as lithium chloride in the right angle arrangement (we first satisfied ourselves that lithium gives no protons of ranges as great as our minimum); or as "Arochlor"—a chlorinated diphenyl which is used commercially as an insulator for condensers. This latter is remarkably suitable for our purpose; it melts easily and flows into smooth uniform layers of any desired thickness. Phosphorus was bombarded as red phosphorus and layers were made by mixing it with vaseline into a paste and warming it on the backing surface until it flowed out uniformly. A thin layer can be obtained fairly easily in this way.

Experimental Procedure and Results

The experimental procedure is similar to that previously described.[5] Protons ejected from targets under bombardment by alpha-particles from a Th C′ source are detected by the counter and their energies measured by absorption. The sources used varied in strength between one and three millicuries as measured by direct counting of the number of alpha-particles emitted in a small solid angle. In order to eliminate natural protons from the source and recoil protons from hydrogen in the target, the counter, target and alpha-particle source were so arranged that the detected protons were moving in a direction which was approximately at right angles to the incident beam of alpha-particles.[6] This "right angle" arrangement was used in two modifications. In the first, the alpha-particle source was placed very near and parallel to the target; curves *A* of Figs. 1, 2 and 3 were thus obtained. In the second modification the source was so placed that the spread in the angle between alpha-particle trajectory and path of ejected proton was as small as possible (44°); this tends to minimize the distortion of the groups. Since the target now subtends a smaller solid angle the yield of protons is less as curves *B* of the same figures indicate.

In order to measure the maximum energy of the ejected protons, counter, target and source were arranged in line[6] so that the minimum angle between the alpha-particle and counted proton paths was zero. This "forward" arrangement is particularly suitable for examining groups of protons of range greater than 40 cm; for it permits greater solid angles between source and target and therefore greater yields of protons. Natural and recoil protons from source and target mask all groups of range less than 40 cm. The principal difficulty with the "forward" method is obtaining a target of uniform stopping power which is sufficiently thin to transmit protons.

The results obtained, with these three arrangements for targets of potassium, chlorine and phosphorus, are shown in Figs. 1, 2 and 3, respectively. In each case the number, *N*, of protons ejected per minute per millicurie of Th C′ is plotted as ordinate against the range *R* of the protons in centimeters of standard air. Due to the different geometrical conditions of each arrangement, a certain group of protons may be better resolved in one curve than in another. Curves *A* are to be regarded as relatively rough at absorptions less than 40 cm. Between 100 and 500 particles were counted at each point plotted. The rather low number of 100 particles at a point applies only to the long range low yield groups where the main interest is in the presence or absence of a group. Our counter background, due to contamination, etc., was not more than four counts per hour: the background to be subtracted when a strong source is near the counter was around twelve per hour. At the extreme ranges the actual yield was therefore generally double the background. For the groups at smaller absorptions we found it preferable to use better geometrical conditions and smaller counts. Even so, the fact that the separation in range grows less for smaller energies (due to the range energy relation) means that there is some doubt about the precise end point of groups having short ranges. This is particularly true in the case of phosphorus and the analysis of the results for that element is to be regarded as less certain than for the two previous elements. As, however, this element has been previously analyzed by Paton, and May and Vaidyanathan, we contented ourselves with confirming their work, and so showing our findings are consistent with the other workers in this field.

[6] See, for example, Fig. 1 of our previous paper (reference 5).

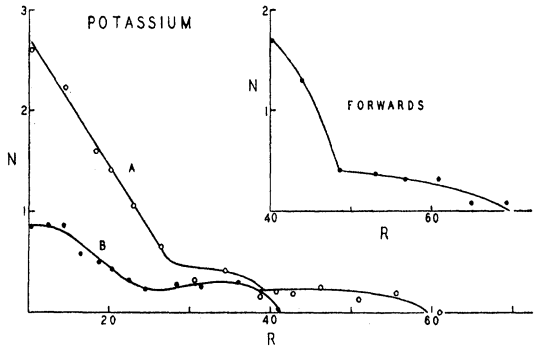

FIG. 1. Yield of protons per minute per millicurie (N) *versus* absorption in centimeters air equivalent (R).

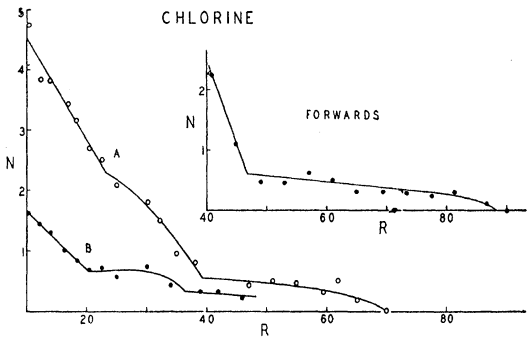

FIG. 2. Yield of protons per minute per millicurie (N) *versus* absorption in centimeters air equivalent (R).

Potassium

Potassium yields three groups of protons as shown in Fig. 1. The most energetic group (here called group 1) has a range of 70 cm forward and 59 cm at right angles; the second group has a range of 49 cm forward and 41 cm at right angles in curve B, or 39 in curve A where it is badly resolved; the third group has a range of 25 cm at right angles in curve B or 27 cm (curve A). Its range in the forward direction is too low to be measured as already explained.

These protons result from the reaction:

$$K^{39}+He^{4}\rightarrow Ca^{42}+H^{1}(+Q).$$

Knowing the velocities of alpha-particle and proton and the masses of all particles involved in the reaction, it is possible to compute[7] the energy change Q corresponding to each group of protons. The values (in Mev) thus found for this reaction are given in Table I together with the relative yields of each group in the last column. The letters (A) and (B) indicate the values corresponding to curves (A) and (B), respectively.

TABLE I. *Values of Q and relative yields for the three proton groups from potassium.*

	Forward		Right Angle		Best Value of Q	Relative Yield
	Range (cm)	Q value	Range	Q value		
Group 1	70	−1.0	59	−1.1 (A)	−1.0	1
Group 2	49	−2.3	41 39	−2.4 (B) −2.3 (A)	−2.3	4
Group 3			25 27	−3.7 (B) −3.4 (A)	−3.6	12

[7] This is discussed in more detail in our previous paper.

Chlorine

The results obtained for chlorine are shown in Fig. 2. The most energetic group (1) has a range of 88 cm forward and 70 cm at right angles; the second group a range of 47 cm forward, at right angles 38 cm (curve A) and 36 cm (curve B); the third group a range at right angles of 21 cm (curve A) and 20 cm (curve B). It is assumed that the most abundant isotope of chlorine is responsible for all three groups (this assumption is further justified in the discussion) which are consequently emitted according to the reaction

$$Cl^{35}+He^{4}\rightarrow A^{38}+H^{1}(+Q)$$

in which the calculated nuclear energy change (Q) values are given in Table II.

Phosphorus

Fig. 3 shows the results obtained for phosphorus. The dotted line indicates the natural and recoil protons which have a range of 40 cm in the forward direction. The region containing the protons of medium range is not easy to analyze. The way in which we have drawn our lines appears to us to fit our results best, but it is clear from the figure that too great a reliance cannot be placed

TABLE II. *Values of Q and relative yields for the three proton groups from chlorine.*

	Forward		Right Angle		Best Value of Q	Relative Yield
	Range	Q	Range	Q		
Group 1	88	+0.1	70	−0.3	+0.1	1
Group 2	47	−2.4	38 36	−2.5 (A) −2.7 (B)	−2.5	3
Group 3			21 20	−4.1 (A) −4.2 (B)	−4.2	3

on exact values of ranges. We feel the most likely analysis is into four groups of protons arising from the reaction:

$$P^{31}+He^{4}\rightarrow S^{34}+H^{1}.$$

The most energetic group (1) has a range of 85 cm forward and 72 at right angles; the second a range of 64 cm forward and 56 at right angles; the third a range at right angles of 35 cm (curve *A*) and 34 cm (curve *B*)—it may possibly show at 47 cm forward; the fourth a range of 15 cm according to both curves. The calculated energy change values are given in Table III. The first three groups appear in the experiments of Paton[3] and May and Vaidyanathan,[2] the fourth gives protons of energies too low to be detected in their work. Their values are, respectively, 0.0; −1.5; 3.0; and −0.1; −1.4; −2.9. The agreement with our figures is reasonably good, particularly as in none of the experiments is a perfect resolution of groups 2 and 3 obtained. We found no evidence of a very long range group of positive Q value.

Possibility of resonance effects

The possibility of resonance effects was tested by repeating absorption curves at lower incident particle energies. We found that the yield falls rapidly for all groups as the incident energy is reduced and that the ranges also vary rapidly in about the way expected if the groups are due to excited states and not critical incident particle energies. The detection of groups arising from resonance levels probably demands still better resolution, using thin targets and more prolonged counting. The study of such levels was not attempted in this work. Energy change values calculated from reduced range experiments are: potassium, $Q=-2.6$; phosphorus, $Q=-2.5$; chlorine, $Q=-2.2$, which agree reasonably well with the predicted values −2.4; −2.6; −2.4; considering the necessarily rough nature of the measurements.

TABLE III. *Values of Q and of relative yields for the four proton groups from phosphorus.*

	Forward		Right Angles		Best Value of Q	Relative Yield
	Range	Q	Range	Q		
Group 1	85	−0.1	72	0.0	0.0	1
Group 2	64	−1.3	56	−1.1	−1.2	4
Group 3	47 ?	−2.4	35 34	−2.6 (A) −2.7 (B)	−2.6	12
Group 4			15	−4.6 (A, B)	−4.6	12

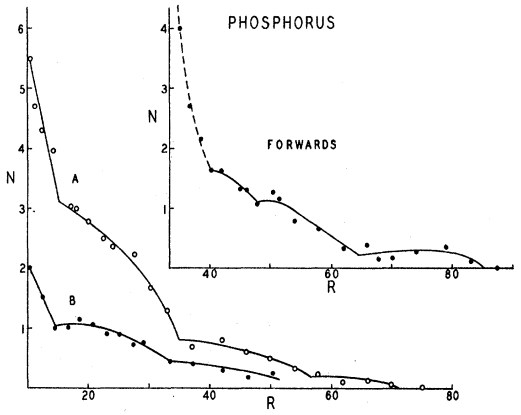

FIG. 3. Yield of protons per minute per millicurie (N) *versus* absorption in centimeters air equivalent (R).

The ranges are given in centimeters air equivalent. We used aluminum screens for absorption, taking 1.64 mg/cm² as equivalent to one centimeter of air. The velocities were derived from the ranges by means of the curves used in the Cavendish Laboratory which are applicable over the ranges measured in our experiments. We give the outside limit of error for all our Q values as 0.3 Mev for K and Cl and groups 1 and 4 for P. Groups 2 and 3 for P cannot very well be assessed as their analysis is uncertain.

Relative yields for different elements

To compare the yields from the different elements we made some additional experiments in which an aluminum target was bombarded under identical conditions. We found the following total yields relative to Al as standard:

Al	1	
P	0.9	
Cl	0.9	(if all due to Cl^{35} 1.20)
K	0.6.	

The experiments on Al suggested the existence of a new group of range about 19 cm which might

TABLE IV. *Values (in Mev) of nuclear energy changes in various reactions.*

$F^{19}\rightarrow Ne^{22}$	$Na^{23}\rightarrow Mg^{26}$	$Al^{27}\rightarrow Si^{30}$	$P^{31}\rightarrow S^{34}$	$Cl^{35}\rightarrow A^{38}$	$K^{39}\rightarrow Ca^{42}$
1.4	1.9	2.1	—	—	—
−0.1	−0.4	−0.2	0.0	0.1	—
−2.1	−2.1	−1.5	−1.2	—	−1.0
−3.2	−3.1	−2.8	−2.6	−2.5	−2.3
		−4.0	−4.6	−4.2	−3.6

mean a new Q value of -4.0 Mev. We wish to investigate this more thoroughly since there is a likelihood that resonance effects are prominent in the aluminum nucleus.

Discussion

We give in Table IV our values for the nuclear energy changes together with those found by May and Vaidyanathan[2] for F^{19} and Na^{23} and Duncanson and Miller[8] for Al^{27}. The possible new Q value for Al^{27} is indicated in italics. There is clearly a tendency for the same groups to appear in each element, the Q value for a particular group rising slightly in general as heavier elements are considered. The most positive Q value disappears at phosphorus and the next at potassium: this is probably because the product nuclei become relatively heavier as the atomic weight increases.

The group at about -1.2 Mev expected in the case of chlorine is absent according to our analysis of our results. In the forward curve there appears a dip at 64 cm range which would give a Q value of -1.4 Mev. We did not find any evidence of a corresponding dip in the right-angle experiments (where the yields were, however, rather low) and so prefer to regard the presence of the group as uncertain. Our experiments do show that some selection rules must operate since the yield of this group, if it is present, is abnormally low.

The average separation of the levels is approximately 1.5 Mev which is greater than the value 0.9 found in the $4n$-type elements studied by Haxel.

Masses of A^{38} and S^{34}

The Q values corresponding to the least energy in the product nuclei, that is the least negative or most positive Q's, permit the derivation of the masses of A^{38} and S^{34} from our experiments on Cl and P. Using the assumed reaction

$$\begin{gathered} Cl^{35}+He^4 \rightarrow A^{38}+H^1+Q \\ 34.9796+4.0039=A^{38}+1.0081+0.0001 \\ (\pm 0.0012)(\pm 0.0002) \qquad (\pm 0.0002) \end{gathered}$$

we find $A^{38}=37.9753\pm 0.0016$. Here we have used Bainbridge's value[9] for the mass of Cl^{35}. If we ascribe the long range group to Cl^{37} we find (again using Bainbridge's value) the mass 39.9734 ± 0.0016 for the mass of A^{40}. Aston's recent value[10] is 39.9754 which lies beyond the limits of error. We therefore feel some confidence in ascribing the groups here found to the more abundant isotope. In view of the fact that the yield is small for great energy release it is unlikely that any proton group due to Cl^{37} would show among the greater yields of the proton groups from Cl^{35}.

The reaction investigated by Haxel[1]

$$Si^{28}+He^4 \rightarrow P^{31}+H^1(+Q)$$

and that here studied

$$P^{31}+He^4 \rightarrow S^{34}+H^1(+Q)$$

enable first the mass of P^{31} to be computed from Aston's value for Si^{28} and from this the mass of S^{34}. Putting in the experimental values we find $P^{31}=30.9844\pm 0.0015$ and $S^{34}=33.9802\pm 0.0015$, the limits of error being somewhat roughly estimated.

The masses of S^{34} and A^{38} are of some interest in view of the experiments of Libby, Peterson and Latimer[11] who find an alpha-ray emitter of gaseous form resulting from the decay of radiochlorine. They suggest that this emitter is A^{38} which passes into S^{34} after losing an alpha-particle. The difference between the masses which we find for these isotopes is insufficient to permit the emission of an alpha-particle so that it may be necessary to suppose the existence of two forms of A^{38}.

We wish to express our thanks to Professor A. F. Kovarik for his interest in the work and to Professor L. W. McKeehan for help in writing the manuscript.

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