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Radioactive Isotopes of Scandium from Calcium and Potassium by Alpha-Particle Bombardment

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A study has been made of the radioactive isotopes of scandium formed from calcium and potassium by bombardment with alpha-particles. Sc^{43} has been separated chemically from calcium, its half-life being 4.0 ± 0.1 hours. No evidence has been obtained of Sc^{46} or Sc^{47}. Two radioactive isotopes of scandium, *viz.* Sc^{42} and Sc^{44}, have been isolated from potassium, these having half-lives of 4.1 ± 0.1 hours and 52 ± 3 hours, respectively. Cloud chamber studies of the positrons emitted by Sc^{43} and Sc^{42} show that the upper limits of the two spectra are 1.3 (8) and 1.6 (3) Mev, respectively.

INTRODUCTION

THE radioactivity induced in calcium by alpha-particle bombardment was first studied by Frisch[1] who observed the formation of Sc^{43} in the reaction

$$Ca^{40}+He^4 \rightarrow Sc^{43}+H^1; \quad Sc^{43} \rightarrow Ca^{43}+e^+.$$

The emitted protons have been studied by Pollard and Brasefield.[2]

A radioactivity induced in potassium by activation with alpha-particles was detected by Zyw,[3] who reported that it decayed to half-value in three hours. Zyw concluded that the radioactive isotope was Sc^{42} or Sc^{44} formed in one or other of the reactions

$$K^{39,\,41}+He^4 \rightarrow Sc^{42,\,44}+n^1; \quad Sc^{42,\,44} \rightarrow Ca^{42,\,44}+e^+.$$

No second period was detected.

In a preliminary account of some results obtained by activating potassium with 11 Mev alpha-particles it was suggested[4] that both Sc^{42} and Sc^{44} are formed and, moreover, it was concluded that Sc^{42} and Sc^{43} have very similar half-lives. This observation was somewhat unexpected so that a careful investigation of the alpha-particle induced radioactivities of calcium and potassium was undertaken. It is the purpose of the present paper to report the more extended results obtained.

APPARATUS

The alpha-particles of 11 Mev energy were produced by accelerating doubly charged helium ions in the Berkeley cyclotron under conditions already described.[4] The alpha-particle and deuteron peaks were well resolved so that there was no deuteron contamination of the alpha-particle beam. This was verified by bombarding paper with the alpha-particles. No activity was observed though the characteristic period of N^{13} can be readily detected when there is any deuteron contamination. The bombarding currents used varied from 0.1 to 0.2 microampere.

The decay of the radioactive samples was measured by means of a Lauritsen quartz fiber electroscope.

CHEMICAL SEPARATION OF THE ACTIVE SCANDIUM

Calcium was activated in the form of metal and potassium as potassium fluoride and chloride. After irradiation the calcium was dissolved in dilute HCl, the potassium salts being dissolved in water. Inactive scandium chloride was then added followed by ammonium hydroxide. The precipitated scandium hydroxide was filtered off, washed and thoroughly dried.

DECAY OF THE SCANDIUM PRECIPITATE FROM CALCIUM

In a previous paper[4] the decay curve of the radioactivity induced in calcium by alpha-particle bombardment was shown. This decay curve corresponded to a single period of 4.0 hours,

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* Commonwealth Fund Fellow.
[1] Frisch, Nature **136**, 220 (1935).
[2] Pollard and Brasefield, Phys. Rev. **51**, 8 (1937).
[3] Zyw, Nature **134**, 64 (1934).
[4] Walke, Phys. Rev. **51**, 439 (1937) (note added in proof).

though there was evidence of a tail which suggested that there might be some deuteron contamination. In the present experiments, using a pure alpha-particle beam, the decay of the chemically separated scandium was observed. The decay curve shown in Fig. 1 is strictly linear for 50 hours, the half-life being 4.0 hours. A slight departure from linearity occurs when the corrected intensity is close to the background of the electroscope but, as can be seen, the initial intensity of any longer period must be less than 10^{-4} of that of the 4-hour period. It is thus clear that the period of 4.0±0.1 hours must be associated with Sc^{43} formed thus

$$Ca^{40}+He^{4}\rightarrow Sc^{43}+H^{1};\quad Sc^{43}\rightarrow Ca^{43}+e^{+}.$$

There is no definite evidence for any longer periods and, moreover, the enlarged portion of the early decay curve of calcium metal (Fig. 1) suggests that there are no short periods present (unless the half-lives are of the order 1–2 minutes or less).

These facts are of interest in connection with other reactions which might be expected to occur. As previously observed transmutations using alpha-particles are such that protons or neutrons are ejected from the resulting compound nuclei, one would anticipate that the following reactions might take place

$$Ca^{42,\,43,\,44}+He^{4}\rightarrow Sc^{45,\,46,\,47}+H^{1},$$
$$Ca^{40,\,42,\,43,\,44}+He^{4}\rightarrow Ti^{43,\,45,\,46,\,47}+n^{1}.$$

Of the product nuclei Sc^{45}, Ti^{46} and Ti^{47} are stable, but one would expect that radioactivity due to the scandium isotopes Sc^{46} and Sc^{47} might be detected. However, unpublished experiments on the activation of scandium with deuterons have shown that the half-life of Sc^{46} is of the order 80 days and this fact together with the low abundance of Ca^{43} (0.17 percent) explain why no evidence of the reaction

$$Ca^{43}+He^{4}\rightarrow Sc^{46}+H^{1}$$

has been obtained. Nothing as yet is known of the properties of Sc^{47}, and assuming that it might be formed in these experiments, we may conclude that its half-life is either very short or very long. The same would appear to be true of Ti^{43}, unless the reaction in which it is formed is an improbable one, as it would then not be readily observable in the presence of Sc^{43}.

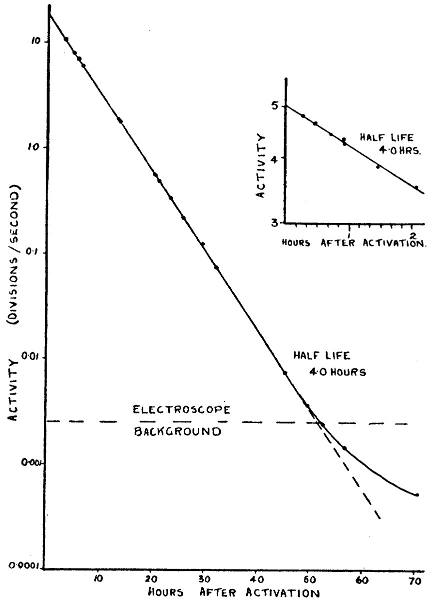

FIG. 1. Decay of the activity of a scandium precipitate from calcium metal after activation with 11 Mev alpha-particles. The inset figure shows on an enlarged time scale the early decay of the activity of calcium metal.

DECAY OF THE SCANDIUM PRECIPITATE FROM POTASSIUM

The usual reactions in which a proton is ejected from a nucleus after capture of an alpha-particle suggest that the stable nuclei Ca^{42} and Ca^{44} will be formed in the reactions

$$K^{39,\,41}+He^{4}\rightarrow Ca^{42,\,44}+H^{1}.$$

On the other hand the ejection of a neutron will lead to the formation of the radioactive scandium isotopes Sc^{42} and Sc^{44} which then decay by emitting positrons to give rise to the stable calcium isotopes with the same mass numbers.

In the present experiments samples of KF and KCl were bombarded with alpha-particles, the decay of the chemically separated radioactive scandium being measured. In the case of KCl only two periods were observed having half-lives of 4.1±0.1 hours and 52±3 hours, respectively. With KF, however, a trace of an additional very long period was detected, this being due to the occlusion of small amounts of Na^{22} in the scan-

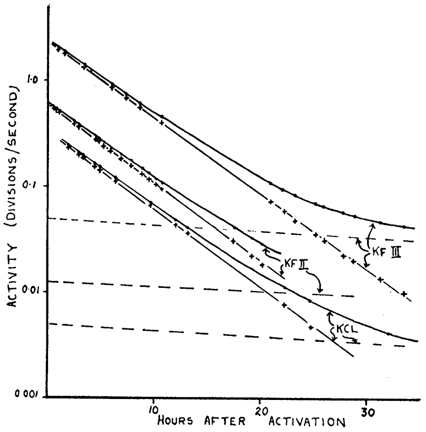

FIG. 2. Early decay of the activity of several scandium precipitates from various potassium salts after activation with 11 Mev alpha-particles. The points · represent total activity. Those marked + have been corrected for the activity due to the 52-hour period which is shown by the lines denoted thus - - - -.

dium hydroxide (no carrier sodium was added). The Na^{22} is formed in the reaction[5]

$$F^{19}+He^4 \rightarrow Na^{22}+n^1.$$

In Fig. 2 are shown the early portions of the decay curves of several such samples, and in Fig. 3 the decay curves of the longer period activities.

Since a radioactive isotope of scandium with half-life 52±2 hours has been separated from calcium after deuteron activation,[4] it is apparent that this period must be associated with Sc^{44} as this is the only radioactive scandium isotope which can be formed by reactions of already well-known types both from calcium+deuterons and potassium+alpha-particles. Thus we have

$$Ca^{43}+H^2 \rightarrow Sc^{44}+n^1, \quad K^{41}+He^4 \rightarrow Sc^{44}+n^1.$$

The 4.1 hour period would then be associated with Sc^{42}.

(These experiments thus enable the mass numbers of the three radioactive scandium isotopes formed by activating calcium with deuterons[4] to be determined. The 4.0 hour period has already been shown to be due to Sc^{43}. The 52±2 hour period must now be associated with Sc^{44} and the 53±3 minute period with Sc^{41} and not *vice versa* as tentatively suggested in the previous paper.)

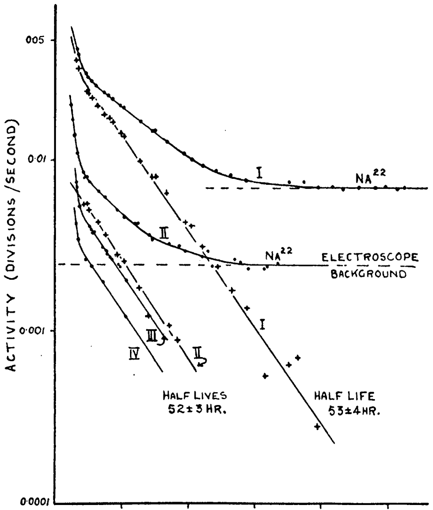

FIG. 3. Long period activities of several precipitates from various potassium salts. The points marked · represent total activity. Those denoted by + have been corrected for the activity due to Na^{22}. I and II are from KF. III and IV from KCl.

The thick target saturation yields of these radioactive bodies corrected for the finite period of bombardment are

4.1 hour period
10^7 alpha-particles per active atom,
52 hour period
3.5×10^9 alpha-particles per active atom.

The greater probability of the formation of the isotope with the 4.1 hour period suggests too that this period should be associated with the reaction involving the more abundant isotope *viz.* K^{39}. Hence for equal abundances of both isotopes we have

Sc^{42}	1×10^7 alpha-particles per active atom,
Sc^{44}	0.6×10^7 alpha-particles per active atom.

The half-life of Sc^{42} is then very little different from that of Sc^{43} (though all the measurements made suggest that it is longer by approximately 10 minutes). In consequence it was at first suspected that the effect was due to calcium contamination (since the calcium reaction is so much more probable than that involving potassium). However, all the samples used were of reagent quality, the KF being stated to be free from all impurities except a trace of chloride, and

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[5] Frisch, Nature **136**, 220 (1935).

the KCl containing less than 0.005 percent of Ca, Mg and NH_4, whereas it would be necessary to assume a minimum calcium content of approximately 5 percent to account for the observed intensity. Thus the activity obtained is 1000 times as great as can be accounted for by the known amount of calcium impurity.

It is then necessary, if the 4.1 hour period is due to Sc^{43}, that it should be formed from one of the known isotopes of potassium. The following reactions might be possible

$$K^{39}+He^4 \rightarrow Sc^{43}+\gamma, \qquad \text{I}$$

$$K^{40}+He^4 \rightarrow Sc^{43}+n^1, \qquad \text{II}$$

$$K^{41}+He^4 \rightarrow Sc^{43}+2n^1. \qquad \text{III}$$

Reaction I would require the radiative capture of an alpha-particle with 11 Mev energy, a form of reaction which has not yet been detected and which would appear to be highly improbable. Reaction II can be excluded since K^{40} is present in an abundance of only one part in 8500. On the other hand the third reaction might be possible according to the nuclear model proposed by Bohr.

However, absorption measurements suggested that the positrons emitted by the isotope with the 4.1 hour period are more penetrating than those emitted by Sc^{43}, so that it was thought that a definite decision concerning the mass number of the isotope formed in the potassium reaction would be reached by comparing the energy distributions of the positrons emitted by the two samples.

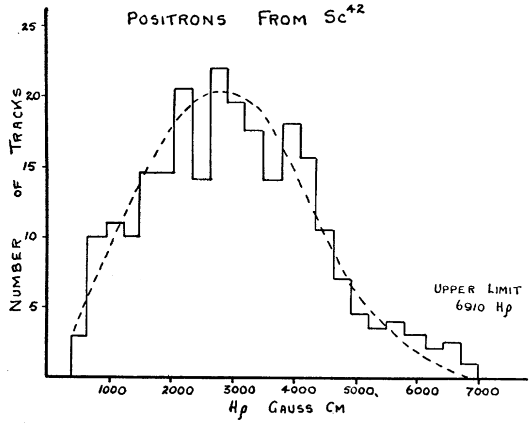

FIG. 4. Momentum distribution of positrons from Sc^{42}. Magnetic field 288 gauss. Number of tracks measured 480. Upper limit by inspection 6910 $H\rho$ 1.6 (3) Mev.

ENERGY DISTRIBUTIONS

The energy distributions were obtained by photographing the tracks produced by the emitted particles in traversing a large hydrogen filled expansion chamber 12″ in diameter. The chamber had been designed so that the magnetic field in which the particles were deflected was very uniform throughout the whole volume of the chamber.[6] The positrons from Sc^{43} were photographed in a field of 328 gauss, the distribution being based on measurements on 258 tracks. Those from Sc^{42} were bent in a magnetic field of 288 gauss, the distribution being based on 480 tracks.

The scandium precipitates were of approximately the same size and mass and were supported on small pieces of wood. The positrons entered the cloud chamber through a thin mica window 0.0006″ in thickness, $\frac{3}{4}$″ in length and $\frac{3}{16}$″ in width. No collimating slits were used.

The energies of the particles were obtained by the method adopted by Kurie, Richardson and Paxton,[7] the film being replaced in the camera, the radius of curvature ρ of the reprojected images of the tracks being measured. In this way a distribution of particles as a function of ρ (and thus of $H\rho$ since H was known) was obtained. From the maximum value of $H\rho$ obtained by inspection of the distribution curve the energy of the end point of the β-ray spectrum was calculated.

As a result of these experiments it was found

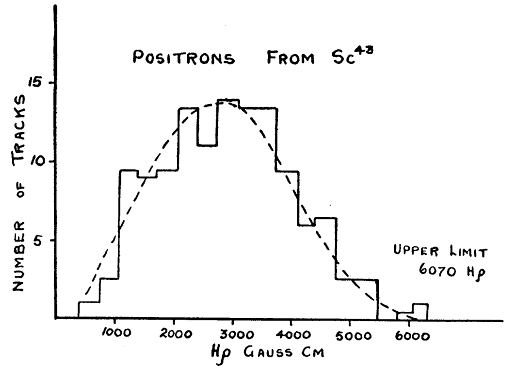

FIG. 5. Momentum distribution of positrons from Sc^{43}. Magnetic field 328 gauss. Number of tracks measured 258. Upper limit by inspection 6070 $H\rho$ 1.3 (8) Mev.

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[6] Details of this chamber have not yet been published.

[7] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).

that the energy of the positrons emitted by the isotope with the half-life 4.1 hours is greater by approximately 250,000 ev than that of the positrons from Sc^{43}. It is thus clear that the 4.1 hour period must be associated with Sc^{42} and not with Sc^{43} formed by one of the reactions I, II and III.

The energy distributions of the positrons from Sc^{42} and Sc^{43} are shown in Figs. 4 and 5. The upper limits of the two spectra are 1.6 (3) and 1.3 (8) Mev, respectively. The end point of Sc^{43} agrees well with the value 1.4 Mev deduced from the absorption measurements in aluminum previously reported.[4]

The upper limit of Sc^{43} is, however, considerably higher than that obtained by Jacobsen[8] using an air-filled expansion chamber.

In Fig. 6 are shown sample photographs of the positrons emitted by the two isotopes, and in Fig. 7 is shown a comparison between the decay of the activities of the scandium precipitates from calcium and potassium after activation under similar conditions. In spite of the similarity between the half-lives of Sc^{43} and Sc^{42} it can be seen that the decay curves are quite different.

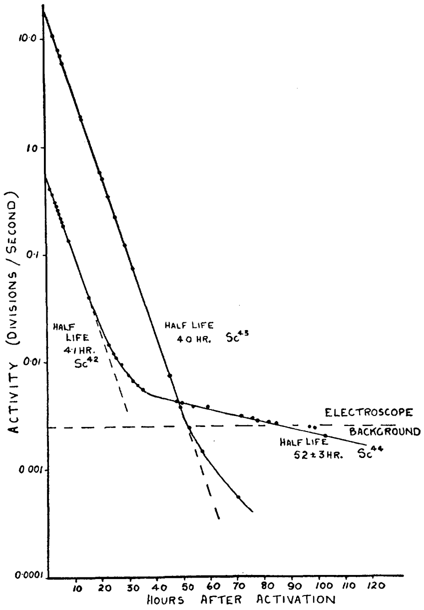

FIG. 7. Comparison between decay curves of scandium precipitates from potassium and calcium after activation with alpha-particles.

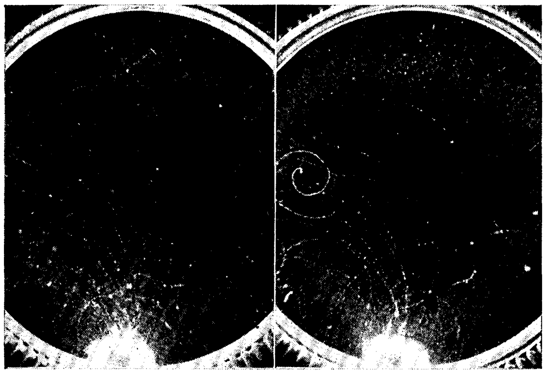

FIG. 6. Sample photographs of positrons from Sc^{42} (*A*) and Sc^{43} (*B*).

SUMMARY

In summarizing we may state that the evidence now presented, together with that obtained in the previous investigation,[4] indicates that four positron radioactive isotopes of scandium have been detected, namely Sc^{41}, Sc^{42}, Sc^{43} and Sc^{44} these being formed in the reactions:—

Sc^{41} (half-life 53±3 min. energy 1.8×10^{6} ev)

$$\mathrm{Ca}^{40}+\mathrm{H}^{2}\rightarrow\mathrm{Sc}^{41}+n^{1}.$$

Sc^{42} (half-life 4.1±0.1 hr. energy 1.6 (3)$\times10^{6}$ ev)

$$\mathrm{K}^{39}+\mathrm{He}^{4}\rightarrow\mathrm{Sc}^{42}+n^{1},$$

Sc^{43} (half-life 4.0±0.1 hr. energy 1.3 (8)$\times10^{6}$ ev)

$$\mathrm{Ca}^{42}+\mathrm{H}^{2}\rightarrow\mathrm{Sc}^{43}+n^{1},$$
$$\mathrm{Ca}^{40}+\mathrm{He}^{4}\rightarrow\mathrm{Sc}^{43}+\mathrm{H}^{1}.$$

Sc^{44} (half-life 52±2 hr.)

$$\mathrm{Ca}^{43}+\mathrm{H}^{2}\rightarrow\mathrm{Sc}^{44}+n^{1},$$
$$\mathrm{K}^{41}+\mathrm{He}^{4}\rightarrow\mathrm{Sc}^{44}+n^{1}.$$

ACKNOWLEDGMENTS

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[8] Jacobsen, Nature **139**, 879 (1937).

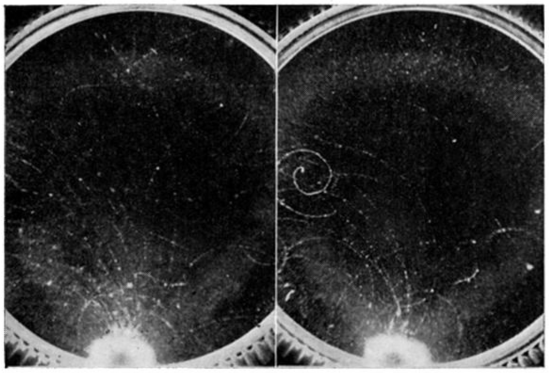

FIG. 6. Sample photographs of positrons from Sc^{42} (*A*) and Sc^{43} (*B*).