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The Radioactive Isotopes of Scandium and Their Properties

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The results of further studies of the radioactive isotopes of scandium can be summarized as follows. (a) The activity of half-life 53±3 min., now measured more accurately as 57±2 min., produced by bombarding calcium with deuterons, which emits β-particles of energy 1.8±0.1 Mev previously assigned to Sc^{41} is shown to be probably due to Sc^{49}. Sc^{49} can be produced by the decay of Ca^{49} and from titanium by bombardment with fast neutrons. It emits no γ-radiation. (b) Sc^{42}, half-life 13.4±0.3 days, emits positrons of maximum energy 1.4±0.1 Mev. (c) The continuous spectrum of Sc^{43} is complex, there being two groups of positrons and γ-radiation of energy 1.0±0.1 Mev. (d) The 52-hour isomer of Sc^{44} is the metastable form decaying by emitting highly internally converted γ-radiation of energy 250 kev. (e) There is only one form of Sc^{46} of half-life 85±1 days, emitting β-rays of energy 0.26±0.01 Mev (>95 percent) and 1.5±0.1 Mev (<5 percent) and γ-radiation of energy 1.25±0.1 Mev. (f) Sc^{47}, half-life 63±2 hours, emits β-rays of energy 1.1±0.1 Mev. (g) Sc^{48}, half-life 44±1 hours, emits β-rays of energy 0.5±0.1 Mev (~90 percent) and 1.4±0.1 Mev (~10 percent) and γ-radiation of energy 0.9±0.1 Mev. The following previously unreported reactions have been established:

$Ca^{48}+H^2 \rightarrow Sc^{49}+n^1$ $\quad Sc^{49}\rightarrow Ti^{49}+e^-$
$Ti^{49}+n^1 \rightarrow Sc^{49}+H^1$
$K^{39}+He^4\rightarrow Sc^{42}+n^1$ $\quad Sc^{42}\rightarrow Ca^{42}+e^+$
$Ca^{43}+He^4\rightarrow Sc^{46}+H^1$ $\quad Sc^{46}\rightarrow Ti^{46}+e^-$
$Ca^{44}+He^4\rightarrow Sc^{47}+H^1$ $\quad Sc^{47}\rightarrow Ti^{47}+e^-$

A. INTRODUCTION

A NUMBER of investigations of the radioactive isotopes of scandium have previously been made, but there has been some disagreement as to the half-lives of various isotopes, and a number of differences of interpretation of results have been reported. In consequence, it seemed worth while to repeat several of the earlier experiments, using materials of the highest possible purity so as to be the better able to distinguish between true scandium activities and those due to impurities. As, moreover, the properties of some of the reported isotopes were not known, it was hoped to investigate them, since it was clear that the high currents available from the Berkeley cyclotrons would allow the production of strong sources of the various active bodies. The present paper is an account of the new results which have been obtained.

For convenience of reference, the stable isotopes referred to in the text are given in Table I.

B. APPARATUS

In these experiments slow and fast neutron investigations were carried out using the 37-inch cyclotron as a source of neutrons. The beryllium target was normally bombarded with 50 microamperes of 8-Mev deuterons, irradiations lasting from one to twenty hours. In consequence, very strong samples were available, even of the long period activities.

In the production of radioactive scandium

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isotopes from potassium and calcium by α-particles of high energy, the 60-inch cyclotron in the Crocker Radiation Laboratory was used. During these experiments, currents of 0.6 microampere of 32-Mev α-particles were available, and samples were bombarded in general for 5 microampere hours. There was no deuteron contamination of the α-particle beam.

Decay and absorption measurements were made using a standard Lauritsen quartz fiber electroscope. β-ray energies have been obtained by making absorption measurements in aluminum. These energies have been corrected for absorption by the electroscope window and have been estimated by applying Feather's range-energy relation. The energies of the γ-rays were obtained by measuring their absorption in lead, the geometrical arrangement being calibrated by means of known γ-rays.

C. Sc^{41} AND Sc^{49}

In a previous investigation of the induced radioactivity of calcium[1] it was established that three scandium isotopes are formed when calcium is bombarded with high speed deuterons. The assignments, half-lives and energies of emitted particles were as follows: Sc^{41} 53 ± 3 minutes, $E=1.8\pm0.1$ Mev, Sc^{43} 4.0 hours, $E=1.4\pm0.1$ Mev, Sc^{44} 4.1 hours and 52 ± 2 hours, $E=1.6\pm0.1$ Mev.

The assignments were then unique, for no isotope of calcium heavier than Ca^{44} was known; and as the 53-minute period was not observed in any other reactions, it was natural to assume that it must be due to Sc^{41} formed from the very abundant Ca^{40}. Thus,

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

It was always observed that a considerable number of negative electrons were emitted from the body with half-life 53 minutes, and these were at first thought to be Compton electrons. More careful experiments have shown, however, that it is probable that all the particles emitted by the 53-minute body are negative electrons, which indicates that this isotope is in fact Sc^{49} and not Sc^{41}. Further measurements on a number of samples have shown, moreover, that the half-life is longer than previously given, the new value being 57 ± 2 minutes. By absorption experiments, it has been established that this body emits no γ-radiation which is further evidence against its being Sc^{41}, for Sc^{41} being a positron emitter would be accompanied by annihilation radiation.

Professor Wigner pointed out in a stimulating discussion of the properties of Sc^{41} that, on the basis of the current assumption of equal interactions between all pairs of elementary particles, one can estimate the half-life and maximum energy of the positron spectrum of this isotope, as has been done for the analogous nuclei Ne^{19}, Mg^{23}, etc.[2] The isobars Sc^{41}, Ca^{41} are of the type $(n-p)=\pm1$, and thus the mass difference between them may be calculated from the Coulomb forces alone. On this assumption the half-life of Sc^{41} should be not longer than some tenths of a second, and the upper limit of the positron spectrum should be of the order 5.0 Mev. The observed half-life 57 ± 2 minutes is thus far too long, and the emitted particles ($E=1.8$ Mev) have far too low an energy for the nucleus to be Sc^{41}.

In this connection it is significant that, if Sc^{41} were the 57-minute body, Ca^{41} should be produced by its decay. Recent work to be reported later[3] shows that one form of Ca^{41} has a half-life of 8.5 days so that it should be possible to observe this period in the scandium precipitate from calcium+deuterons, and further it should be possible to extract active calcium from the scandium precipitate after the decay of the 57-minute period. All such experiments have yielded negative results, which is consistent with the assignment of the 57-minute activity to Sc^{49}.

In addition, if the active body is Sc^{49}, it should

TABLE I. *Stable isotopes of elements near scandium.*

Element	Atomic Number	Mass Numbers and Abundance					
Potassium	19	39 100	40 0.012	41 7.15			
Calcium	20	40 100	42 0.66	43 0.15	44 2.13	46 0.0034	48 0.191
Scandium	21	45 100					
Titanium	22	46 10.82	47 10.56	48 100	49 7.50	50 7.27	
Vanadium	23	51 100					

[1] H. Walke, Phys. Rev. **51**, 439 (1937).

[2] White, Delsasso, Fox and Creutz, Phys. Rev. **56**, 512 (1939).

[3] Walke, Thompson and Holt, this issue, p. 177.

be possible to produce it by the reaction

$$Ca^{48}+n^1\rightarrow Ca^{49}; \qquad Ca^{49}\rightarrow Sc^{49}+e^-$$

and so to separate a radioactive isotope of scandium from calcium which has been activated with slow neutrons.

Such experiments have been performed using spectroscopically pure calcium oxide (Hilger 11814), calcium metal and calcium hydroxide, and in all cases an activity has been separated chemically with scandium. The scandium precipitates were redissolved and reprecipitated in the presence of inactive calcium, potassium and sodium many times; yet the precipitates remained active and decayed with a period of 57 ± 2 minutes. The active scandium is produced by the decay of Ca^{49} as will be discussed in detail in a further paper.[4]

Additional confirmation of this assignment is given by the fact that a radioactivity of half-life 57 ± 2 minutes has been obtained by bombarding titanium with fast neutrons. It is probably Sc^{49} formed in the reaction

$$Ti^{49}+n^1\rightarrow Sc^{49}+H^1.$$

It is likely that this is the active scandium isotope separated by Pool, Cork and Thornton[4] from titanium which had been bombarded with fast neutrons, but to which they assigned a half-life of 1.7 hours.

We may, therefore, conclude on the basis of the above discussion that Sc^{41} has not yet been observed, but is probably a positron emitter of half-life of the order of some tenths of a second and that the 57 ± 2-minute period previously assigned by the author to Sc^{41} is in fact to be identified with Sc^{49} decaying by electron emission to form the stable Ti^{49}.

D. Sc^{42}

Of the two radioactive scandium isotopes which should be produced by bombarding potassium with alpha-particles of high energy, only one, Sc^{44}, has so far been identified. The failure to observe Sc^{42} combined with the high abundance of K^{39} suggested that this body might have a relatively long half-life. This was indicated by previous results of the author[5] who observed such a long period activity in all active scandium samples separated from potassium which had been bombarded with α-particles. Since the early work was carried out using KF it was then supposed that the long period activity might be due to Na^{22} from the action of α-particles on the fluorine.

High purity potassium chloride free of fluoride was therefore bombarded with 5 microampere hours of α-particles of 32-Mev energy and from it a strongly active scandium sample was chemically separated. Following the decay of the 52-hour isomer of Sc^{44}, a new radioactive isotope of scandium was obtained. Its half-life is 13.5 ± 0.3 days, the decay having been measured for more than seven half-lives. The energy of the emitted positrons is 1.4 ± 0.1 Mev, this value being obtained from absorption measurements in aluminum. This body is most probably to be associated with Sc^{42}, produced in the reaction

$$K^{39}+He^4\rightarrow Sc^{42}+n^1; \qquad Sc^{42}\rightarrow Ca^{42}+e^+.$$

No other activity was observed.

E. The Isomers of Sc^{44}

It has been established by several independent nuclear reactions that Sc^{44} can exist in two isomeric forms[6] with half-lives of 4.1 ± 0.1 and 52 ± 2 hours, respectively. Up to the present, however, it has not been established whether these isomers are genetically related nor has the metastable form been identified.

In this section will be discussed evidence whereby this has been ascertained.

The evidence has been obtained by making careful absorption measurements over the whole energy region from 0–2 Mev for both isomers. Very strong samples were produced by bombarding high purity potassium chloride with 32-Mev α-particles for ~5 microampere hours. (The bombardment was carried out during two days.) A very thin precipitate of scandium hydroxide was separated and absorption measurements were made immediately after separation (ratio 4-hour period to 52-hour period 10 : 1) and 2 days after separation (ratio 52-hour period to 4-hour period 100 : 1). It was found that the

[4] Pool, Cork and Thornton, Phys. Rev. **52**, 239 (1937).
[5] H. Walke, Phys. Rev. **52**, 400 (1937).
[6] Burcham, Goldhaber and Hill, Nature **141**, 510 (1938); J. M. Cork and R. L. Thornton, Phys. Rev. **53**, 866 (1938).

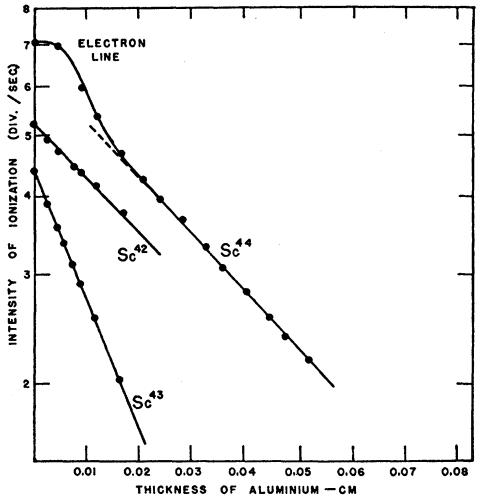

FIG. 1. Absorption in aluminum of low energy radiations from Sc^{42}, Sc^{43} and Sc^{44}.

main part of the absorption curves and the endpoints were identical, which at once suggested that the isomers were genetically related and that the positron spectrum from both was due to the same active isotope. The values for the maximum energy were 1.50 ± 0.05 in reasonable agreement with the previous value (obtained from cloud-chamber studies) of 1.6 ± 0.1 Mev.

A careful examination of the low energy region, however, disclosed that a line of electrons of energy 250 kev was being emitted by the 52-hour activity. This was observed superposed on the low energy region of the spectrum as shown in Fig. 1. The hump due to the conversion electrons is not caused by a poor geometrical arrangement for the absorption of the low energy radiations from Sc^{43} and Sc^{42} (isotopes whose upper limits are close to that of Sc^{44}) show under identical conditions no such effect.[7]

By making absorption measurements at different times, it was established that the conversion electrons are associated with the 52-hour period.

These results suggest that the 52-hour period of Sc^{44} is due to a metastable state of Sc^{44} 250 kev above the ground state which decays by γ-transitions to the ground state from which the positrons (due to the 4.1-hour transformation product which is in equilibrium with its parent) are emitted. The γ-ray due to the decay of the metastable level is highly internally converted and thus gives rise to the conversion electrons. These observations have been confirmed by Mr. A. C. Helmholz, who has been kind enough to photograph the electron line with a magnetic spectrograph. The value thus obtained for the energy of the line is 255 kev.

It has been found in addition that the 52-hour isomer of Sc^{44} emits a weak intensity of low energy γ-radiation. Absorption measurements in lead yield a value for the energy close to 250 kv, which indicates that the γ-radiation due to the transition between the isomeric state and the ground state of Sc^{44} is not totally internally converted.[8]

Dr. J. W. Kennedy of the Department of Chemistry has attempted to separate these isomers chemically without success. Scandium acetyl acetonate was synthesized from a sample of Sc^{44} and was dissolved in chloroform. After standing for some hours, the solution was shaken with water and the two solutions separated. Inactive scandium was then added to the aqueous fractions and was precipitated as oxalate. It was found to be inactive. One cannot conclude from this experiment, however, that the chemical separation of the isomers is not possible. It is not unlikely that in the present case the ejected scandium ion recombines with the acetyl acetonate very rapidly so that the concentration of free ions is too small to allow the formation of an appreciable activity in the aqueous extract.

DuBridge and his co-workers[9] have produced the isomers of Sc^{44} by bombarding calcium with high speed protons, the reaction being

$$Ca^{44}+H^1\rightarrow Sc^{44}+n^1.$$

The author has repeated these experiments and has obtained confirmatory results.

F. Sc^{43}

The comparison between the absorption curves of Sc^{42}, Sc^{43} * and Sc^{44} shown in Fig. 1 indicates

[7] In fact, the absorption curve for Sc^{42} was obtained from the same scandium precipitate which had been used for studying the isomers after the 52-hour activity had completely died away.

[8] No soft γ-radiation was observed with a sample of Sc^{43} under the same conditions which is evidence against the observed effect in Sc^{44} being due to the geometrical arrangement.

[9] Private communication.

* The source of Sc^{43} used was obtained by bombarding calcium metal with 32-Mev α-particles.

that, whereas the spectra of Sc^{42} and Sc^{44} are similar and probably simple, there are far more low energy positrons emitted by Sc^{43}, though the upper limit of its spectrum 1.4 ± 0.1 Mev is close to that of Sc^{42} and Sc^{44} (1.4 ± 0.1 Mev and 1.6 ± 0.1 Mev, respectively). This suggested that the β-spectrum of Sc^{43} might be complex and a search was accordingly made for a γ-ray of energy greater than that of annihilation radiation (0.5 Mev). Evidence was obtained for a strong γ-radiation of energy 1.0 ± 0.1 Mev which points to the existence of two components in the spectrum of Sc^{43} with endpoints at ~0.4 Mev and 1.4 Mev, the γ-ray being due to transitions between an excited state of the product nucleus Ca^{43} and the ground state.

These absorption measurements are further evidence that the two 4-hour periods of Sc^{43} and Sc^{44}, respectively are actually due to different radioactive isotopes.

G. Isomers and Properties of Sc^{46}

Several investigations of the radioactivities induced in scandium by slow neutrons and fast deuterons have been made,[10] and it has been suggested that Sc^{46} nuclei may exist in three different isomeric states. Hevesy and Levi's[10] early work, for example, gave evidence for two active bodies chemically separable with scandium formed by irradiating scandium with neutrons, the half-lives being two months and greater than a year, respectively. These workers did not identify the long period activity with certainty but suggested that the half-life of two months should be associated with Sc^{46}.

In addition, Cork and Thornton[6] observed a period of 1.1 hours in scandium which had been activated with slow neutrons. They therefore ascribed this activity also to Sc^{46} and suggested that this isotope could exist in three isomeric forms with half-lives 1.1 hours, 88 days and >1 year. In this section it will be shown that only one form of Sc^{46} has been established, its half-life being 85 ± 1 days.

Recently, high purity scandium oxide has been rendered strongly radioactive with slow neutrons and a careful search has been made for an isomer of Sc^{46} of half-life ~1 hour. No evidence at all for such a body has been obtained. A very weak activity of half-life 2.5 hours was detected, but this was so much less intense than the 85-day activity that it is very probably due to a trace (0.1 percent) of dysprosium impurity.

In order to be certain that the postulated 1.1-hour activity was not due to a metastable form of Sc^{45}, scandium oxide was also strongly activated with fast neutrons. The only activities observed were the 12.5-hour period of K^{42} due to the well-known reaction

$$Sc^{45}+n^1\rightarrow K^{42}+He^4; \qquad K^{42}\rightarrow Ca^{42}+e^-$$

and that due to Sc^{46}, confirming previous results.[11]

In a recent paper Walke, Williams and Evans[12] have suggested that the long period activity of half-life greater than a year, and also ascribed to Sc^{46}, is probably due to a trace of some impurity. This suggestion was made because of the failure to observe any departure from linearity of the decay curve of a strong sample of Sc^{46} whose decay had been followed for more than 500 days. The author has continued to measure the activity of this source which has now decayed for nearly 11 half-lives, without change of half-life (85 ± 1 days), and whose activity has now almost disappeared, yet no trace of any longer period has been observed. The decay from 840–900 days is shown in Fig. 2.

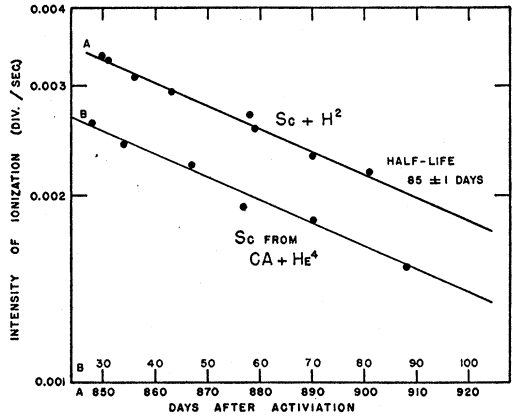

FIG. 2. Decay curves of Sc^{46}.

[10] Hevesy and Levi, K. Danske Vidensk. Selskab. **14**, 5 (1936); **15**, 11 (1938). H. Walke, Phys. Rev. **52**, 669 (1937). J. M. Cork and R. L. Thornton, reference 6.

[11] D. G. Hurst and H. Walke, Phys. Rev. **51**, 1033 (1937).

[12] Walke, Williams and Evans, Proc. Roy. Soc. **A171**, 360 (1939).

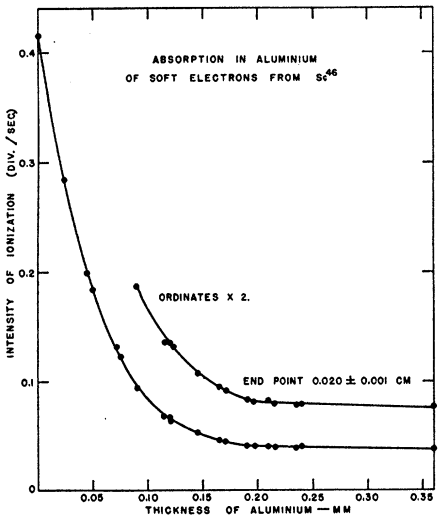

FIG. 3a. Absorption in aluminum of main group of β-rays from Sc^{46}.

This curve suggests that the previously observed activity of half-life greater than a year was probably due to contamination by one of the naturally occurring radioactive bodies (e.g., a thorium decay product).

We may thus conclude that the two activities of half-lives 1.1 hours and >1 year reported by Cork and Thornton[6] and Hevesy and Levi[10] are due to impurities and not to isomers of Sc^{46} which has the half-life 85 ± 1 days.

Walke, Williams and Evans[12] have also shown that the Sc^{46} decays by K-electron capture as well as by β-ray emission. The branching ratio could not be established very accurately on account of the uncertainty in the correction to be applied for absorption of the Ca$K\alpha$ radiation in the scandium oxide source. It was apparent, however, that probably as many nuclei decay by the one process as the other. Hence, as approximately one quantum of γ-radiation per electron was observed, it was not possible to identify the nucleus in which the γ-radiation arose. Walke, Williams and Evans[12] found that the upper energy limit of the β-rays was 0.26 Mev, the γ-radiation having an energy of approximately 1.0 Mev.

The author has repeated the absorption measurement using a thin but very strong source of Sc^{46} and has confirmed the upper limit (0.26 ± 0.1 Mev) of the main group of disintegration electrons.[13] But careful measurements have disclosed the existence of a second group of hard β-rays of maximum energy 1.5 ± 0.1 Mev, present to an extent of <5 percent of the main group. The absorption curves are shown in Figs. 3a and b. The γ-radiation appears to be homogeneous, the energy as measured with the very strong source being 1.25 ± 0.1 Mev. These results suggest that the γ-radiation arises from transitions between an excited state of Ti^{46} at 1.25 Mev and the ground state, the groups of disintegration electrons being due to β-decay to the excited and ground state, respectively. The absence of positrons and annihilation radiation indicates that the K electron is probably captured into the ground state of Ca^{46}, the energy difference between this state and the ground state of Sc^{46} being less than 1.0 Mev.

In addition to the reactions already reported,[14] Sc^{46} has recently been produced by bombarding calcium metal for 5 microampere hours with alpha-particles of energy 32 Mev. The active isotope was chemically separated as scandium fluoride and was identified by its half-life and by absorption measurements. Sc^{46} has thus been formed by the reaction

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

(The decay curve of Sc^{46} separated from calcium after activation with 32-Mev α-particles is shown in Fig. 2.)

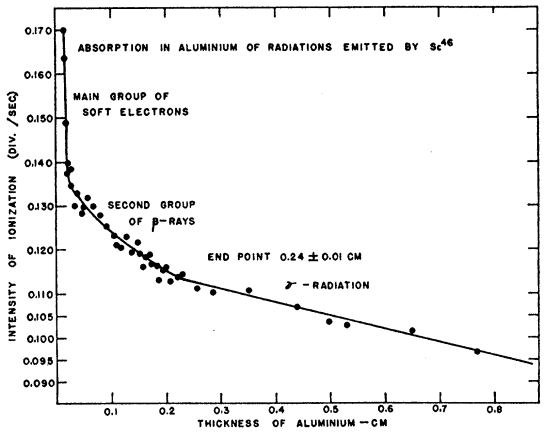

FIG. 3b. Absorption in aluminum of hard β-rays from Sc^{46}.

[13] The range energy relation for homogeneous β-rays was used to obtain this value as Feather's rule is not valid below 0.7 Mev.

[14] The reaction $Ti^{46}+n^{1}\rightarrow Sc^{46}+H^{1}$ has been confirmed in the course of the present investigation.

H. Sc^{47}

The only reactions of known type whereby Sc^{47} could be formed are as below:

$$Ca^{44}+He^4\rightarrow Sc^{47}+H^1; \quad Sc^{47}\rightarrow Ti^{47}+e^-$$
$$Ti^{47}+n^1\rightarrow Sc^{47}+H^1.$$

By assuming that the period of 28 hours observed by Pool, Cork and Thornton[4] in titanium bombarded with fast neutrons was the same as the 42-hour period previously observed by the author[15] (and identified by him as Sc^{48}) Cork and Thornton[6] associated this activity with Sc^{47}, the only basis for the assignment being the very doubtful assumption that Sc^{48} should have a short half-life. As shown previously, however, and as confirmed in the next section, the assignment and half-life reported by the author is correct. There has thus been as yet no definite evidence for Sc^{47}.

A new radioactive isotope of scandium has recently been produced by bombarding calcium metal for 5 microampere hours with alpha-particles of energy 32 Mev. This body which decays with a half-life 63 ± 2 hours emits β-particles of maximum energy 1.1 ± 0.1 Mev and has probably to be identified with Sc^{47}. It is not certain than any γ-radiation accompanies its decay, for Sc^{46} is also produced in the calcium (see next section) and the γ-radiation observed may well be due only to it. The decay curve of this body is shown in Fig. 4.

Dr. E. Segrè, to whom the author is grateful for his cooperation, was kind enough to analyze chemically a sample of the bombarded calcium metal. Scandium and titanium carriers were added, the former (which was precipitated first) being recovered as fluoride, the latter as oxide. In this way scandium free of titanium is obtained, but the titanium can be contaminated with scandium. Most of the activity was found in the scandium precipitate, and as the decay of the weak activity of the recovered titanium was similar to that of the scandium, it has been assumed that the titanium activity was due to traces of the active scandium.

The decay curve of the separated scandium was similar to that of the unseparated calcium metal, there being observed two activities with half-lives 64 ± 3 hours and 85 ± 1 days (Sc^{46}).

That the new body is not an isomer of Sc^{43}

[15] H. Walke, Phys. Rev. **52**, 777 (1937).

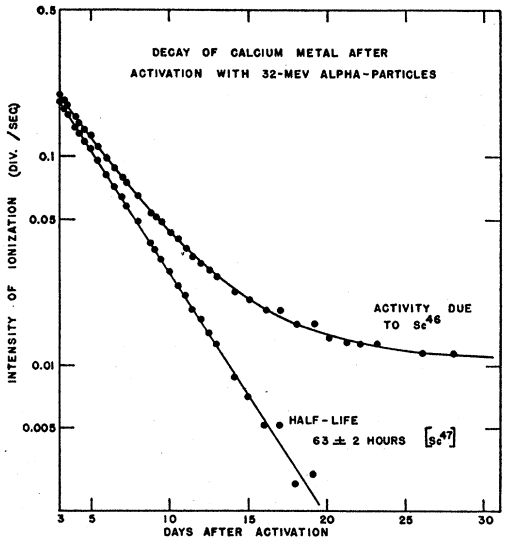

FIG. 4. Decay curve of Sc^{47}.

is suggested by the failure to observe this activity in strong sources of Sc^{43} produced in calcium with deuterons. That it is not an isomer of Sc^{42}, Sc^{44}, Sc^{46} or Sc^{48} is apparent from Sections D, F, G, I. (Moreover neither Sc^{42}, Sc^{44} nor Sc^{48} can be produced by bombarding calcium with alpha-particles by any known reaction.) Further the abundance of Ca^{46} is so small (0.0036 percent) that it is unlikely to be an isomeric form of Sc^{49} formed thus

$$Ca^{46}+He^4\rightarrow Sc^{49}+H^1.$$

Hence it must either be due to Sc^{47} or Sc^{51} produced in the reactions

$$Ca^{44}+He^4\rightarrow Sc^{47}+H^1; \quad Sc^{47}\rightarrow Ti^{47}+e^-, \quad (1)$$
$$Ca^{48}+He^4\rightarrow Sc^{51}+H^1; \quad Sc^{51}\rightarrow Ti^{51}+e^-. \quad (2)$$

If it were the latter, then, as Ti^{51} is also unstable, it should be possible to extract the 72-day activity of Ti^{51} from its parent with which it would be in equilibrium. No active titanium has been obtained which excludes this possibility. The greater abundance of Ca^{44} (Ca^{44} is more than ten times as abundant as Ca^{48}) also favors reaction (1).

We therefore tentatively assign this new radioactive isotope of scandium mass number 47.

There is some evidence that this body is also produced from titanium with fast neutrons; for, although the absorption curves from titanium show exactly the same characteristics as those of Sc^{48}, the half-life of the more active samples is somewhat longer than 44 hours. With the weaker

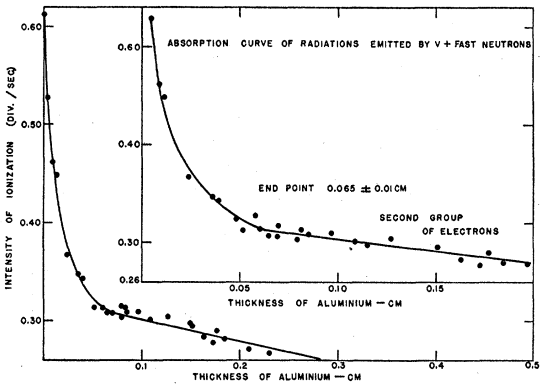

FIG. 5a. Absorption in aluminum of soft β-ray group emitted by Sc^{48}.

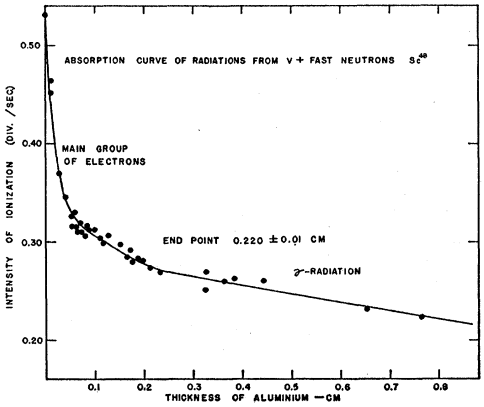

FIG. 5b. Absorption in aluminum of hard β-rays emitted by Sc^{48}.

activities previously used,[15] the half-life 42 hours was obtained. It, thus, seems likely that the present samples contain both Sc^{48} and Sc^{47} and that the mixture of the two periods 44 hours and 63 hours gives a spurious half-life intermediate between them of the order 50 hours.

I. Sc^{48}

In a previous report[15] it has been shown that a radioactive isotope, which was chemically separated with scandium, of half-life 42 ± 3 hours and ascribed to Sc^{48} can be produced by bombarding vanadium and titanium metal with fast neutrons, the reactions being

$$V^{51}+n^1\rightarrow Sc^{48}+He^4; \qquad Sc^{48}\rightarrow Ti^{48}+e^-$$
$$Ti^{48}+n^1\rightarrow Sc^{48}+H^1.$$

However no estimate of the energy of the emitted radiations could be made at that time, for the activities were not sufficiently strong. In the present experiments very active samples have been produced and the previous results confirmed. The properties of the active body have also been studied in some detail.

The half-life of Sc^{48} has been more accurately measured and is 44 ± 1 hours, the decay of the activity having been followed for more than nine half-lives. In addition absorption curves of the radiations emitted have been obtained using sources of Sc^{48} produced both from titanium and vanadium. These curves are quite identical and are further evidence for the correctness of the previous assignment. The active body emits β-particles and γ-rays, the former consisting of two groups of energy 0.5 ± 0.1 (90 percent)[16] and 1.4 ± 0.1 Mev ($\sim$10 percent), respectively. The γ-ray energy has also been measured, this being 0.9 ± 0.1 Mev. The absorption curves of the β-rays are shown in Figs. 5a and b.

As the γ-ray energy is nearly equal to the energy difference between the two β-ray groups, it appears likely that an excited state of Ti^{48} exists at about 0.9 Mev above the ground state, the two groups of disintegration electrons being due to β-decay of Sc^{48} to the excited state and ground state of Ti^{48}, respectively.

In this connection, it is significant that Pollard[17] has observed excited states of Ti^{48} at 1.1 ± 0.1 Mev and 2.3 ± 0.1 Mev in the reactions

$$Sc^{45}+He^4\rightarrow Ti^{48}+H^1$$

and that Richardson[18] has reported the emission of strong γ-radiation of energy 1.0 ± 0.1 Mev by V^{48}, his results suggesting that four quanta of 1.0-Mev radiation are emitted per positron. These observations are consistent if we suppose that the level of Ti^{48} at 1.0 Mev has been excited in all three reactions; namely,

$$Sc^{48}\rightarrow Ti^{48}+e^-$$
$$Sc^{45}+He^4\rightarrow Ti^{48}+H^1$$
$$V^{48}\rightarrow Ti^{48}+e^+.$$

The results of Pollard[17] show further that a second level of Ti^{48} occurs at about 2.0 Mev and the existence of such a state is necessary to explain the anomalously high intensity of 1.0-Mev radiation observed by Richardson.[18] In fact, Richardson's results require the existence of further levels at 3 and perhaps 4 Mev unless some of the γ-radiation observed arises in some other process. Some of the γ-radiation in this

[16] The range energy relation for homogeneous β-rays was used to obtain this value as Feather's rule is not applicable below 0.7 Mev.

[17] E. Pollard, Phys. Rev. **54**, 411 (1938).

[18] J. R. Richardson, Phys. Rev. **53**, 124 (1938).

case may arise as a result of K-electron capture, for the measurements of Walke, Williams and Evans[12] show that approximately one-third of the V^{48} nuclei decay by this process.

It may be pointed out, too, that the isomer of Ti^{51} of half-life 72 days is produced as well as V^{48} when titanium is bombarded with deuterons.[7] As Ti^{51} emits γ-radiation of energy 1.0 Mev, it is possible that some of the γ-radiation attributed by Richardson to V^{48} may have been due to this isotope. However, the relative intensities of the two activities show that at least 75 percent of the radiation observed by Richardson must be due to V^{48} and that therefore at least three levels of Ti^{48} are necessary to explain this result. No γ-radiation of energy >1.0 Mev has been observed and moreover no positrons from V^{48} have been detected of energy >1.1 Mev, the spectrum of which appears to be essentially simple. These results suggest that the 1.0-Mev γ-rays found by Richardson are emitted in cascade transitions. Coincidence experiments to test this point are in progress.

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K-Electron Capture and Internal Conversion in Cr^{51}

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Cr^{51} has been chemically isolated from titanium which has been bombarded with high speed alpha-particles and chromium which has been activated with deuterons. Its half-life is 26.5 ± 1.0 days and its identification depends on its formation in the reactions

$$Ti^{48}+He^{4}\rightarrow Cr^{51}+n^{1}; \quad Cr^{50}+H^{2}\rightarrow Cr^{51}+H^{1}; \quad Cr^{50}+n^{1}\rightarrow Cr^{51}+\gamma.$$

Cr^{51} decays mainly by K-electron capture but is probably unstable against positron emission as it emits strong γ-radiation of energy 0.5 Mev and 1.0 Mev. No positrons of energy $>100{,}000$ ev have been detected, the lower limit of the ratio K capture to emission of positrons of energy $>100{,}000$ ev being 10,000.

The γ-ray of energy 1.0 Mev is due to a nuclear transition in V^{51}. It is internally converted to an extent of 0.1 percent, the conversion electrons having been found by absorption measurements. Electrons of energy 0.35 ± 0.05 Mev are also emitted by a strong source of Cr^{51}. It is probable that these are recoil electrons due to the 0.5-Mev γ-rays.

INTRODUCTION

IT has recently been shown by Walke, Williams and Evans[1] that V^{47} of half-life 600 days decays almost entirely by K-electron capture. This result was somewhat difficult to understand theoretically, for as was pointed out by Professor Wigner, one would expect V^{47} to be less stable than V^{49} yet a form of V^{49} is known which emits positrons of energy 1.9 Mev. Since the hypothesis that the 600-day activity might be an isomeric form of V^{49} could not be definitely excluded, we

* Exhibition of 1851 Senior Student. Present address George Hold Physics Laboratory, University of Liverpool, Liverpool, England. Word of Dr. Walke's untimely death reached this country while this paper was in proof.

[1] Walke, Williams and Evans, Proc. Roy. Soc. **A171**, 360 (1939).