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The Induced Radioactivity of Scandium

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A study has been made of the radioactivities induced in scandium by bombardment with deuterons, alpha-particles and slow and fast neutrons. Sc^{46} has been produced by deuteron and slow neutron activation. This isotope emits low energy electrons and soft gamma-radiation. The energy distribution of the electrons has been investigated by means of a large hydrogen filled expansion chamber. The upper limit of the spectrum is at 0.89(5) Mev in reasonably good agreement with range measurements made using aluminum absorbers. The half-life of Sc^{46} is 85±2 days. Alpha-particle bombardment of scandium gives rise to V^{48} which emits positrons and gamma-rays and decays to half-value in 16.2±0.3 days. Irradiation of scandium with fast neutrons from the Be^9+H^2 reaction results in the formation of K^{42} only. Bombardment with the neutrons from the $Li+H^2$ reaction, however, yields K^{42} and both Sc^{43} and Sc^{44}. The scandium isotopes emit positrons and decay with half-lives of 4.0±0.1 hours and 52±2 hours, respectively. Under these conditions the reaction $Sc^{45}+n^1\rightarrow Sc^{43}+3n^1$ is twice as probable as $Sc^{45}+n^1\rightarrow Sc^{44}+2n^1$. No evidence has been obtained of the reaction $Sc^{45}+n^1\rightarrow Ca^{45}+H^1$.

INTRODUCTION

THE induced radioactivity of scandium was first studied by von Hevesy and Levi[1] who irradiated scandium oxide for a few days using a radon-beryllium source of 200–300 millicuries. These investigators observed the formation of K^{42} and Sc^{46} according to the reactions

$$Sc^{45}+n^1\rightarrow K^{42}+He^4;\quad K^{42}\rightarrow Ca^{42}+e^-;$$
$$Sc^{45}+n^1\rightarrow Sc^{46}+\gamma;\quad Sc^{46}\rightarrow Ti^{46}+e^-,$$

the half-lives of which were reported as 16 hours and two months, respectively. (Aston has shown that scandium has only one isotope, its mass number being 45.)

Recently Pool, Cork and Thornton[2] have irradiated scandium with the fast neutrons from a lithium target bombarded with deuterons and have observed the formation of Sc^{43} and Sc^{44} in addition to K^{42}.

The present paper is a report of an investigation of the radioactivities induced in scandium oxide by bombardment with deuterons, alpha-particles, slow neutrons, and fast neutrons from both beryllium and lithium targets bombarded with deuterons. On account of the high intensity of the effects observed more accurate values of the half-lives of Sc^{46} and K^{42} have been obtained. In addition, V^{48} has been identified.

APPARATUS

The activations with deuterons, alpha-particles and neutrons from beryllium were carried out using the Berkeley cyclotron under conditions already described.[3] The very high energy neutrons from the $Li+H^2$ reaction were produced by bombarding lithium metal which was compressed into a cavity in a brass plate and which was

* Commonwealth Fund Fellow.
[1] von Hevesy and Levi, Det. Kgl. Danske Videnskabernes Selskab Math. Fysiske Meddelelser. **14**, 5 (1936).
[2] Pool, Cork and Thornton, Phys. Rev. **52**, 41 (1937).
[3] Walke, Phys. Rev. **51**, 439 (1937).

efficiently water cooled. In consequence it was found possible to bombard the lithium with deuteron currents as high as 15 microamperes.

Measurements of the decay of the radioactive samples were carried out using a Lauritsen type quartz fiber electroscope.

Activation with Deuterons

Several samples of scandium oxide were bombarded with deuterons, and it was found that a long lived isotope was formed. In consequence chemical separations were carried out and Sc^{46} was isolated by several processes. For example, one sample of the oxide was activated for approximately 45 microampere-hours and was divided into three portions. To one portion which was dissolved in $6N$ HNO_3 was added inactive phosphoric acid followed by 5 cc of HNO_3 and 5 cc of $(NH_4)_2MoO_4$. The solution was heated to 70° and allowed to stand for 10–15 minutes. The precipitate of ammonium phosphomolybdate was found to be inactive showing that no radiophosphorus was present in the active sample.

The residual solution from this procedure was analyzed by the specific tests for scandium given by Noyes and Bray[4] as follows: Scandium hydroxide was precipitated from the nitrate solution by the addition of NH_4OH and was filtered off and washed. It was then dissolved in 5–10 cc of $6N$ HCl, the solution being subsequently evaporated almost to dryness. It was then transferred to a platinum dish being rinsed in with water. The solution was then evaporated completely to dryness and to the residue was added 2 cc of water and 0.5–1.0 cc of $27N$ HF, 1 cc of $6N$ HCl and 9 cc of water. The solution was heated to 100° for about 5 minutes and filtered through a waxed funnel.

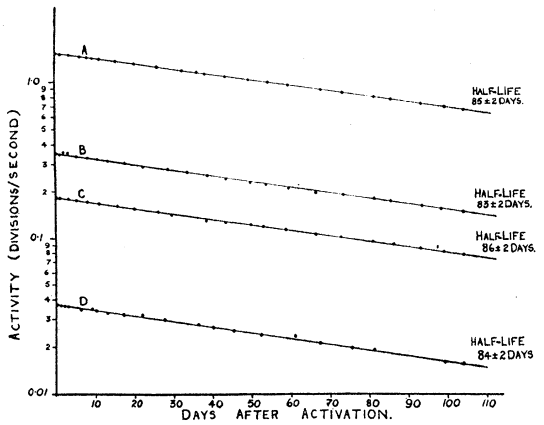

FIG. 1. Decay curves of various samples of Sc^{45}. *A* is the $\beta+\gamma$-ray decay curve of unseparated Sc_2O_3 after activation with deuterons. *B* is the decay curve of Sc_2O_3 recovered from Sc_2O_3 following activation with deuterons and separated chemically by the oxalate procedure. *C* is the decay curve of the γ-radiation from sample *A* filtered through 1 mm of lead and 3.2 mm of aluminum. *D* is the decay curve of spectroscopically pure Sc_2O_3 activated with slow neutrons.

[4] Noyes and Bray, *System of Qualitative Analysis for the Rare Elements.*

The precipitate was transferred to a platinum dish and to it was added 10 cc of $6N$ NH_4OH and 5 cc of $27N$ HF, the solution being heated nearly to boiling for 2–3 minutes. It was next filtered and to the filtrate was added 4 cc of $18N$ H_2SO_4. The mixture was allowed to stand for ten minutes and a white translucent precipitate formed. Finally 10 cc of water were added and sufficient $6N$ NH_4OH to make the solution alkaline. The $Sc(OH)_3$ precipitate was filtered off and found to be active. This test proves conclusively that the radioactive body formed is an isotope of scandium.

When it was thus established that the isotope Sc^{46} had been isolated the other portions of the sample were treated by different processes. From one $Sc(OH)_3$ was precipitated by the addition of $6N$ NH_4OH and from the other Sc_2O_3 was kindly recovered for the author by Dr. Philip Schutz of the department of chemistry. Dr. Schutz precipitated the scandium as oxalate in a solution of about $1N$ acidity. The oxalate was then filtered off and roasted for several hours at 700°C.

All the samples were found to be strongly active and observations of their decay have shown that the half-life of Sc^{46} is 85 ± 2 days. This value is somewhat higher than that given by Hevesy and Levi,[1] namely two months. The yield of Sc^{46} in the reaction

$$Sc^{45}+H^2 \rightarrow Sc^{46}+H^1$$

is approximately 9×10^7 deuterons per active atom.

Activation with Slow Neutrons

A further indication that the isotope concerned is Sc^{46} is given by the fact that the same active body has been formed by irradiating scandium oxide with slow neutrons. The sample

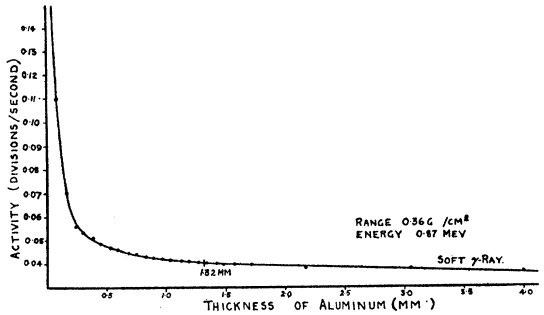

FIG. 2. Absorption curve in aluminum of radiations emitted by Sc_2O_3 recovered from the oxalate precipitate separated from Sc_2O_3 after activation with deuterons. Range of electrons 0.36 g/cm². Energy 0.87 Mev.

used in this experiment was spectroscopically pure. Several grams were activated in a cube of paraffin of side 10″ placed immediately behind the beryllium target which was bombarded with a current of 12 microamperes of deuterons. The radioactivity observed decayed with a single period of 84±2 days.

It is thus clear that Sc^{46} has been formed in the two reactions

$$Sc^{45}+H^2\rightarrow Sc^{46}+H^1,$$
$$Sc^{45}+n^1\rightarrow Sc^{46}+\gamma.$$

Decay curves of this isotope are shown in Fig. 1.

PROPERTIES OF Sc^{46}

Magnetic deflection of the particles emitted by Sc^{46} showed them to be negative electrons. It was observed that a gamma-ray was also present. The energy of the β-rays was then determined by measuring their range in aluminum. The absorption curve obtained is shown in Fig. 2. The range of the electrons is 0.36 g/cm² so that the maximum energy calculated according to Feather's formula is 0.87 Mev. The absorption curve when compared with that of Sc^{43} suggests that the energy of the gamma-ray is less than 0.5 Mev since it is much more absorbed by the aluminum than annihilation radiation.

The energy distribution of the electrons emitted by Sc_2O_3 recovered from the oxalate procedure has been studied by means of the large hydrogen filled expansion chamber mentioned in a previous paper.[5] The electrons were deflected in a field of 276 oersteds and their energy determined by the method already discussed[6] in considering the energy distribution of the positrons from Sc^{42} and Sc^{43}. Measurements were made on 312 tracks, the resulting momentum distribution being shown in Fig. 3. The upper limit of the spectrum is at $4350H\rho$, 0.89(5) Mev in good agreement with the value obtained from the range measurements. The dotted curve in Fig. 3 has been fitted to the distribution of tracks by inspection. It does not refer to any theoretical curve. The upper limit has also been determined by inspection. No attempt has been made to extrapolate beyond the observed track of highest energy nor has the end point been adjusted to fit any theory of β-decay.

The spectrum is characterized by the sharp maximum at $1500H\rho$.

ACTIVATION WITH ALPHA-PARTICLES

Following bombardment with 11 Mev alpha-particles scandium oxide was found to emit positrons and gamma-radiation. The activity decays to half-value in 16.2±0.3 days. The reaction involved is

$$Sc^{45}+He^4\rightarrow V^{48}+n^1;\quad V^{48}\rightarrow Ti^{48}+e^+$$

as the emission of a proton yields the stable titanium isotope Ti^{48}.

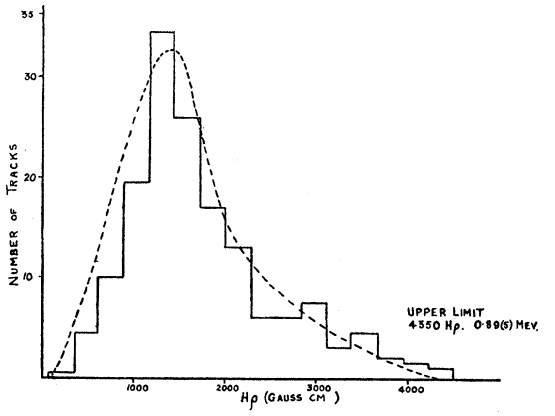

FIG. 3. Momentum distribution of electrons emitted by Sc_2O_3 recovered from oxalate procedure. Magnetic field 276 oersteds. Number of tracks measured 312. Upper limit 4350 $H\rho$. Energy 0.89(5) Mev. The dotted curve has been fitted to the distribution by inspection without reference to any theory. The upper limit has also been estimated by inspection of the distribution. No attempt has been made to extrapolate beyond the highest energy track observed nor to fit this to any theory.

[5] Walke, Phys. Rev. **52**, 400 (1937).

A chemical analysis showed that the active body is an isotope of vanadium.

The irradiated sample of scandium oxide was dissolved in 6*N* HCl and a little ammonium metavanadate was added. The equivalent quantity of lead nitrate was then added and 6*N* NH_4OH gently stirred into the mixture until the lead vanadate precipitate separated out. A little $Sc(OH)_3$ came down as well but the lead vanadate was redissolved in dilute HCl and inactive scandium was added to the solution. The vanadium was then reprecipitated as lead vanadate and after filtering and washing was thoroughly dried. This precipitate was found to be radioactive, decaying to half-value in 16.3 $\pm$0.3 days.

It is thus clear that bombardment of scandium with 11 Mev alpha-particles gives rise to V^{48}, this isotope having a half-life of 16.2$\pm$0.3 days. The same isotope has been separated chemically from titanium after activation with deuterons. In Fig. 4 are shown some decay curves of V^{48}. A comparison between the decay of two radioactive vanadium precipitates isolated from $Sc^{45}+He^4$ and $Ti^{47}+H^2$ is shown in this figure. By the deuteron activation of titanium very strong samples of V^{48} can be obtained so that it is proposed to consider the properties of this isotope in a subsequent paper.

The yield of V^{48} in the reaction studied is approximately 2×10^7 alpha-particles per active atom.

Activation with Fast Neutrons

A. Neutrons from beryllium bombarded with deuterons

When scandium oxide was bombarded with fast neutrons from beryllium+deuterons, a radioactive isotope was detected which decayed to half-value in 12.5$\pm$0.2 hours. Chemical analysis as already discussed in a previous paper[6] showed this to be an isotope of potassium namely K^{42}. The decay curve of the chemically separated potassium was published in the paper mentioned above.

After extracting the active potassium, scandium was precipitated from the solution and was found to be inactive and moreover calcium precipitated as oxalate was also inactive. This result agrees with the findings of Hevesy and Levi.[1] Thus the only reaction which takes place when scandium is bombarded with fast neutrons from the Be^9+H^2 reaction is that in which K^{42} is formed, namely

$$Sc^{45}+n^1\rightarrow K^{42}+He^4.$$

B. Neutrons from lithium bombarded with deuterons

Pool, Cork and Thornton[2] have recently obtained evidence for the formation of Sc^{43} and Sc^{44} from Sc^{45} when bombarded with the very energetic neutrons from the Li and H^2 reaction. During the course of the present investigation the same reactions were independently detected by the author. The results obtained are in good agreement with those reported by Pool, Cork and Thornton.

One sample which was contained in a cadmium box filled with boric oxide was irradiated for three hours close to a lithium target which was bombarded with 15 microamperes of deuterons. The scandium was separated from the lithium target by 1/4″ of brass, 1/32″ of cadmium and 1/4″ thickness of boric oxide. The sample was found to be very active and was chemically analyzed, as below.

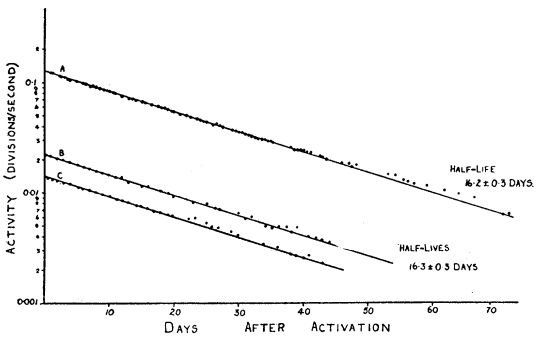

FIG. 4. Decay curves of V^{48}. *A* refers to a sample of Sc_2O_3 after activation with 0.2 microampere of 11 Mev alpha-particles for approximately three hours. *B* refers to a vanadium precipitate separated from titanium after activation with deuterons; *C*, vanadium precipitate separated chemically from Sc_2O_3 after activation with 11 Mev alpha-particles.

The Sc_2O_3 was dissolved in 6*N* HCl and a little inactive KCl, $CaCl_2$ and titanium nitrate were added. The solution was evaporated to 3 cc and 5 cc of 16*N* HNO_3 were added, the

[6] Hurst and Walke, Phys. Rev. **51**, 1033 (1937).

mixture being once more evaporated to 2–3 cc. Five cc of perchloric acid were then poured into the solution, the mixture being again evaporated to a few cc. The precipitated potassium per-

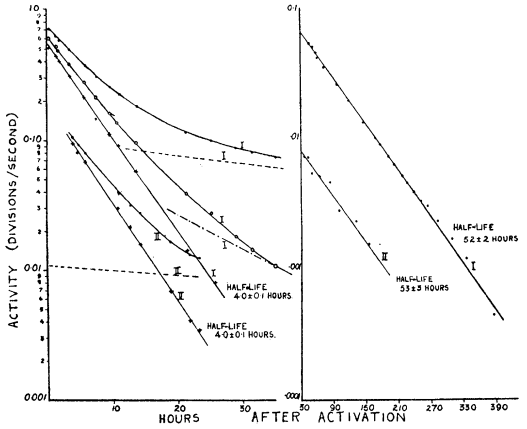

FIG. 5. Decay curves of Sc_2O_3 after irradiation with neutrons from the $Li+H^2$ reaction. The curves marked *I* refer to a spectroscopically pure sample of Sc_2O_3 which had been activated for 14 hours, the bombarding deuteron currents being 15 microamperes. This activity has been corrected for a trace of Sc^{46} formed by slow neutrons. The curves marked *II* refer to Sc_2O_3 separated chemically by the oxalate procedure from activated Sc_2O_3. The points shown by closed circles represent total activity. Those marked by open circles have been corrected for the activity due to K^{42} which is indicated by a dashed and dotted line (sample 1 only). The crosses have been corrected for the long period which is shown by dashed lines.

chlorate was filtered off and found to be weakly active. Ten cc of water were finally added to the filtrate, the solution being heated for about 15 minutes. In this way the titanium was precipitated as TiO_2. It was filtered off and found to be inactive.

The scandium was then precipitated in acid solution as oxalate and filtered off. After washing it was converted to oxide by prolonged roasting at red heat. The scandium oxide was found to be very active. The particles emitted were investigated by means of a magnetic trochoid analyzer[7] and were found to be positrons. The decay of this sample showed the presence of two radioactive isotopes with half-lives of 4.0 ± 0.1 hours and 53 ± 3 hours, respectively.

In a subsequent experiment a spectroscopically pure sample of Sc_2O_3 was irradiated for about fourteen hours to intensify the long period. It was found with this sample that the longer period is 52 ± 2 hours in excellent agreement with previous results obtained by the author.[3, 6] Decay curves of these samples are shown in Fig. 5.

These results confirm the report of Pool, Cork and Thornton[2] that scandium whem bombarded with neutrons of energy 14–20 Mev can emit three neutrons as well as two neutrons. Thus we have the reactions:

$$Sc^{45}+n^1\rightarrow Sc^{43}+3n^1,$$
$$Sc^{45}+n^1\rightarrow Sc^{44}+2n^1.$$

By extrapolating to saturation it has been found that the reaction in which three neutrons are emitted is twice as probable under the conditions of these experiments as that in which two neutrons are ejected. It thus appears from these results that the Sc^{46} formed in a highly excited state by the reaction $Sc^{45}+n^1$ "evaporates" more readily three neutrons of relatively low energy than two neutrons of higher energy. This is in accord with recent views proposed by Professor Bohr.

In another experiment calcium was extracted from the active scandium oxide but it was found to be inactive. Thus the reaction

$$Sc^{45}+n^1\rightarrow Ca^{45}+H^1$$

appears to be a relatively improbable one.

ACKNOWLEDGMENTS

It is a pleasure once more for the author to record his gratitude to Professor E. O. Lawrence for continued encouragement. The author is also very grateful to Dr. W. Libby of the department of chemistry who kindly placed at his disposal several grams of the purest scandium oxide available and to Dr. Hugh C. Paxton who took the cloud chamber photographs of the electrons of Sc^{46}. The friendship and cooperation of the staff of the Radiation Laboratory is also gratefully acknowledged.

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[7] It is a pleasure to thank Mr. E. Lyman for the use of the trochoid analyzer.