The Induced Radioactivity of Titanium and Vanadium

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A study has been made of the radioactivities induced in titanium and vanadium by irradiation with deuterons, slow and fast neutrons and in titanium with 11 Mev alpha-particles. Bombardment of titanium with deuterons renders it extremely radioactive, the radiations emitted being mainly positrons and hard gamma-rays. An analysis of the decay curve shows the presence of six radioactive isotopes. Of these three have been found to be chemically inseparable from vanadium. Evidence is considered which suggests that the isotopes formed are V^{48} half-life 16.0 ± 0.2 days, V^{49} half-life 33 ± 1 minutes and V^{50} half-life 3.7 ± 0.2 hours. A short lived activity of half-life 2.8 minutes is probably due to Ti^{51} as the same isotope is formed when titanium is bombarded with slow neutrons. There is evidence of a weak activity with a half-life of 50 hours which is probably due to Sc^{44} formed in the reaction $Ti^{46}+H^2\rightarrow Sc^{44}+He^4$. Sc^{46} is also formed as evidenced by the presence of an isotope with a half-period of 85 ± 5 days and by the energy distribution of the soft negative electrons which accompany the positrons. The energy distribution of the positrons emitted by V^{48} has been studied using a large hydrogen-filled cloud chamber. The upper limit of the spectrum is at 1.0 (5) Mev, in reasonably good agreement with the value 1.1 (5) Mev deduced from absorption measurements in aluminum. The maximum energy of the positrons from V^{49} as determined by absorption measurements in aluminum is approximately 1.9 Mev. V^{49} and V^{50} have also been formed by bombarding titanium with 11 Mev alpha-particles. In addition two new periods of 68 ± 4 hours and longer than 180 days have been detected. The isotopes responsible for these activities have not been identified. When bombarded with fast neutrons it seems likely that Ca^{45}, Sc^{48} and Sc^{46} are formed from titanium. Sc^{48} is also produced by the transmutation $V^{51}+n^1\rightarrow Sc^{48}+He^4$, its half-life being 41 ± 3 hours. In addition, evidence has been obtained for the reaction $V^{51}+n^1\rightarrow V^{50}+2n^1$. This reaction can be induced by the fast neutrons from the Be^9+H^2 reaction, though it is more probable when $Li+H^2$ neutrons are used V^{52} has been produced in several reactions; its half-life is 3.9 ± 0.1 minutes.

INTRODUCTION

IN a previous communication[1] it was shown that when calcium is bombarded with deuterons reactions of the type $Ca^A+H^2\rightarrow Sc^{A+1}+n^1$ are very probable. The present paper is a report of experiments made on the induced radioactivity of titanium which disclosed that the same type of reaction is very probable with this element. During this study a positron radioactive isotope was discovered which has been identified as V^{48}, which has some rather unusual properties. Included in this paper is a preliminary discussion of these properties.

By a number of nuclear reactions it has been found possible to identify the mass numbers of some previously undetected radioactive isotopes.

The deuterons, neutrons and alpha-particles used in this investigation were produced in the Berkeley cyclotron under conditions similar to those mentioned in other papers.[1] Decay measurements were made using a Lauritsen type quartz fiber electroscope, the absorption of radiations being observed by interposing aluminum and lead sheets between the sample and the electroscope window.

BOMBARDMENT OF TITANIUM WITH DEUTERONS AND SLOW NEUTRONS

Metallic titanium and chemically pure TiO_2 were activated with 5.5 Mev deuterons. The metal was found to contain sodium so that the analysis of the decay curve was made using samples of TiO_2. The powdered metal, however, is readily soluble in dilute nitric acid so that chemical analyses were carried out using the activated metal.

In a preliminary study of the radioactivity induced in titanium by deuterons, a small quantity of the metal was activated for 12 microampere hours. The sample was found to be so intensely radioactive that it was only possible to make measurement on its decay by interposing 16 mm of aluminum between it and the electroscope window. Under these conditions the fiber discharged at the rate of five divisions per second (which is equivalent to 5×10^4 electrons entering the electroscope per second).

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

The early decay of the activity was rapid showing the presence of a short lived isotope. On correcting for the ionization due to longer lived bodies it was found that the half-life of this isotope is 2.8 ± 0.1 minutes. By activating titanium with slow neutrons the same radioactive substance was produced as the decay of the activity indicates a half-life of 2.9 ± 0.1 minutes. This isotope emits negative electrons and gamma-radiation. The mass numbers and percentage abundances of the isotopes of titanium and neighboring elements as given by Aston are as below:

Calcium	40(96.76%)	42(0.77%)	43(0.17%)	44(2 30%)	
Scandium	45(100%)				
Titanium	46(8.5%)	47(7.8%)	48(71.3%)	49(5.5%)	50(6.9%)
Vanadium	51(100%).				

Since titanium has stable isotopes for all mass numbers from 46 to 50 inclusive the half-life of 2.9 ± 0.1 minutes observed by activating titanium with slow neutrons must be associated with Ti^{51}. Thus Ti^{51} has been formed in the two reactions:

$$Ti^{50}+n^{1}\rightarrow Ti^{51}+\gamma;\quad Ti^{51}\rightarrow V^{51}+e^{-}$$
$$Ti^{50}+H^{2}\rightarrow Ti^{51}+H^{1}.$$

For convenience the decay curves of this isotope are shown with those of other short lived bodies in Fig. 11 at the end of the paper.

After the Ti^{51} has died away the decay curve indicates the existence of several isotopes. Cloud chamber observations show that the sample emits large numbers of positrons, though too many electrons are seen to be accounted for entirely by Compton recoils from the annihilation radiation. Moreover, the metal shows a very strong activity of half-life 15 hours which emits negative electrons of approximately two million volts energy and hard gamma-radiation. These properties are characteristic of Na^{24} which is probably formed from sodium contamination as it is not observed at all with the chemically pure TiO_2. Thus many of the negative electrons seen in the cloud chamber are due to sodium contamination. On the other hand a certain number of electrons persist for several months and as will be discussed later it is quite likely that these are due to Sc^{46} formed in the reaction

$$Ti^{48}+H^{2}\rightarrow Sc^{46}+He^{4};\quad Sc^{46}\rightarrow Ti^{46}+e^{-}.$$

A detailed analysis of the decay curve of the radioactivity induced in titanium by deuterons indicates the existence of three main periods (in addition to the period due to Ti^{51}) with values 33 ± 1 minutes, 3.7 ± 0.2 hours and 16.0 ± 0.2 days. There is also a weak activity with a half-life of approximately 50 hours, together with a long period of 85 ± 5 days, which is only observed in samples which have been very strongly activated. This last half-life is the same as that of Sc^{46} and cloud chamber evidence to be considered later suggests that this isotope is formed. The 50 hour period might well be due to Sc^{44} [2] though the weak activity of this isotope does not allow of an accurate determination of its half-life.

The strong positron activity suggested, however, that most of the radioactive bodies must be isotopic with vanadium and this was confirmed by chemical analyses using activated titanium metal. (The chemical separation adopted was suggested to the author by Dr. Glen Seaborg of the department of chemistry.)

About 30 mg of active titanium metal in the form of powder was dissolved in $6N.HNO_3$ which was gently heated and to the resulting solution was added 25 mg of Sc_2O_3 and 1 cc of $M/4.NH_4VO_3$. The mixture was evaporated in a small flask until its volume was reduced to 3 cc. 5 cc of $16N.HNO_3$ was added and the solution evaporated until approximately 3 cc were left. Nine cc of $9N.HClO_4$ were then added, evaporation again being proceeded with until only 3–4 cc remained. Ten cc of water were gradually added, the mixture being boiled gently for 10–15 minutes. In this way the titanium was precipitated as oxide; it was filtered out and rejected.

To the filtrate was added $6N.NH_4OH$ until the solution was just neutral. Two cc of $1N.Pb(NO_3)_2$ were added and the vanadium was precipitated as lead vanadate. This was filtered off and washed. To the residual solution was added 1 cc of saturated oxalic acid and the mixture was heated for several minutes. The scandium was thus precipitated as oxalate and was filtered out and thoroughly washed.

Both the vanadium and scandium precipitates were found to be active though the scandium oxalate decayed with a single period of 15 hours. A similar but weaker activity was also found in the vanadium precipitate. These effects were undoubtedly due to the sodium contamination.

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

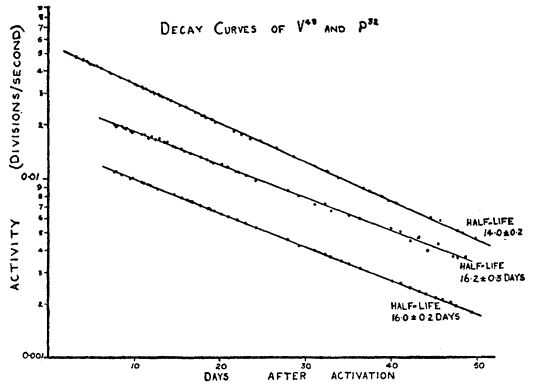

FIG. 1. Decay curves of V^{48} and P^{32}. The half-life 16.0 $\pm$0.2 days is associated with the total activity of a sample of titanium metal after activation with deuterons (shown in this figure = activity $\times 10^{-1}$). The half-life 16.2$\pm$0.3 days is associated with the γ-ray decay of this sample. The γ-radiation was filtered through 1.6 cm of aluminum.

No other period was detected in the scandium precipitate, showing that no short lived scandium isotopes are formed in the reactions under consideration. The intensity of the 50-hour period observed in the unseparated samples was sufficiently weak to make it unlikely that this would be observed in the presence of the strong sodium activity. Moreover, to prevent too great an activity due to the 16-day period (which might have obscured shorter periods) the sample was activated for only 7 microampere hours. Thus the amount of Sc^{46} formed would be inappreciable and could not have been detected. Hence although the chemical separation shows that reactions involving alpha-particle emission following deuteron capture are not highly probable the presence of the weak 50 hour period in the unseparated samples of TiO_2 suggests that Sc^{44} may be formed in the reaction:

$$Ti^{46}+H^2 \rightarrow Sc^{44}+He^4; \quad Sc^{44} \rightarrow Ca^{44}+e^+.$$

Associated with the vanadium precipitate were found the three main periods of 33$\pm$1 minutes, 3.7$\pm$0.2 hours and 16.0$\pm$0.2 days. These bodies are then all radioactive isotopes of vanadium, perhaps formed in reactions of the type

$$Ti^A+H^2 \rightarrow V^{A+1}+n^1; \quad V^{A+1} \rightarrow Ti^{A+1}+e^+,$$

in which stable isotopes of titanium capture the proton of the deuteron to form radioactive isotopes of vanadium which decay by positron emission to produce stable titanium isotopes with mass numbers greater by unity than the original titanium isotopes.

By bombarding a sample of TiO_2 free from sodium contamination with 10 microamperes of deuterons for only 10 minutes it was found possible to verify that the emitted particles are mainly positrons by deflecting them in a magnetic field. No negative electrons could be detected.

IDENTIFICATION OF THE RADIOACTIVE VANADIUM ISOTOPES

Of the four possible vanadium isotopes $V^{47, 48, 49}$ and V^{50} which could be formed in the reactions under consideration only one, namely V^{48}, could be produced from scandium by bombardment with alpha-particles. The reaction involved is:

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

In such experiments[3] the formation of a positron radioactive isotope was observed which was chemically separated with vanadium and which decayed with a half-life of 16.2$\pm$0.3 days. Thus the isotope with half-life 16.0$\pm$0.2 days formed by the activation of titanium with deuterons must be V^{48}. In Fig. 1 is shown a comparison between decay curves of this isotope and that of P^{32}. The remaining two periods can then be associated with V^{47}, V^{49} or V^{50}.

Of these isotopes only two, *viz.* V^{49} and V^{50} could be formed by bombarding titanium with alpha-particles in the reactions

$$Ti^{46, 47}+He^4 \rightarrow V^{49, 50}+H^1.$$

In this connection it is significant that titanium when activated with 11 Mev alpha-particles becomes quite strongly radioactive. The activity induced is complex in character but can be analyzed into well-defined periods. The two shortest half-lives observed have the values 34$\pm$1 minutes and 3.8$\pm$0.2 hours. These values agree within the limits of experimental error with the two short periods observed with deuterons. Visual observation using a cloud chamber showed that the short period activities formed by the alpha-particle activation of titanium emit mainly if not entirely positrons. A small number of negative electrons were seen but these may have

[3] Walke, "The Induced Radioactivity of Scandium," Phys. Rev. **52**, 669 (1937).

been due to Compton recoil electrons from the annihilation radiation.

This evidence suggests that the periods of 33 ± 1 minutes and 3.7 ± 0.2 hours should be associated with V^{49} and V^{50}. There is thus no definite evidence for V^{47} which if it is formed in the deuteron activation of titanium must have a half-life less than one minute or greater than several months.

In order to distinguish between the two isotopes a search was made for V^{50} formed in the reaction,

$$V^{51}+n^1\rightarrow V^{50}+2n^1.$$

Samples of vanadium metal and vanadic acid were bombarded for many hours with neutrons from beryllium and lithium targets bombarded with deuterons. Only a relatively weak activity was detected but this showed the presence of two radioactive isotopes, one of which decayed with a

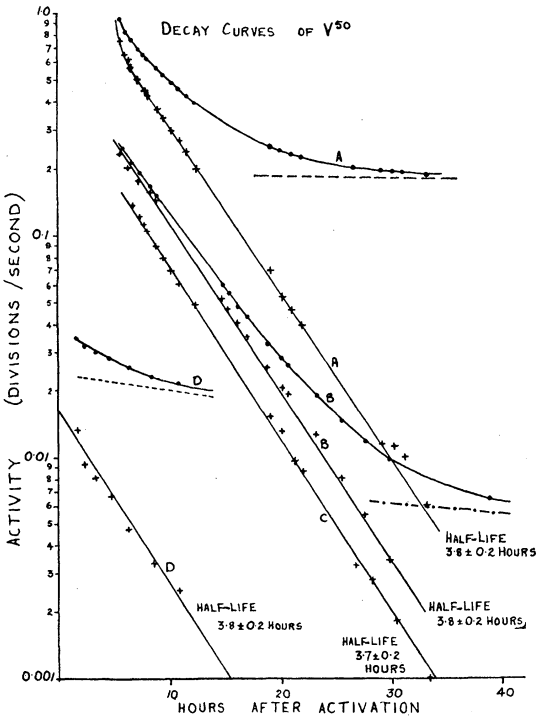

FIG. 2. Decay curves of V^{50}. A. Titanium oxide activated by deuterons. Dots represent total activity; dashes, activity due to longer lived isotopes. The crosses have been corrected for the long period activities. B. Titanium oxide activated by 11 Mev alpha-particles. Dots represent total activity; dots and dashes, activity due to longer periods. The crosses have been corrected for longer lived activities. C. Titanium oxide+deuterons sample II corrected for long lived activities. D. Vanadic acid activated with the fast neutrons from $Li+H^2$ reactions. Total activity shown by dots. Background due to Sc^{48}, dashes. The crosses show the corrected activity.

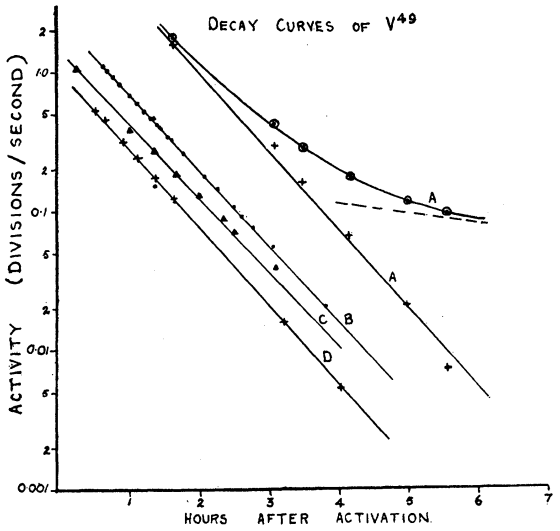

FIG. 3. Decay curves of V^{49}. A. Sample of chemically pure TiO_2 activated with deuterons. Dotted circles, total activity; dashes, activity due to other longer lived isotopes; plus signs, have been corrected for this longer lived activity. B. γ-radiation from titanium metal activated by deuterons after being filtered through 1.6 cm of aluminum. C. $\beta+\gamma\beta$-rays from C.P. titanium oxide activated by 11 Mev alpha-particles. D. γ-radiation from C.P. titanium oxide activated by deuterons. B, C, and D have all been corrected for longer period activities.

half-life of 3.8 ± 0.3 hours, this being observed both with vanadium metal and vanadic acid and with the beryllium and the lithium fast neutrons.

The association of this period (which agrees within the limits of experimental error with the periods of 3.7 ± 0.2 hours and 3.8 ± 0.2 hours detected with titanium bombarded with deuterons and alpha-particles) with vanadium bombarded with fast neutrons thus suggests that it is characteristic of V^{50}. Thus, V^{50} may be formed in the three reactions

$$Ti^{49}+H^2\rightarrow V^{50}+n^1;\quad V^{50}\rightarrow Ti^{50}+e^+$$
$$Ti^{47}+He^4\rightarrow V^{50}+H^1$$
$$V^{51}+n^1\rightarrow V^{50}+2n^1,$$

its half-life being 3.7 ± 0.2 hours.

This evidence is summarized graphically in Fig. 2.

The half-life of 33 ± 1 minutes must then be associated with V^{49} produced in the reactions:

$$Ti^{48}+H^2\rightarrow V^{49}+n^1$$
$$Ti^{46}+He^4\rightarrow V^{49}+H^1.$$

Decay curves of the isotope formed by these reactions are shown in Fig. 3.

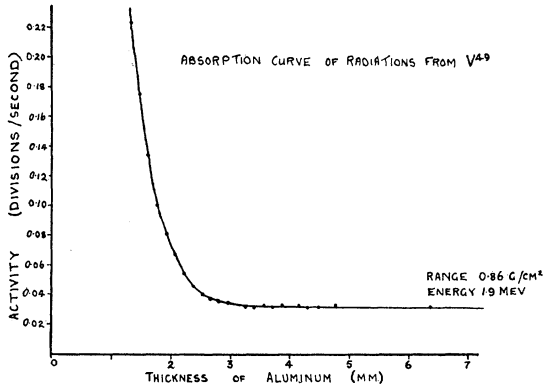

FIG. 4. Absorption curve in aluminum of radiations emitted by V^{49}. Range of positrons 0.86 g/cm². Maximum energy 1.9 Mev.

MAXIMUM ENERGY OF POSITRONS FROM V^{49} AND V^{48}

An estimate of the maximum energy of the positrons emitted by V^{49} has been obtained by making absorption measurements in aluminum. The absorption curve is reproduced in Fig. 4. The range of the positrons is 0.86 g/cm² corresponding by Feather's rule to a maximum energy of approximately 1.9 Mev.

Similar measurements were made on the absorption of the positrons emitted by V^{48}. The range in aluminum as found from the curve of Fig. 5 is 0.51 g/cm² corresponding to an energy of approximately 1.1(5) Mev.

The energy distribution of the positrons emitted by V^{48} has also been studied in the large hydrogen-filled expansion chamber previously discussed.[2] The positron tracks were photographed in a magnetic field of 285 oersteds, measurements on their curvature being made by the reprojection method previously adopted. The curvature of 502 tracks was measured, the resulting momentum distribution being shown in Fig. 6. The upper limit of the spectrum has been estimated by inspection, no attempt having been made to extrapolate beyond the highest energy track measured. The dotted curve shown in Fig. 6 has been fitted to the distribution without reference to any theory of β-decay. The upper limit at 4850 $H\rho = 1.0(5)$ Mev is in reasonably good agreement with the absorption measurements.

In addition to large numbers of positron tracks the cloud chamber pictures showed a small percentage of negative electrons of low energy. Some of these are undoubtedly due to Compton recoil electrons but the number is too great to be accounted for entirely in this manner. Measurements were made on 209 such tracks and it was found that they were distributed very much as in the β-ray spectrum of Sc^{46}. Especially noticeable (Fig. 7) is the well-defined maximum at 1500 $H\rho$ which was shown in a previous paper[3] to be characteristic of Sc^{46}. However, there are several tracks of higher energy than the upper limit of Sc^{46}, there being isolated tracks with energies as high as 7000 $H\rho$. Many of these are probably due to the strong gamma-radiation from V^{48}. However, the sharp maximum at 1500 $H\rho$ and the general form of the distribution when compared with that of Sc^{46} (shown in Fig. 7 as the dotted curve) suggests that most of the low energy electrons are due to this isotope formed in the reaction

$$Ti^{48}+H^2 \rightarrow Sc^{46}+He^4; \quad Sc^{46} \rightarrow Ti^{46}+e^-.$$

These results are supported by the fact that a weak long period of 85±5 days (which agrees with the half-life of Sc^{46} *viz.* 85±2 days) has been found in titanium after activation with deuterons (Fig. 8).

PRODUCTION OF V^{48} FROM CHROMIUM

Experiments have also been carried out to extract radioactive vanadium isotopes from chromium activated with 5.5 Mev deuterons.

In two such experiments negative results were obtained. Chromic oxide was bombarded for about an hour with a beam of 12 microamperes and was chemically separated by Dr. Glen Seaborg into three fractions containing manga-

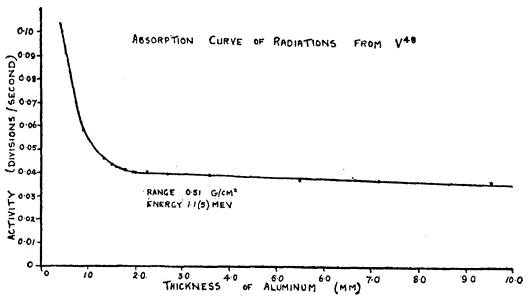

FIG. 5. Absorption curve in aluminum of the radiations emitted by V^{48}. Range of positrons 0.51 g/cm². Maximum energy 1.1(5) Mev.

nese, chromium and vanadium. The manganese was extracted as dioxide and was filtered off. It was found to be quite active as will be reported later by Doctors Livingood and Seaborg. From the residual solution chromium was precipitated as lead chromate by adding lead nitrate in acid solution. After filtering off the precipitate of lead chromate excess of lead was removed from the filtrate by passing into it H_2S. The precipitated lead sulphide was removed and the vanadium brought back to the pentavalent state by warming the solution with bromine. This was finally made just neutral by the addition of NH_4OH and lead vanadate was precipitated by adding lead acetate.

The chromium fraction was found to be inactive though a weak activity was found in the vanadium precipitate. This, however, decayed with the characteristic period of Na^{24}. Similar results were obtained from a second example, there being no appreciable activity in either the chromium or vanadium precipitates. It thus seems likely that the half-lives of Cr^{55} and Cr^{51} are either very short or very long. Moreover, the failure to observe any activity in the vanadium precipitate suggests that the reaction

$$Cr^{52}+H^2\rightarrow V^{50}+He^4$$

is a rather improbable one.

More recently, however, a piece of copper coated with an electrolytic deposit of metallic chromium was bombarded with deuterons for sixty microampere hours. This sample was rendered strongly radioactive and from it Dr. Seaborg has separated for the author a radioactive isotope of vanadium. This emits only positrons and gamma-radiation and decays to half-value in 16.0 ± 0.3 days. It is thus V^{48} formed in the reaction

$$Cr^{50}+H^2\rightarrow V^{48}+He^4;\quad V^{48}\rightarrow Ti^{48}+e^+.$$

The chromium fraction was also weakly radioactive, observations of its decay showing that the isotope or isotopes formed are long lived.

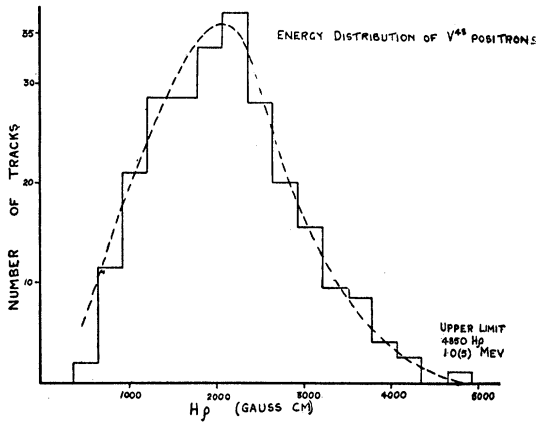

FIG. 6. Momentum distribution of the positrons from V^{48}. Magnetic field 285 oersteds. Number of tracks measured 502. Upper limit by inspection 4850 $H\rho=1.0(5)$ Mev. Curve shown by dashes has been fitted to the distribution by inspection. No attempt has been made to extrapolate beyond the highest energy track measured nor to fit the distribution to any theoretical curve.

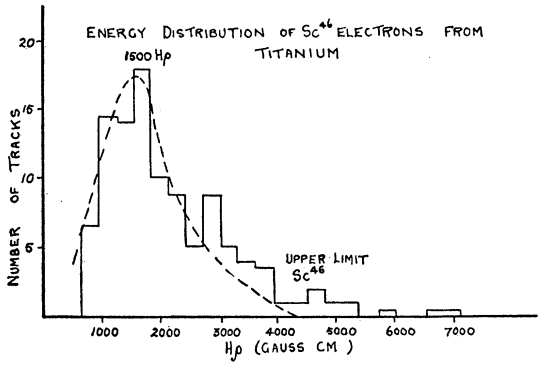

FIG. 7. Momentum distribution of negative electrons emitted by titanium metal after activation with deuterons. The dashed curve is that of Sc^{46} (as obtained by previous measurements on the electrons emitted by chemically separated scandium oxide after activation with deuterons) fitted to the distribution at $1500H\rho$.

YIELDS OF THE RADIOACTIVE ISOTOPES FORMED WHEN TITANIUM IS BOMBARDED WITH DEUTERONS

By correcting for the finite period of bombardment the saturation of yields of the isotopes formed when titanium is bombarded with deuterons have been calculated. By multiplying these values by the relative abundance of the parent isotope we may obtain relative cross sections of the reactions which occur. These results are summarized in Table I:

A striking fact which emerges from these figures is the high probability of the formation of V^{48}, especially if it is produced by the reaction

$$Ti^{47}+H^2\rightarrow V^{48}+n^1,$$

since this is so much more probable than the formation of V^{49} by a similar reaction. This great

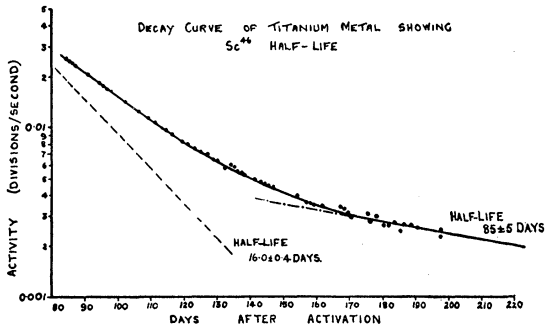

FIG. 8. End portion of decay curve of a sample of titanium metal after activation with deuterons showing the presence of 85±5 day period due to Sc^{46}.

difference might be explicable if V^{48} were also being formed in another reaction, especially if such a reaction involved the very abundant isotope Ti^{48}. A possible reaction according to the nuclear model proposed by Professor Bohr is:

$$Ti^{48}+H^{2}\rightarrow V^{48}+2n^{1}.$$

If this is the case, then the highly excited V^{50} formed by the penetration of the deuteron into the Ti^{48} nucleus evaporates two neutrons at the nuclear temperature resulting rather than ejecting one high energy neutron on which is concentrated most of the energy available in the transformation.

If such processes involving multiple neutron emission do occur, the formation of V^{48} should result in a relatively high neutron yield from titanium bombarded with deuterons. Dr. Luis Alvarez has compared the number of neutrons emitted from a titanium target bombarded with 15 microamperes of deuterons of 5.5 Mev energy with the number emitted by a beryllium target under the same conditions, and finds a ratio of 2 to 5.

PROPERTIES OF V^{48}

The gamma-ray intensity from V^{48} seemed to be much higher relative to the positron intensity than was observed with other positron radioactive isotopes such as Sc^{43} etc. Accordingly rough absorption measurements on the gamma-radiation were made using lead absorbers. Plotted on semi-logarithmic paper a linear absorption curve was obtained of which the slope was considerably less than would be expected if only annihilation radiation were being absorbed. It was thus shown that more penetrating gamma-rays accompanied the annihilation radiation. The fact has been recently proved by Dr. J. Reginald Richardson, who will report his results in more detail later. Dr. Richardson has investigated the distribution of Compton electrons ejected from a thin celluloid absorber by the gamma-rays from a strongly active titanium source in an expansion chamber. The distribution shows the existence of two well marked peaks corresponding to gamma-ray energies of 0.5 and 1.0 Mev, respectively. The measurements suggest that there are approximately twice as many quanta with energy 1.0 Mev as 0.5 Mev, i.e., there are 4 quanta of million-volt gamma-radiation emitted for every positron. This radiation may be due to nuclear γ-ray transitions but a complicated level system would have to be invoked to account for this high ratio of gamma-radiation to positron emission.

On the other hand this fact may be related to the phenomenon of nuclear capture of the K electrons which Dr. Luis Alvarez discovered occurs with V^{48}.[4] Dr. Alvarez studied the absorption in thin sheets of aluminum of the rays emitted by an active titanium sample which was acted on by a magnetic field so that no positrons could reach his thin walled counter. The absorption curve showed the presence of the characteristic K radiation of titanium. This is emitted as the K orbit which is emptied by the capture of the K electron by the radioactive nucleus is filled by an electron from an outer orbit. The 1.0 Mev γ-radiation emitted from V^{48} may in some way be connected with the capture of the K electron.

Since V^{48} emits four quanta of 1.0 Mev gamma-radiation per positron and as it has such a high probability of formation from titanium bombarded with deuterons a sample of the metal bombarded for about 100 microampere hours forms a rather convenient and relatively strong

TABLE I. *Relative cross sections of the reactions which occur when titanium is bombarded with deuterons.*

RADIOACTIVE ISOTOPE	HALF-LIFE	RELATIVE CROSS SECTIONS DEUTERONS PER ACTIVE ATOM × ABUNDANCE
Ti^{51}	2.9±0.1 min.	2.8×10^{7}
V^{50}	3.7±0.2 hours	1.7×10^{8}
V^{49}	33 ±1 min.	2.1×10^{9}
V^{48}	16.0±0.2 days	4×10^{6}
Sc^{44}	52 ±2 hours	1.9×10^{9}
Sc^{46}	85 ±2 days	1.4×10^{10}

[4] Alvarez, Phys. Rev. **52**, 134 (1937).

source of gamma-radiation. The fact that its half-life is as long as 16 days enables it to be used for quite long periods of time.

Activation of Titanium with 11 Mev Alpha-Particles

As has already been mentioned in the discussion of the deuteron induced radioactivities of titanium, bombardment of titanium with 11 Mev alpha-particles gives rise to V^{49} and V^{50}. These isotopes were identified by their half-lives. Visual observations using a cloud chamber showed that the great majority of the particles emitted are positrons.

In addition to these isotopes, however, two other radioactive bodies have been detected with half-lives of 68 ± 4 hours and approximately 200 days, respectively. The value of the long period cannot be determined accurately as its intensity is weak and fluctuations are considerable. However, one can say that its half-life is probably greater than 180 days.

The yields of the various isotopes are given in Table II.

The reactions which might occur when titanium is bombarded with alpha-particles (excluding those in which V^{49} and V^{50} are formed) are as below:

$$Ti^{48,\ 49,\ 50}+He^{4}\rightarrow V^{51,\ 52,\ 53}+H^{1},$$

in which the ejection of a proton follows the capture of the bombarding alpha-particle and

$$Ti^{46\ 47,\ 48,\ 49,\ 50}+He^{4}\rightarrow Cr^{49,\ 50,\ 51,\ 52,\ 53}+n^{1},$$

in which a neutron is ejected by the compound nucleus formed by the capture of the alpha-particle. Of these nuclei V^{51} and $Cr^{50,\ 52}$ and Cr^{53} are stable so that possible radioactive nuclei which might be formed are V^{52} and V^{53} and Cr^{49} and Cr^{51}. The half-life of V^{52} has been found to be 3.9 ± 0.1 minutes but no evidence for such a short period was found when a sample of titanium metal was bombarded for only five minutes. The activity produced decayed with the half-life of 33 minutes, though the presence of the 3.7 hour period in small intensity was suggested by the gradual bending of the curve after one hour's decay. Thus the reaction

$$Ti^{49}+He^{4}\rightarrow V^{52}+H^{1}$$

must be a relatively improbable one. The half-lives of 68 ± 4 hours and >180 days are then probably associated with two of the isotopes Cr^{49}, Cr^{51} and V^{53}. The intensity of the two longer periods is such that the sign of emitted particles could not be determined with the cloud chamber.

Table II. *Yield of active atoms when titanium is bombarded with 11 Mev alpha-particles.*

Radioactive Isotope	Half-Life	Yield Alpha-Particles/ Active Atom
V^{49}	33 ±1 min.	5×10^{6}
V^{50}	3.7 ± 0.2 hours	7.5×10^{6}
?	68 ±4 hours	3.5×10^{6}
?	>180 days	1×10^{6}

Bombardment of Titanium with Fast Neutrons

A. Neutrons from beryllium bombarded with deuterons

As was mentioned in a previous paper[1] the bombardment of titanium with fast neutrons results in the formation of Ca^{45} which decays to half-value in 2.4 ± 0.2 hours by the emission of negative electrons according to the reaction

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

Following prolonged bombardment, however, two additional periods of 14.5 ± 0.3 hours and 75 ± 5 hours were detected, the latter being relatively weak. The 14.5-hour period is undoubtedly due to Na^{24} formed from the sodium present as impurity in the titanium as observed in the deuteron experiments. The long period, however, may well be much shorter than measured as experiments with the higher energies available using the $Li+H^{2}$ neutrons have disclosed a further very long period which has the effect of shortening the observed half-life of the order 80 hours to 42 ± 4 hours. Hence, although it is possible that the apparent half-life of 75 ± 5 hours is to be associated with a new radioactive isotope it seems more likely from the results of experiments with the more energetic neutrons that this period is due to a combination of a shorter period and a weak longer period which would have been detected had the period of observation been prolonged. On this assumption we will consider in greater detail the experiments

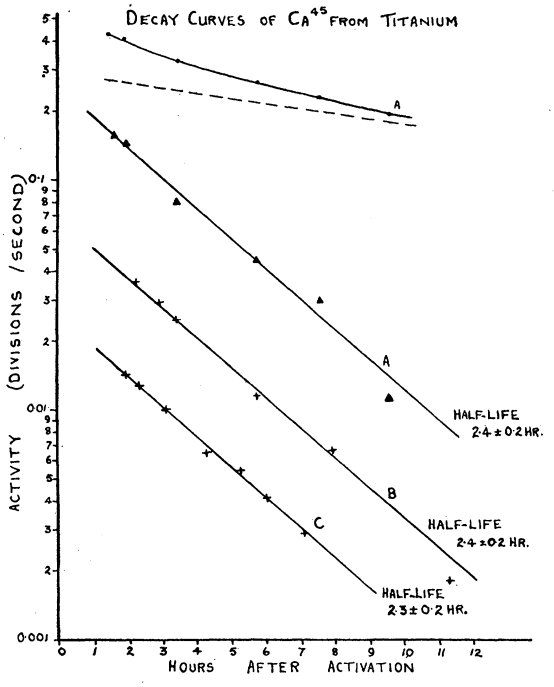

FIG. 9. Decay curves of 2.4 hour period from titanium activated by fast neutrons. A. Titanium metal powder Li+H^2 neutrons. Dots indicate total activity, dashes, background due to other longer periods. The points, solid triangles, have been corrected for these longer periods. B and C are decay curves of titanium metal after activation with fast neutrons from Be+H^2 reaction. The crosses have been corrected for longer period activities.

made by bombarding titanium with the fast neutrons from the Li+H^2 reaction.

B. Neutrons from lithium bombarded with deuterons

The radioactivity induced in titanium after activation with the 14–20 Mev neutrons from lithium bombarded with 5.5 Mev deuterons was found to be relatively strong, the decay curve showing the presence of several radioactive isotopes. Of these the shortest has a half-life of 2.4±0.2 hours due to the formation of Ca^{45}. The decay curves associated with this isotope are shown in Fig. 9. There is also a period of value 14.5±0.3 hours due to the sodium contamination. In addition, however, are present two isotopes, one of which has a half-life of 40±3 hours and the second of which is long lived. Observations made for a period of about five weeks suggest that the half-life of this body is of the order 85±5 days. Both these isotopes emit negative electrons as determined by means of a trochoid analyzer.

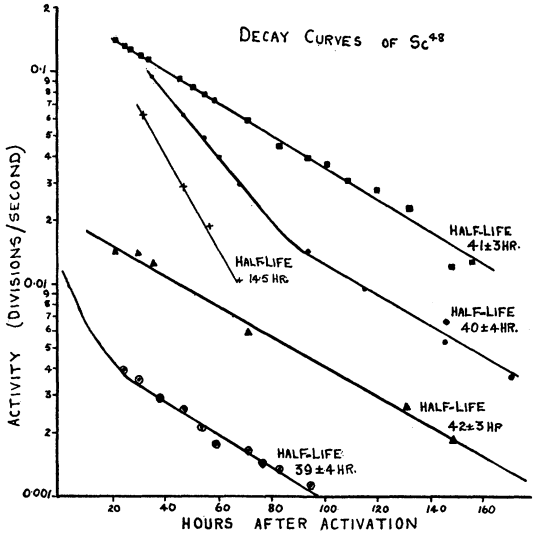

FIG. 10. Decay curves of Sc^{48}. The squares indicate activity of vanadic acid after activation with Li+H^2 neutrons (corrected for trace of very weak longer period). The dotted curve is that of titanium metal powder after activation with Li+H^2 neutrons showing 40 hour period and sodium contamination. The solid triangles represent the decay of scandium precipitate from titanium metal after activation with Li+H^2 neutrons. These last two curves have been corrected for the activity due to the 85-day period. Dots show the decay of vanadium metal after activation with the fast neutrons from a Be+H^2 source.

That they are isotopes of scandium is suggested by a somewhat rough chemical separation which was carried out as below.

The titanium was dissolved in $6N.HNO_3$ which was gently heated. To the resulting solution was added some inactive Sc_2O_3 and $CaCl_2$. The mixture was evaporated until its volume was reduced considerably and was distilled first with $16N.HNO_3$ and then with $9N.HClO_4$. Finally water was added, the solution being warmed gently for 10–15 minutes. By this method the titanium was precipitated as oxide. This precipitate was found to be weakly active though the presence of sodium in the metal makes it seem likely that this weak activity may be due to contamination.

Scandium was then precipitated from the filtrate by the addition of ammonium hydroxide. Most of the activity was retained by the precipitated hydroxide, the decay curve of which shows the presence of two radioactive isotopes, both of which emit negative electrons. The shorter period has the half-life 42±3 hours. The other is very long and measurements made for a month suggest

that it probably has the same value as the long period observed with the unseparated sample of metal, namely 85 ± 5 days.

This period agrees well with that of Sc^{46} *viz.* 85 ± 2 days. It thus seems likely that this isotope has been formed by the reaction

$$Ti^{46}+n^1\rightarrow Sc^{46}+H^1;\quad Sc^{46}\rightarrow Ti^{46}+e^-.$$

There may of course be still longer activities associated with the samples. However, time does not permit the author to look for such periods. On abundance grounds one would expect that Sc^{48} should be formed by a similar reaction, in which a proton is ejected from Ti^{48} for this isotope is present to an extent of 71 percent. Sc^{48} could also be formed by the ejection of an alpha-particle from vanadium, thus

$$V^{51}+n^1\rightarrow Sc^{48}+He^4.$$

Accordingly a search was made for this isotope by bombarding vanadium metal and vanadic acid with fast neutrons. The metal was bombarded for many hours with the fast neutrons from a beryllium target bombarded with deuterons and a weak activity was detected. The decay curve showed the presence of two isotopes with half-lives of 3.8 ± 0.3 hours (which is probably due to V^{50} as already discussed) and 39 ± 3 hours which agrees within the limits of experimental error with the period of 42 hours found with titanium (see Fig. 10). A sample of vanadic acid was then irradiated with the fast neutrons from a lithium target bombarded with 15 microamperes of 5.5 Mev deuterons. The activity was considerably enhanced and two periods were again observed together with a trace of a longer period which has not been identified but which may be due to contamination. The two half-lives were found to be 3.8 ± 0.3 hours and 41 ± 3 hours. The particles emitted by the isotope with half-life 41 ± 3 hours were found by means of a trochoid analyzer to be negative electrons.

This evidence thus suggests that Sc^{48} has been formed by the two reactions

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

its half-life being 41 ± 3 hours.

It is interesting in connection with these results to note that Pool, Cork and Thornton[5] have recently completed a survey of the activities induced in many elements by the fast neutrons emitted by a lithium target bombarded with deuterons. In vanadium they have observed a very weak period of 1.8 days (43 hours) which agrees well with the value 41 ± 3 hours observed by the author. They have not, however, detected the 3.8 hour period. The present experiments (see Fig. 2) have shown that the reaction $V^{51}+n^1\rightarrow V^{50}+2n^1$ is not a very probable one so that the failure of Pool, Cork and Thornton to observe this period might be due to the fact that their samples were not as strong as those used in the present experiments.

With titanium they observed periods of 1.7 hours and 28 hours, neither of which have been detected by the author. The isotopes responsible are stated to emit negative electrons. The evidence which has been presented here would suggest that the 28-hour period may be a combi-

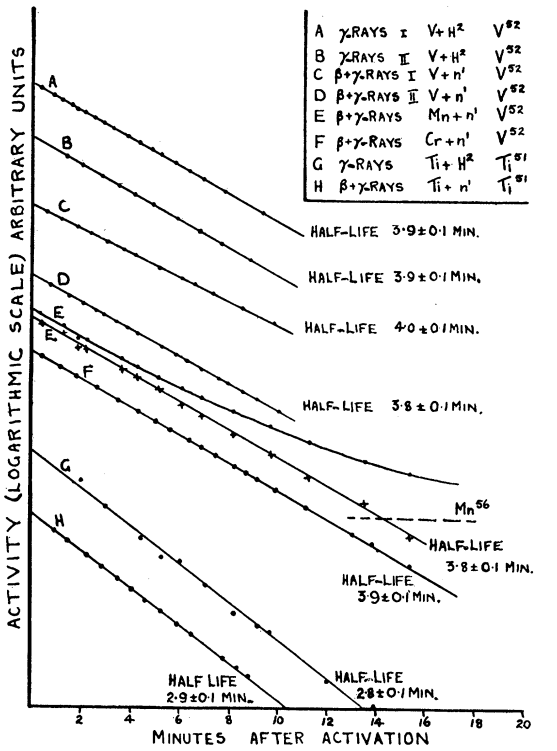

FIG. 11. Decay curves of short period activities of vanadium and titanium.

[5] Pool, Cork and Thornton, Phys. Rev. **52**, 239 (1937).

nation of the 41-hour period and the 14.5-hour period. The 1.7-hour period might well correspond with the 2.4-hour period observed by the author.

The Production of V^{52}

Vanadium when bombarded with deuterons or slow neutrons becomes strongly radioactive, emitting negative electrons and gamma-rays. The same isotope is formed in each case, namely V^{52} (half-life 3.9 ± 0.1 m) according to the reactions,

$$V^{51}+H^2\rightarrow V^{52}+H^1;\quad V^{52}\rightarrow Cr^{52}+e^-$$
$$V^{51}+n^1\rightarrow V^{52}+\gamma.$$

This has been confirmed by producing the same isotope by bombarding chromium and manganese with fast neutrons. In each case the decay curves show the presence of an isotope whose half-life is 3.9 ± 0.1 minutes. V^{52} is accordingly produced in the reactions

$$Cr^{52}+n^1\rightarrow V^{52}+H^1$$
$$Mn^{55}+n^1\rightarrow V^{52}+He^4.$$

Decay curves illustrating these reactions are shown in Fig. 11.

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Note on the Interaction Between Nuclei and Electromagnetic Radiation

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The exchange character of nuclear forces makes it impossible to formulate in a consistent way the coupling between the electromagnetic field and a nucleus described by a model which involves only heavy particles. This difficulty does not occur in a theory which introduces light particles as carriers of the charge in the exchange processes. The actual contribution of these light particles to the transition probabilities is proved to be negligible in the limit of wavelengths of the radiation large compared with nuclear dimensions and nonrelativistic motion of the heavy particles. In this limit one is justified in taking as coupling term $-(\mathbf{ED})$, where $\mathbf{D}$ is the dipole moment calculated from the heavy particle model, and $\mathbf{E}$ is the electric field. A marked influence of the exchange processes on the radiation properties of the nucleus exists even in the limit considered.

FOR the treatment of the nucleus as a mechanical system, it is considered as built up solely of protons and neutrons. To get agreement with the observed mass defects of light nuclei, one has to assume the interaction forces between these heavy particles to be of finite range and to be—at least partly—exchange forces. One would like to use this model also for calculating probabilities of emission and absorption of gamma radiation. Here, however, a serious difficulty appears, as Condon and Breit have pointed out.[1] It is not possible to justify any specific form of the interaction between nuclei and radiation from the heavy particle model only. In fact, because of the exchange processes implied by the

[1] E. U. Condon and G. Breit, Phys. Rev. **49**, 904 (1936).