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.

ACKNOWLEDGMENTS

In conclusion the author wishes to express his deep gratitude to Professor E. O. Lawrence for the generous hospitality which he has extended to him. The numerous kindnesses he has been accorded by the staff of the Radiation Laboratory are also gratefully acknowledged.

It is a pleasure to thank the Vanadium Corporation of America and Messrs. N. V. Philips Gloeilampenfabrieken of Eindhoven, Holland, who so generously donated the high purity vanadium and titanium with which some of these experiments have been performed.

The author is also grateful to Professor W. Libby of the Department of Chemistry who was kind enough to lend him several grams of scandium oxide of highest purity.

Grateful acknowledgment is made of the grants made to the laboratories by the Rockefeller Foundation and the Research Corporation. Thanks are also due to W.P.A. project, No. 10,695, for preparation of diagrams.

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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).

have tested this possibility by endeavoring to detect the new radioactive isotope in other reactions. In particular, the long period activities which can be induced in titanium by bombardment with α-particles of high energy have been investigated, for if the new isotope were an isomer of V^{49}, it should be produced by the reaction

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

since previous experiments by one of us have shown that the short-lived V^{49} (half-life 33 minutes) can thus be formed.

For these investigations Professor Alvarez was kind enough to send us a sample of titanium metal which had been bombarded with 16-Mev α-particles for 16 microampere hours.

As a result of these experiments we have failed to observe the 600-day vanadium activity which is consistent with the previous assignment to V^{47}. However, we have discovered another isotope which decays by K-electron capture, and we ascribe it to Cr^{51}. This body has rather unusual properties which have been studied in some detail. In the present paper these properties are discussed.

The stable isotopes to which reference will be made in the text are appended in Table I.

Apparatus

The apparatus which has been principally employed to study the K-capture process is the large cloud chamber designed by Williams.[2] It was used as in the experiments on V^{47}, the rate of decay of the strong x-ray emission being measured by counting photoelectron tracks in the manner previously described by Walke, Williams and Evans.[1]

The energy of the emitted electrons and the absorption in aluminum of the x-radiation (and thus the atomic number of the emitting atom) were determined by means of a thin-walled counter used as recommended by Feather.[3] When recording x-rays, electrons from the source were prevented from reaching the counter by placing the sample between the polepieces of a small electromagnet.

TABLE I. *Stable isotopes to which reference is made in the text.*

Element	Mass Numbers and Abundance				
22 Ti	46	47	48	49	50
	10.82	10.56	100	7.50	7.27
23 V	51				
	100				
24 Cr	50		52	53	54
	5.36		100	11.26	2.75

[2] E. J. Williams, Proc. Roy. Soc. **A172**, 194 (1939).

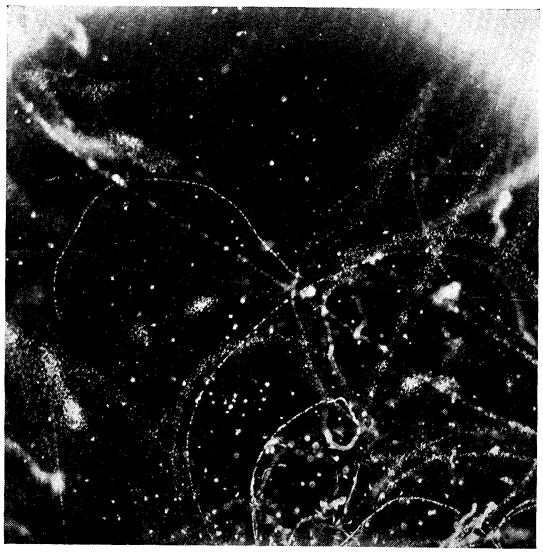

FIG. 1. Wilson chamber photograph showing short photoelectron tracts due to the emission of $VK\alpha$ radiation from a source of $Ti+He^4$. Secondary recoil electrons can also be seen. The rather high background of old tracks is due to the strong γ-radiation, which causes the emission of recoil electrons from the walls of the chamber and the brass shutter covering the source.

The energies of the γ-rays were obtained by measuring the range of their recoil electrons. The method adopted was the standard one of counting coincidences in two thin-walled counters between which aluminum foils could be placed, the recoil electrons being ejected from the wall of the counter nearest the source.

The rate of decay of the total activity and of the γ-radiation was obtained by ionization measurements made with a Lauritsen quartz fiber electroscope.

Identification and Half-Life of Cr^{51}

After the short-lived activities induced in titanium by alpha-particle bombardment have died away, the remaining activity* decays with

[3] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

* In a previous paper one of us (H.W.) has reported a long period of half-life $\sim$200 days, induced in TiO_2 by α-particles of energy 11 Mev. Continued observations

a single period of 26.5±1.0 days. Absorption measurements demonstrated that more than 10 percent of the ionization observed with an electroscope was due to γ-radiation which suggested that the emitted electrons were probably of secondary origin. Examination of the radiations using the cloud chamber showed that the ionizing particles were negative electrons, though a very intense x-ray emission was detected, the cloud chamber being filled with short range photoelectron tracks (see Fig. 1). These results suggested at once that the new isotope was probably decaying by K-electron capture, and this has been confirmed by more detailed investigations.

In the first place, the half-lives of the total activity, of the electrons of the γ-rays and of the K rays were carefully compared, and it was established that these are identical, namely 26.5±1.0 days as shown in Fig. 2. It was thus apparent that all the radiations were emitted by the same active isotope.

A careful chemical analysis was then carried out for us by Professor C. Perrier of the University of Palermo, to whom we wish to express our thanks for his generous cooperation, and it was proved that the activity can be chemically separated with chromium. From the chromium precipitate we were able to confirm the emission of the K radiation and the γ-rays both by absorption measurements and with the cloud chamber. The activity of this precipitate also decayed with the half-life 26.5±1.0 days.

The following arguments indicate that the responsible isotope is probably Cr^{51}.

By bombarding titanium with α-particles, only two possible radioactive isotopes of chromium may be produced, namely, Cr^{49} and Cr^{51}, the reactions being:—

$$Ti^{46}+He^4 \rightarrow Cr^{49}+n^1$$
$$Ti^{48}+He^4 \rightarrow Cr^{51}+n^1$$

and both of these should be positron radioactive. Thus:—

$$Cr^{49} \rightarrow V^{49}+e^+; \qquad V^{49} \rightarrow Ti^{49}+e^+$$
$$Cr^{51} \rightarrow V^{51}+e^+.$$

As it is known, however, that V^{49} has the half-life 33 minutes and emits positrons of maximum energy 1.9 Mev, then, if the radioactive isotope were Cr^{49} the transformation product V^{49} should be in equilibrium with its parent and energetic positrons should be observed accompanying the activity of half-life 26.5 days. None have been detected which excludes Cr^{49} as the active body, and indicates that Cr^{51} is the isotope under discussion.

Confirmatory evidence for associating the 26.5-day activity with Cr^{51} has been obtained by bombarding chromium with 8-Mev deuterons. From the activated metal a radioactive isotope of chromium has been chemically separated* which decays with the half-life 26.5 days (see Fig. 2), and the same body has been produced by bombarding chromium metal with *slow* neutrons. Cr^{49} could not be formed by any known reactions by activating chromium with these particles, but Cr^{51} can be produced as below

$$Cr^{50}+H^2 \rightarrow Cr^{51}+H^1$$
$$Cr^{50}+n^1 \rightarrow Cr^{51}+\gamma.$$

Moreover the production of the 26.5-day activity by bombarding chromium with *slow* neutrons rules out the possibility that the active isotope might be a metastable state of one of the stable chromium isotopes.

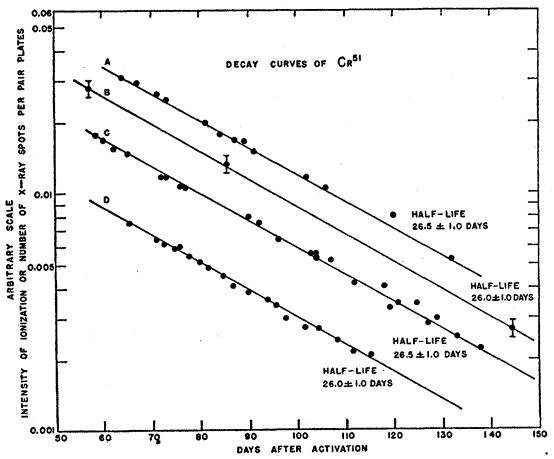

FIG. 2. Decay curves of Cr^{51}. A. γ-ray decay Ti+He^4; B. x-ray decay Ti+He^4 (first point 272 "spots" per plate); C. decay of total activity Ti+He^4. D. decay of total activity of chromium precipitate separated from chromium+deuterons.

have shown that the half-life is 450 days the emitted particles being positrons of energy ~0.35 Mev. However no evidence for this activity has been obtained from the very pure titanium metal and we therefore conclude that the effect observed with the TiO_2 must be due to some impurity (as yet not identified).

* It is a pleasure to thank Dr. G. Seaborg of the Department of Chemistry for extracting the active chromium.

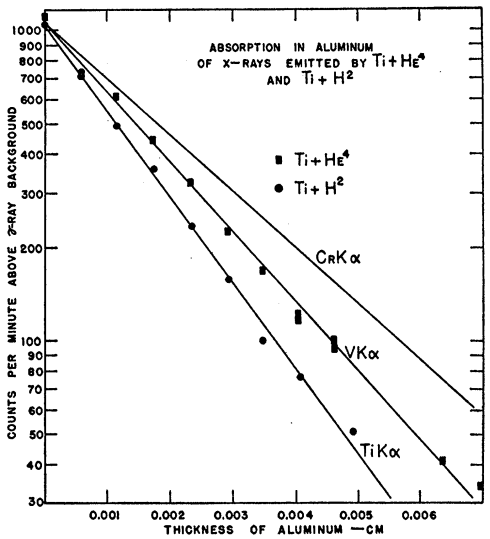

FIG. 3. Absorption in aluminum of x-radiation emitted by Ti+He⁴(Cr⁵¹).

TRANSFORMATION OF Cr^{51} BY K-ELECTRON CAPTURE

Strictly speaking the observation of the K radiation provides evidence only for the removal of K electrons from the atoms concerned and in order definitely to establish the transformation of nuclei by electron capture it must be shown as Alvarez[4] has emphasized that no other process is responsible for their removal. In the case of V^{47} previously investigated it was proved conclusively that only K-electron capture could account for the observed x-radiation. The K rays from Cr^{51}, however, are accompanied by a high intensity of γ-radiation and some electrons also and it is therefore necessary to prove that they are not responsible for the removal of the K electrons.

The atomic number of the atom emitting the K radiation was determined by measuring the absorption coefficient of the radiation in aluminum using a Geiger-Müller counter as detector. The absorption coefficient was compared directly with that of Ti$K\alpha$ by making measurements on a strong source of V^{47} (in the form of titanium metal which had been bombarded with deuterons)[1] and on the sample under investigation using the same geometrical conditions and the same aluminum absorbers. It was thus established that the responsible atom has atomic number 23 ± 0.1 and is therefore undoubtedly vanadium. This is shown clearly by the absorption curves of Fig. 3. It was similarly confirmed that V$K\alpha$ radiation is emitted by the chemically separated chromium.

The above results are consistent with the supposition that the K radiation results from the capture of a K electron by the nucleus of a chromium atom, for in that case the K radiation emitted would be that of the vanadium atom resulting from the capture. No other hypothesis fits the facts. Let us suppose for instance that the K electron of a chromium atom is removed by electronic or quantum radiation from other chromium atoms. In this case the K radiation emitted would be that of *chromium*. This would also be so if the K electron were removed by internal conversion of γ-radiation from the nucleus of the same atom. If it was removed by a disintegration *electron* from the nucleus of the same atom the K radiation emitted would be that of *manganese*. Thus the fact that the K radiation is that of *vanadium* rules out all these processes.

There remains however the possibility that the chromium nucleus emits a slow positron which either removes a K electron in leaving the atom or leaves the product vanadium nucleus in an excited state the γ-ray quantum subsequently emitted being internally converted. The K radiation emitted would in this case be that of vanadium. However owing to the annihilation of the positrons two quanta of energy 0.5 Mev would also be emitted for every nuclear transformation. In the case of Cr^{51} such γ-rays are in fact observed as will be discussed more fully in the next section. But the number of x-rays observed is greater by a factor of twenty than can be accounted for in this way. It may be concluded therefore that the majority of Cr^{51} nuclei decay by K-electron capture and that this process is the main cause of the strong x-ray emission observed.

ELECTRONS AND γ-RAYS FROM Cr^{51}

In addition to V$K\alpha$ radiation titanium metal after bombardment with high speed α-particles emits two groups of electrons and two γ-rays. The energies of the electrons as determined by

[4] L. W. Alvarez, Phys. Rev. **54**, 486 (1938).

absorption measurements are 0.35 ± 0.02 Mev and 1.0 ± 0.1 Mev, respectively, the γ-ray values being 0.5 ± 0.02 Mev and 1.0 ± 0.1 Mev.

The electrons of energy 1.0 ± 0.1 Mev constitute an electron line and not a continuous distribution as can be seen from the absorption curves of Fig. 4. Their energy is so close to that of the hard γ-ray that it is highly probable that they are produced by its internal conversion.

The excitation of γ-radiation of energy 1.0 Mev by the K-capture process suggests that Cr^{51} is actually unstable against decay by positron emission. However a careful search using the cloud chamber has failed to reveal the emission of positrons of energy $>100{,}000$ ev, the lower limit we can set to be probability of K capture to that of the emission of positrons with more than 100,000 ev energy being 10,000. We cannot, however, exclude the possibility that positrons of lower energy are emitted, since such particles would have a very short range and the curvature of their paths in a magnetic field would not be sufficiently uniform to allow the determination of their sign with certainty. The observation of γ-radiation of energy 0.5 ± 0.02 Mev suggests that slow positrons are, in fact, emitted and that this γ-radiation is due to their annihilation.

On the basis of Møller's[5] calculations an estimate can be made of the upper limit of the positron spectrum by assuming that the observed γ-rays of energy 0.5 Mev are due to positron annihilation.

The relative probability of the alternative modes of transformation by positron emission and electron capture depend on certain detailed features of the theories of β-decay, the requirements in this respect of Fermi's[6] theory being very different from those of the modification by Uhlenbeck and Konopinski.[7] The results thus obtained for Cr^{51} show, however, that if the Uhlenbeck-Konopinski theory is valid the maximum energy of the emitted positrons should be 0.5 Mev which is quite out of the question, for such particles would have easily been observed with the cloud chamber. The Fermi theory yields an upper limit of ~0.2 Mev which is certainly in better agreement with our observations, although even this value would seem to be rather higher than is consistent with our results.

The electrons of maximum energy 0.35 ± 0.05 Mev are probably recoil electrons ejected from the source by the annihilation radiation.* The number of these electrons is small being only 0.5 percent of the number of quanta of energy 0.5 Mev.

The value calculated for titanium metal of the dimensions used, assuming that the electrons are in fact produced in this way, is in good agreement with this figure being also 0.5 percent.†

That the electrons do not constitute a normal β-distribution is shown from the absorption curve of Fig. 5.

Further evidence that the electrons are of secondary origin was obtained by placing above the sample an inactive piece of titanium of the same dimensions as the radioactive material and photographing with the cloud chamber the recoil electrons ejected from the upper plate by the γ-rays from the source. The number of recoil electrons thus observed was almost as large as the number emitted from the source itself.

It therefore seems probable that all the electrons emitted by Cr^{51} are of secondary origin, being either recoil or conversion electrons produced by γ-radiation.

Internal Conversion in Cr^{51}

The γ-ray of energy 1.0 ± 0.1 Mev is due to an upper state of V^{51} which is excited following K capture by Cr^{51}. This excited state of V^{51} has also been observed by Davidson, Jun and

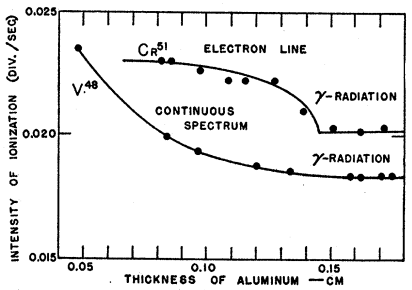

FIG. 4. Absorption curves of β-rays of energy 1.0 Mev from Cr^{51} and V^{48} showing conversion electrons from Cr^{51}.

[5] C. Møller, Physik. Zeits. Sowjetunion **11**, 9 (1937).
[6] E. Fermi, Zeits. f. Physik **88**, 160 (1934).
[7] G. E. Uhlenbeck and E. J. Konopinski, Phys. Rev. **48**, 7 (1935).

* The maximum energy of recoil electrons from γ-radiation of energy 0.8 Mev is 0.33 Mev.

† We wish to thank Professor J. R. Oppenheimer for making this estimate for us.

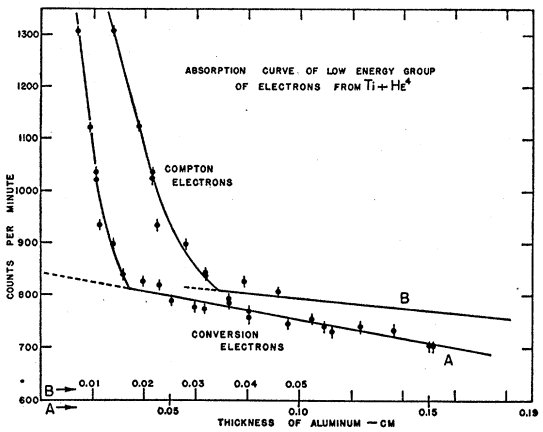

FIG. 5. Absorption curve of low energy electrons from Ti+He⁴.

Pollard[8] in the reactions

$$Ti^{48}+He^{4}\rightarrow V^{51}+H^{1} \qquad (\gamma=1.1\pm0.1 \text{ Mev})$$

and by Walke, Williams and Evans[1] by the decay of Ti^{51} thus

$$Ti^{51}\rightarrow V^{51}+e^{-} \qquad (\gamma=1.0\pm0.1 \text{ Mev}).$$

The discovery that the γ-radiation is internally converted was somewhat unexpected and we have therefore made an estimate of the internal conversion coefficient. This has necessitated assuming a value for the γ-ray efficiency of the counter used, but this may be estimated from the results of Sizoo and Willemsen.[9] In consequence it appears that the internal conversion coefficient is of the order 10^{-3}. (The actual calculated result is 3×10^{-3}.)

This high value for the internal conversion coefficient indicates that a large difference of spin must exist between this state of V^{51} and the ground state. On the basis of the formulae given by Dancoff and Morrison[10] it may be estimated that the spin change in the transition in which the γ-ray is formed must be of the order 4 units. Since the nuclear spin of the ground state of V^{51} is 9/2 it may well be that the spin of the excited state is $\frac{1}{2}$.

It is possible also to estimate the fraction of the Cr^{51} nuclei which decay by capturing the K electron into this excited state of V^{51}. The number is actually rather small being of the order 2–3 percent.

ACKNOWLEDGMENTS

It is once more a pleasure to acknowledge our indebtedness to the staff of the Radiation Laboratory of the University of California for their most generous cooperation. We wish especially to thank Professor E. O. Lawrence whose gifts of radioactive material have made this work possible. We are also grateful to Professor J. Chadwick, F.R.S., for his helpful advice and continued interest.

The gifts of high purity titanium from Messrs. N. V. Philip Gloeilampenfabrieken of Eindhoven, Holland, and high purity chromium from the National Physical Laboratory, England, are acknowledged gratefully.

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This research has been aided by grants to the Radiation Laboratory by the Rockefeller Foundation and the Research Corporation. Assistance with preparation of diagrams has been given by W.P.A. project No. 10695.

[8] Davidson, Jun and Pollard, Phys. Rev. **54**, 408 (1938).
[9] G. J. Sizoo and H. Willemsen, Physica **5**, 105 (1938).
[10] S. M. Dancoff and P. Morrison, Phys. Rev. **55**, 122 (1939).

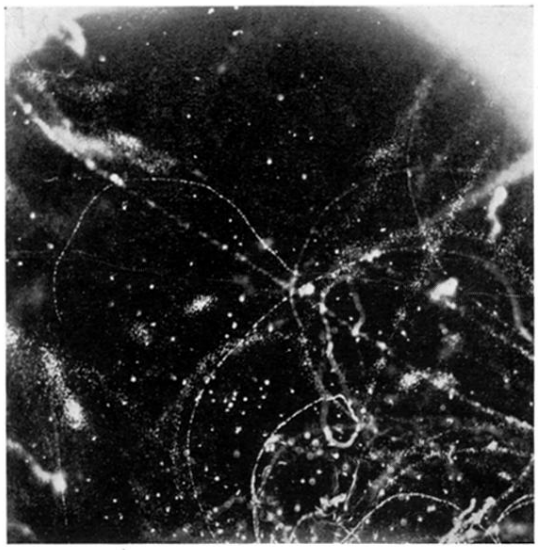

FIG. 1. Wilson chamber photograph showing short photoelectron tracts due to the emission of V$K\alpha$ radiation from a source of Ti+He^4. Secondary recoil electrons can also be seen. The rather high background of old tracks is due to the strong γ-radiation, which causes the emission of recoil electrons from the walls of the chamber and the brass shutter covering the source.