Radioactive Isotopes of Vanadium

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Further consideration of the experimental facts concerning the active V of a half-life of 600 days leads to the conclusion that it should be attributed to V^{49} rather than to V^{47} as hitherto proposed. The relatively low yields of V^{50} in the (d, n) reaction and of V^{52} in the (α, p) reaction suggest the existence of not yet discovered long-lived isomers of these nuclei.

THE purpose of this paper is to discuss some of the radioactive isotopes of V, pointing out that there seems to be evidence for the assignment of the 600-day activity to V^{49} rather than to V^{47} and that there are indications for the probable existence of long-lived isomers of V^{50} and V^{52}. No new experimental evidence is presented.

For the convenience of the reader the stable isotopes of the elements involved in the discussion are given in Table I.

THE 600-DAY ACTIVITY

The long-lived V was studied by Walke, Williams and Evans[1] and tentatively attributed by them to V^{47}, partly because of the absence of any other activity which might be ascribed to that isotope, and partly because of reluctance to make the assumption of nuclear isomerism when not necessary. Their assignment was apparently confirmed by the later work of Walke, Thompson and Holt,[2] who were unable to observe this active substance in a sample of Ti which had been well bombarded by α-particles. Such bombardment can produce V nuclei of masses from 49 to 53 inclusive by the (α, p) reaction. The 600-day active V is strong in the deuteron-bombarded Ti, the possible masses being 47 to 51 inclusive. V^{47} and V^{48} are thus the two isotopes that can be produced by bombardment of Ti with deuterons but not with α-particles. V^{48} is known to have a half-life of 16 days and is unambiguously identified by its production in the $Sc^{45}(\alpha, n)V^{48}$ and $Cr^{50}(d, \alpha)V^{48}$ reactions. V^{47} was thus left for the 600-day activity. It may be shown as follows, however, that if the 600-day active V is either V^{49} or V^{50} its intensity in the α-bombarded Ti would have been too low for it to have been observed, thus removing the basis for the argument in favor of V^{47}.

In their sample of α-bombarded Ti Walke, Thompson and Holt[2] did find an active substance having a half-life of 26.5 days that they proved to be Cr^{51} produced in the $Ti^{48}(\alpha, n)Cr^{51}$ reaction. They showed that the Cr^{51} decays almost entirely by K capture, with resulting strong production of the K radiation of V. The "spots" produced by these x-rays in cloud-chamber pictures were observed in the same way as those from the 600-day active V had been by Walke, Williams and Evans.[1] 57 days after activation the Cr^{51} gave 272 spots per plate. From this one calculates an initial intensity of 1200 spots per plate. Since the sensitivity for the detection of the x-rays from the active V must be substantially the same as for those from Cr^{51}, the intensity of the 600-day V to be expected may be calculated from the initial activity of the Cr^{51}. (The difference between the sensitivities for detection of Ti x-rays and V x-rays, respectively, is negligible in the semi-quantitative argument that follows.) Provisionally ascribing the 600-day active V to an isomer of V^{50}, the calculation goes as follows. The value of 1200 for Cr^{51} must be multiplied by a factor of 26.5/600 to take account of the different decay constant, by a factor of 10.56/100 because of the relative abundance of Ti^{47} and

TABLE I. *Stable isotopes.*

ELEMENT	MASS NUMBERS AND ABUNDANCES				
21 Sc	45(100)				
22 Ti	46(10.82)	47(10.56)	48(100)	49(7.50)	50(7.27)
23 V	51(100)				
24 Cr	50(5.36)		52(100)	53(11.26)	54(2.75)

[1] Walke, Williams and Evans, Proc. Roy. Soc. **A171**, 360 (1939).
[2] Walke, Thompson and Holt, Phys. Rev. **57**, 171 (1940).

Ti^{48} (V^{50} assumed to be produced in the $Ti^{47}(\alpha, p)V^{50}$ reaction), and by a factor much less than unity because of the relative probabilities of ejection of protons and of neutrons from the compound nuclei. From Fig. 3 of the paper of Weisskopf and Ewing[3] we may take 1/10 as a conservative estimate of the relative probability of the escape of protons and neutrons from compound nuclei having energies of $\sim$22 Mev or less, as were produced in the bombardment by 16-Mev α-particles. The predicted initial activity of the 600-day substance in spots per plate is thus

$$1200\times\frac{26.5}{600}\times\frac{10.56}{100}\times\frac{1}{10}\sim 0.5.$$

Such an intensity could not have been observed in the experiments of Walke, Thompson and Holt since their last set of observations gives 27 ± 2.5 spots per plate, as taken from their Fig. 2. These experiments, therefore, do not preclude the assignment of the 600-day activity to V^{50}. The conclusion does not depend on a too literal acceptance of the results of Weisskopf and Ewing, which are of only approximate validity for nuclei of mass $\sim$50. Any factor in accord with the general principle that (α, p) reactions are appreciably less probable than (α, n) reactions would give a low result from which the same conclusion would be drawn.

If the 600-day activity is attributed to an isomer of V^{49} the argument is not so compelling. V^{49} nuclei would be produced directly in the $Ti^{46}(\alpha, p)V^{49}$ reaction and also indirectly through the $Ti^{46}(\alpha, n)Cr^{49}$ reaction. Cr^{49}, not yet identified experimentally, undoubtedly decays to V^{49} by emission of positrons or by K capture. Since Cr^{49} is further removed from the bottom of the "valley" of the stable nuclei than is Cr^{51} it may be expected to have a much shorter half-life and thus to have escaped observation in the experiments of Walke, Thompson and Holt. It is highly probable that in the well-aged sample of Ti studied by them practically all of the Cr^{49} had decayed to V^{49} and that whatever amount of the latter was present had been produced chiefly from active Cr^{49} rather than more directly by the (α, p) process. A calculation like the one made above gives 5 spots per plate for the effective initial intensity of the 600-day activity if it is ascribed to V^{49}. The abundances of Ti^{46} and Ti^{47} are nearly the same and the factor of 1/10 is omitted since it is the (α, n) process which is now relevant for both Cr^{51} and V^{49}. This activity would have decayed to 4 spots per plate after 145 days at which time the activity of the Cr^{51} was 27 ± 2.5. This calculated value of 4 is too close to the standard error of 2.5 for it to be concluded with assurance that the 600-day activity may not be attributed to V^{49}.

Although the foregoing argument does not decide between V^{49} and V^{50} it does seem to obviate the necessity of attributing the long-lived V to V^{47}. As Wigner pointed out to Walke and collaborators[1,2] the decay of V^{47} almost entirely by K capture would be very difficult to understand theoretically.

From their measurements on a sample of Ti which had been bombarded with fast deuterons Walke, Williams and Evans[1] concluded that the cross section for formation of 600-day V^{47} in the $Ti^{46}(d, n)V^{47}$ reaction is 10 times as great as that for the formation of V^{48} in the $Ti^{47}(d, n)V^{48}$ reaction. For other assignments of the 600-day activity the calculation has to be modified merely so as to take account of the different abundance of the appropriate Ti isotope. If we assume the 600-day active nuclei to be V^{50} the factor of 10 is to be multiplied by 10.82/7.50 to give 14 for the ratio of cross sections, for the assumption of V^{49} it must be multiplied by 10.82/100 to get 1. The value of 1 is entirely reasonable, whereas a value of 14 is unlikely. The bombardment of Ti^{47} and Ti^{49} nuclei by deuterons of 5 Mev of energy should produce compound nuclei of V^{49} and V^{51} excited to something like 19 Mev. There is no apparent reason why the probabilities of formation of these compound nuclei should differ markedly from each other, although the alternative possible occurrence of the Oppenheimer-Phillips process makes it more difficult to estimate just what these probabilities are. The energy of excitation of these compound nuclei is high enough so that the general considerations of the paper of Weisskopf and Ewing[3] are applicable. There seems to be no reason why the escape of a neutron from the excited nucleus of V^{51} should be 14 times as

[3] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

probable as that for escape from a V^{49} nucleus. This eliminates V^{50} as a possibility for the 600-day activity, leaving only V^{49}. The value of 1 for the ratio of the cross sections for production of V^{48} and V^{49} is what one would expect, granting the same probability of formation of both compound nuclei, V^{49} and V^{50}.

In the latter argument the 33-min. activity attributed to V^{49} has been ignored. This is permissible since measurements by Walke[4] indicate a low yield of such active nuclei, negligible in comparison with that of the V^{48} and the 600-day nuclei. His assignment of this half-life to V^{49} seems to be unambiguous since 49 is the only mass number of a V isotope producible in both the Ti(d, n)V and Ti(α, p)V reactions that could not be produced by bombarding V^{51} with fast neutrons.

It seems reasonable to conclude that there are two isomers of V^{49}, decaying with half-lives of 600 days and 33 hours, the latter being the more highly excited and of a much lower probability of formation. Isomers of such relative half-lives and energies have already been found[5] for Ag^{106}.

Possible Long-Lived Isomers of V^{50} and V^{52}

Walke[4] produced an active positron-emitting V having a half-life of 3.7 hr. by various methods which seemed to show conclusively that it is to be attributed to V^{50}. The cross section for its formation, however, was very low compared to that for V^{48}. At the time Walke suggested that the apparent large yield of V^{48} might possibly be explained by the occurrence of the $Ti^{48}(d, 2n)V^{48}$ reaction involving the abundant 48 isotope of Ti. The subsequent finding of the large cross section for the formation of the 600-day V obviated the necessity of considering the V^{48} yield to be unusually large, and requiring special explanation. It seems that the energy of excitation is hardly high enough for the $(d, 2n)$ process to be a relatively probable one. In spite of the obvious difficulties of making accurate estimates of relative cross sections the difference between those for V^{50} and V^{48} is so great that it must be considered significant. Either the cross sections for the $Ti^{47}(d, n)V^{48}$ and $Ti^{49}(d, n)V^{50}$ processes are greatly different for reasons not yet clear, or else there must be formation of other, as yet undiscovered, V^{50} nuclei in considerable quantity. They would have to be of very short or of very long half-life to have escaped detection. It is entirely possible that they decay to Cr^{50} by emission of very soft negative beta-rays.

Walke also found that Ti which had been bombarded with 11-Mev α-particles showed the 33-min. and 3.7-hr. active V's and an unidentified substance having a half-life of 68 hr. He was unable, however, to find any indication of V^{52}, which has a half-life of 3.9 min., and should thus be especially easy to detect. As Walke pointed out, the cross section of the $Ti^{49}(\alpha, p)V^{52}$ process is apparently very much less than that for $Ti^{47}(\alpha, p)V^{50}$. This is contrary to theoretical expectation[3] and leads one to suspect the existence of a more probable isomer of V^{52} which has escaped detection so far, presumably because of a long half-life and low energy of beta-particles.

[4] H. Walke, Phys. Rev. **52**, 777 (1937), especially Table I on p. 783.

[5] For references see J. J. Livingood and G. T. Seaborg, Rev. Mod. Phys. **12**, 30 (1940).