Decay of Ti^{51} and Cr^{51}†

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The radiations of Ti^{51} (5.8 min) and Cr^{51} (27 day) have been investigated with beta- and gamma-scintillation spectrometers. Gamma rays having energies of 0.323, 0.605, and 0.928 Mev and relative intensities of 95.8:1.4:4.2, respectively, were observed to accompany the decay of Ti^{51}. Two beta groups were observed of energy 2.13 and 1.5 Mev, having relative intensities of 94.4 and 5.6, respectively. The 2.13-Mev transition leads to the 0.323-Mev level of V^{51}. There is no evidence for a beta transition to the ground state of V^{51}. Cr^{51} decays by electron capture to both the ground state and the first excited state of V^{51}. The intensity of the capture branch to the 0.323-Mev level was measured to be 9.8 percent. A value of 3.25×10^{-3} was found for the total internal conversion coefficient of the 0.323-Mev gamma transition, indicating that the transition is $M1+E2$. The spin and parity assignments suggested by the experimental data are discussed.

I. INTRODUCTION

VANADIUM-51, daughter nucleus of both Ti^{51} and Cr^{51}, has 23 protons and a measured spin of 7/2. Its ground-state configuration can therefore be described as $(1f_{7/2}{}^3)_{7/2}$. In view of the relatively meager amount of information existing on the excited states of V^{51}, reinvestigation of the radiations of both Ti^{51} and Cr^{51} has been undertaken.[1] In particular, it was hoped that information would be gained regarding the theoretically predicted excited states of the $(1f_{7/2}{}^3)$ configuration.[2,3]

II. DECAY OF Ti^{51}

(a) Source Preparation

The Ti^{51} sources were prepared by neutron irradiation of titanium enriched in Ti^{50} (81.44 percent). The enriched titanium, obtained from Oak Ridge National Laboratory, was in the chemical form TiO_2. Since the spectrographic analysis indicated that none of the detectable impurities had an abundance of >0.1 percent, no further chemical purification of the irradiated titanium was made.

(b) Gamma-Ray Experiments

The gamma-ray spectrum of Ti^{51}, shown in Fig. 1, was obtained with a 2×2 inch NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier. A ten-channel analyzer was used for the recording of data. The entire spectrum of Fig. 1 was found to decay with the half-life of Ti^{51}, which we have measured to be 5.80±0.03 minutes, in excellent agreement with the most recently reported value of 5.79±0.03 minutes.[4] Careful calibration with Au^{198} (411.8 kev), Sb^{124} (603 kev), Cs^{137} (661.6 kev), and Mn^{56} (845 kev) yielded energy values for the three observed Ti^{51} photopeaks of 323±2 kev, 605±4 kev, and 928±5 kev. The relative intensities of the three gammas, based on an empirical curve of photopeak sensitivity *vs* energy, were found to be 95.8:1.4:4.2.

On the basis of the above energies, it appeared likely that the 605- and 323-kev gammas are in coincidence and that the 928-kev gamma is the crossover transition. Therefore, a gamma-gamma coincidence experiment[5] was performed in which the 323-kev photopeak was used as the "gate" and the ten-channel analyzer was set to cover the 600-kev region of the coincidence spectrum. A strong peak was observed at 605-kev, only ~5 percent of which resulted from chance coincidences. The 605- and 323-kev gammas are therefore definitely in coincidence. No other photopeaks were found in the coincidence spectrum. Particular attention was given to the 160-kev region, where a weak photopeak could possibly be obscured in the ungated spectrum by the Compton peak of the 323-kev gamma.

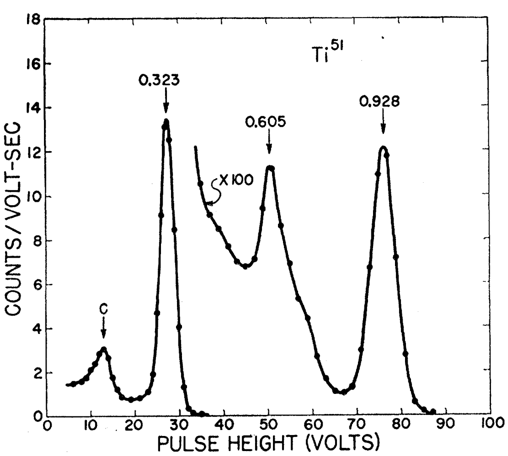

FIG. 1. γ-ray spectrum of Ti^{51}, obtained with a 2-inch NaI(Tl) crystal. The high-energy region is shown on an enlarged scale (100×).

† Work done under the auspices of the U. S. Atomic Energy Commission.

[1] Following completion of the experiments on Ti^{51} described below, accounts of studies of the Ti^{51} decay scheme were published by Jordan, Burson, and Le Blanc, Phys. Rev. **96**, 1582 (1954); R. H. Nussbaum, Thesis, Amsterdam (1954).

[2] D. Kurath, Phys. Rev. **91**, 1430 (1953).

[3] A. R. Edmonds and B. H. Flowers, Proc. Roy. Soc. (London) **A215**, 120 (1952); I. Talmi, Helv. Phys. Acta **25**, 185 (1952).

[4] Sargent, Yaffe, and Gray, Can. J. Phys. **31**, 235 (1953).

[5] For a description of the coincidence apparatus, see Bunker, Mize, and Starner, Phys. Rev. **94**, 1694 (1954).

(c) Beta-Ray Experiments

The beta spectrum of Ti^{51} was examined with a beta scintillation spectrometer consisting of a bare Pilot Plastic Scintillator-B[6] phosphor $1\frac{3}{4}$ inches in diameter and $\frac{3}{4}$-inch thick coupled directly to a DuMont 6292 photomultiplier with Dow Corning 200 fluid. The spectrometer was calibrated with the beta spectrum of P^{32}, whose end-point energy was taken to be 1.705 Mev. The Ti^{51} source consisted of an $\sim$1 mg/cm² deposit of irradiated TiO_2 on Scotch tape backing.

A Fermi analysis of the high-energy portion of the Ti^{51} spectrum is shown in Fig. 2 (upper curve). The end-point region has been corrected for resolution according to the method of Palmer and Laslett.[7] The Fermi plot appears to be straight from the end point of 2.13±0.03 Mev back to at least 1.5 Mev. The linearity of the Fermi plot was unexpected since previous studies[8,9] had indicated the presence of two high-energy beta groups differing in energy by $\sim$0.3 Mev.

Two beta-gamma coincidence experiments provided conclusive proof that the 2.13-Mev beta group goes to the 0.323-Mev level of V^{51}. In the first experiment, the beta spectrum in coincidence with the 323-kev gamma was examined. A Fermi plot of the observed data is shown in Fig. 2 (lower curve). The ungated and concidence spectra clearly have the same end-point energy. From the fact that there is no indication in the ungated spectrum of a beta group of energy $>$2.13 Mev, it is concluded that the intensity of the beta transition to the ground state of V^{51} must be less than 1 percent of the intensity of the 2.13-Mev transition.

The second beta-gamma coincidence experiment merely served to check the results just described. The gamma spectrum was gated with pulses from the beta spectrometer corresponding to energies $\geqslant$1.5 Mev. A calibrated geometry was used in which the photopeak sensitivity (ϵ_γ) of the gamma counter was known. By observing the number of coincidences in the 323-kev photopeak ($N_{\beta\gamma}$) per beta detected (N_β), the fraction (B) of the betas of energy $\geqslant$1.5 Mev which are followed by the 323-kev gamma can be determined from the relation $N_{\beta\gamma}/N_\beta = B\epsilon_\gamma$. The value found for B was 1.00. The probable error in the observed value of B is at least 5 percent since ϵ_γ is not known to better than 5 percent. However, this experiment provides additional proof that the ground-state beta transition, if detectable at all, is extremely weak.

The experiments described thus far suggest that there is an excited state of V^{51} at 928 kev which is populated by a weak Ti^{51} beta group of end-point energy about 1.52 Mev. In order to verify this, an examination was made of the beta spectrum in coincidence with the 928-kev gamma. The coincidence spectrum was found to have an end-point energy of 1.50±0.05 Mev, in relatively good agreement with the energy predicted from the results of the preceding experiments.

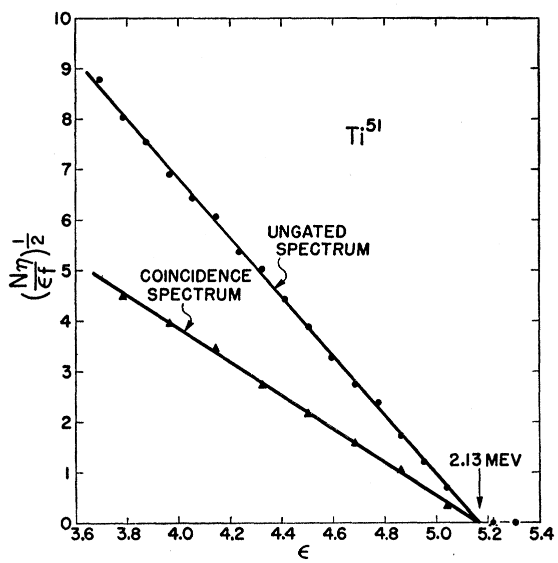

FIG. 2. High-energy portion of the Ti^{51} Fermi plots. "Ungated spectrum" refers to the normal beta spectrum; "coincidence spectrum" refers to the beta spectrum in coincidence with the 0.323-Mev gamma ray.

III. DECAY OF Cr^{51}

(a) Previous Results

Previous studies[10–12] have established that Cr^{51} decays by K-capture to both the ground state and the 0.323-Mev level of V^{51}. The total disintegration energy is known to be 0.750 Mev from the threshold of the $V^{51}(p,n)Cr^{51}$ reaction.[13] The intensity of the capture branch to the excited state has been assigned values ranging from $\sim$3 percent[10] to 21 percent.[12] The internal conversion coefficient of the 0.323-Mev transition has recently been measured to be $\alpha_K = 1.5\times10^{-3}$.[12] Since the true value of α_K and the ft value of the capture branch to the excited state both provide valuable information about the 0.323-Mev level of V^{51}, these quantities have been redetermined.

(b) Source Material

The Cr^{51} source material was obtained from Oak Ridge National Laboratory. Since the radio-chemical

[6] Pilot Chemicals, Inc., 47 Felton Street, Waltham 54, Massachusetts.

[7] J. P. Palmer and L. J. Laslett, Atomic Energy Commission Report AECU-1220, March 14, 1951 (unpublished).

[8] Koester, Maier-Liebnitz, Mayer-Kuckuk, Schmeiser, and Schulze-Pillot, Z. Physik **133**, 319 (1952).

[9] E. der Mateosian, quoted in Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[10] Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta **18**, 259 (1945).

[11] W. S. Lyon, Phys. Rev. **87**, 1126 (1952).

[12] Maeder, Preiswerk, and Steinmann, Helv. Phys. Acta **25**, 461 (1952).

[13] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

purity was known to be >99 percent, no further purification was deemed necessary. The specific activity at the time of the measurements described below was ~300 mc/g Cr.

(c) Branching Ratio Measurement

The intensity of the capture branch to the 0.323-Mev level was measured by means of an x-ray—gamma coincidence experiment. The vanadium K x-rays (~5 kev) were detected with a bare NaI(Tl) crystal $\frac{1}{8}$-inch thick coupled directly to a DuMont 6292 photomultiplier. With the Cr^{51} source in place, the background directly under the x-ray peak amounted to only ~1 percent of the gross counting rate. The gamma detector was a 2×2 inch NaI(Tl) crystal. A calibrated geometry was used in which the photopeak sensitivity (ϵ_γ) of the gamma counter was known. By observing the number of x-ray—gamma coincidences ($N_{x\gamma}$) per x-ray detected (N_x), one can determine the fraction of the Cr^{51} K-capture events (B) which are followed by the 0.323-Mev gamma from the relation $B=N_{x\gamma}/\epsilon_\gamma N_x$. A great advantage of this method is that it does not require knowledge of either the K fluorescent yield or the efficiency of x-ray detection. The value obtained for the branching ratio is $B=0.098$. The estimated probable error in this value is ±0.006, most of which results from lack of precise knowledge of ϵ_γ.

(d) Internal Conversion Measurement

The total internal conversion coefficient of the 323-kev gamma was measured by a comparison method. Thin sources (~1 mg/cm²) of Cr^{51} and Au^{198} were mounted on nylon backing (~0.5 mg/cm²), and the relative strengths of the 323-kev (Cr^{51}) and the 411.8-kev (Au^{198}) gammas were determined with the calibrated 2×2 inch NaI(Tl) crystal. The internal conversion spectra of these two sources were then examined in a magnetic lens spectrometer. Because of the inherent resolution of the spectrometer (~2.2 percent), the individual Cr^{51} conversion lines could not be resolved. Although both the Cr^{51} "line" and the Au^{198} K-line were slightly broadened because of source thickness, low-energy "tailing" was virtually absent, thus permitting an accurate comparison of the areas of these two lines. From the two comparison measurements just described and the theoretical[14,15] K conversion coefficient ($\alpha_K=0.0318$) of the 411.8-kev transition, one can calculate the total internal conversion coefficient (α_T) of the 323-kev gamma. The value thus obtained was $\alpha_T=3.25\times10^{-3}$, which is in reasonably good agreement with the results of Lyon,[11] who has reported that there are 3.0×10^{-4} e^-/x-ray disintegration. On the basis of published theoretical K and L conversion coefficients[14–16] and an assumed $L/(M+N+\cdots)$ ratio of 5, the $K/(L+M+\cdots)$ ratio for the 323-kev transition is calculated to be ~10 (for $M1$ or $E2$ transitions). This results in a value for the K conversion coefficient of $\alpha_K\approx2.95\times10^{-3}$. The experimental uncertainty in this value may be as high as ±10 percent. The two nearest theoretical conversion coefficients are $\beta_K{}^1=1.10\times10^{-3}$ and $\alpha_K{}^2=4.00\times10^{-3}$. The 323-kev transition therefore appears to be $M1+E2$, with the $E2$ component having an intensity of ~64 percent. The fact that the 323-kev level has been formed by Coulomb excitation[17] provides additional proof that the gamma transition is partially $E2$.

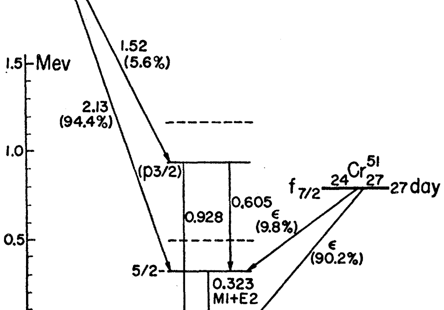

FIG. 3. Proposed decay scheme for Ti^{51} and Cr^{51}. Dotted lines at 0.48 and 1.16 Mev are levels found by inelastic proton scattering.

IV. DISCUSSION

The decay schemes suggested by the above measurements are shown in Fig. 3. The dotted lines at 0.48 Mev and 1.16 Mev are additional levels in V^{51} indicated by inelastic proton scattering experiments.[18]

The logft values associated with the various decay branches of Ti^{51} and Cr^{51} are given in Table I. It would appear that all of the transitions are of the allowed type. Therefore, since the ground state of V^{51} is a 7/2− state, the spin of Cr^{51} must be 5/2−, 7/2−, or 9/2−. It would seem that 7/2− is the only reasonable choice since the odd-particle configuration is $(1f_{7/2}{}^{-1})$, which should result in an $f_{7/2}$ state of relatively high purity.[19]

On the basis of the $M1+E2$ character of the 0.323-Mev gamma, the logft value of the 0.422-Mev K-capture transition, and the $f_{7/2}$ spin of Cr^{51}, a spin assignment of 5/2− or 7/2− is indicated for the 0.323-Mev level of V^{51}. The 7/2− possibility seems highly unlikely, however, since Ti^{51} decays very strongly to this level but does not decay to the 7/2−

[14] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).
[15] Rose, Goertzel, and Swift (privately circulated tables).
[16] Gellman, Griffith, and Stanley, Phys. Rev. **85**, 944 (1952).
[17] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 426 (1954).
[18] Hausman, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).
[19] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

ground state of V^{51}. Therefore, the only spin assignment for the 0.323-Mev level which is consistent with all the experimental data is $5/2-$. This level is very probably the $(1f_{7/2}{}^3)_{5/2}$ state predicted by *jj*-coupling theory.[2,3]

Ti^{51} has 29 neutrons, and from both the single-particle shell model[20] and the empirical data,[21,22] a spin assignment of $p_{3/2}$ would be expected for its ground-state. $f_{5/2}$ is the next most likely choice, but this possibility is excluded by the fact that there is no detectable beta transition to the ground state of V^{51}. Therefore, there would seem to be little doubt that the ground-state configuration of Ti^{51} is $(p_{3/2}{}^1)$. The problem which now arises is that the 2.13-Mev beta transition from Ti^{51} to the $5/2-$ state of V^{51} would appear to be ΔL-forbidden and would therefore not be expected to have a log*ft* value as low as 4.9.[22] The inference is that the $5/2-$ level is not a pure $(1f_{7/2}{}^3)_{5/2}$ configuration but has a sufficient admixture of *p*-state to result in the above anomaly.

On the basis of the level spacings predicted by Kurath,[2] which are in semiquantitative agreement with recent experimental results,[23,24] one would suspect that the level at 0.48 Mev (indicated by inelastic proton scattering) is a $(1f_{7/2}{}^3)_{3/2}$ state. There is no evidence that this level is populated in the decay of either Ti^{51} or Cr^{51}. Nussbaum *et al.*[25] have placed an upper limit on the intensity of the hypothetical 0.48-Mev gamma of 3 percent (relative to the intensity of the 0.323-Mev gamma). From the present experiments, this upper limit can safely be lowered to 0.4 percent. In addition, there is no evidence for the hypothetical ~0.16-Mev transition from the 0.48-Mev level to the 0.323-Mev level, as pointed out in Sec. II (b). It is easy to understand why the level at 0.48-Mev might not be involved in the decay of either Ti^{51} or Cr^{51}. The *K*-capture transition to this level from Cr^{51} would be second forbidden. The direct beta transition from Ti^{51} would be ΔL-forbidden, and the 0.928-Mev level would not necessarily be expected to exhibit detectable gamma branching to the 0.48-Mev level. On the other hand, the transition from the 0.48-Mev level to the ground state would be *E*2, and it is therefore difficult to understand why this level is not excited by Coulomb excitation with alpha particles.[17] A further investigation of the $V^{51}(p,p')$ reaction should probably be made in order to confirm the existence of the 0.48-Mev level.‡

TABLE I. Log*ft* values associated with the decay of Ti^{51} and Cr^{51}.

Parent nuclide	Transition energy (Mev)	Percent branch	log *ft*[a]
Ti^{51}	2.13	94.4	4.90
Ti^{51}	1.52	5.6	5.50
Cr^{51}	0.745	90.2	5.37
Cr^{51}	0.422	9.8	5.84

[a] Values for Ti^{51} were determined from the curves given by S. A. Moszkowski, Phys. Rev. **82**, 35 (1951); values for Cr^{51} were determined by the method outlined by J. K. Major and L. C. Biedenharn, Revs. Modern Phys. **26**, 321 (1954).

On the basis of the log*ft* value (5.5) of the 1.52-Mev beta transition and the proposed $p_{3/2}$ spin assignment for Ti^{51}, the level in V^{51} at 0.928 Mev must be a negative parity state of spin 1/2, 3/2, or 5/2. Since there is good evidence that the first single-particle level of odd-mass nuclides with 21, 23, 25, or 27 identical nucleons usually occurs somewhere between 1.0 and 1.5 Mev,[25] there is reason to believe that the 0.928-Mev level is the first single-particle excited state of V^{51}. From the shell model point of view, one would expect the first single-particle excited state to be either $p_{3/2}$ or $f_{5/2}$, with a tendency for the $p_{3/2}$ state to be lower. It thus seems reasonable to assign a spin of $p_{3/2}$ to the 0.928-Mev level, and a spin of $f_{5/2}$ to the 1.16-Mev level (observed by inelastic proton scattering[18]). The $p_{3/2}$ assignment is compatible with the relative transition probabilities of the 0.605- and 0.928-Mev gamma rays. The $f_{5/2}$ assignment makes the beta transition to the 1.16-Mev level ΔL-forbidden, thus providing a satisfactory explanation of why this beta transition is not observed.

The authors wish to thank Dr. M. Goldhaber for helpful discussions.

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[21] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).
[22] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).
[23] Nussbaum, Wapstra, Nijgh, Ornstein, and Verster, Physica **20**, 165 (1954).
[24] T. Lindqvist and A. C. G. Mitchell, Phys. Rev. **95**, 1535 (1954).
[25] Nussbaum, van Lieshout, and Wapstra, Phys. Rev. **92**, 207 (1953).

‡ *Note added in proof.*—Braams [C. M. Braams, private communication (October, 1954)], quoted by R. H. Nussbaum (see reference 1), has recently re-examined the $V^{51}(p,p')$ reaction and finds evidence for levels in Ti^{51} at 0.321, 0.925, 1.609, and 1.813 Mev. He finds no evidence for levels at 0.48 and 1.16 Mev.