Study of Excited States of V^{47} with the $Ti^{46}(p, \gamma)V^{47}$ Reaction*

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Angular distributions of γ-ray spectra from the $Ti^{46}(p,\gamma)V^{47}$ reaction were observed at the resonances $E_p = 1095.4$, 1127.0, and 1285.7 keV. Accurate level energies and a revised Q value of 5167.9 ± 1.5 keV were obtained. Branching ratios and multipolarity mixing ratios for numerous transitions were determined. The 2.175-MeV level was found to have spin $\frac{5}{2}$. The resonance levels at $E_p = 1095$ and 1286 keV [$E_x(V^{47}) = 6.241$ and 6.425 MeV] were found to have spin $\frac{3}{2}$. The resonance at $E_p = 1127$ keV ($E_x = 6.271$ MeV) has been tentatively identified as the isobaric analog state of the 2.163-MeV level in Ti^{47}, with $J^\pi = \frac{3}{2}^-$.

I. INTRODUCTION

The energies of excited levels in V^{47} up to 2.21 MeV have been determined with the $Ti^{47}(p,n)V^{47}$ reaction[1] and the $Cr^{50}(p,\alpha)V^{47}$ reaction.[2] Levels up to 7.01 MeV have been observed with the $Ti^{46}(He^3,d)V^{47}$ reaction.[3-6] The l values and spectroscopic factors for many levels have been found, and unique level spins could be assigned in a few cases. Dubois has measured the γ-ray yield from resonances in the reaction $Ti^{46}(p,\gamma)V^{47}$ in the range of proton energy from 870 to 1400 keV, which corresponds to V^{47} excitation energies from 6.02 to 6.53 MeV.[7] Later, Albinsson and Dubois observed γ-ray spectra at seven of the resonances found by Dubois, and deduced the decay schemes of the corresponding levels, as well as the energies and decay schemes of a number of bound levels.[8]

In the present work, γ-ray angular distributions were measured for the $Ti^{46}(p,\gamma)V^{47}$ reaction at the resonances $E_p = 1095.4$, 1127.0, and 1285.7 keV. A triple-correlation measurement was also performed at the $E_p = 1095.4$-keV resonance. The aim of this work was to supplement the information available through the $Ti^{46}(He^3,d)V^{47}$ reaction by determining branching ratios and multipolarity mixing ratios for γ-ray transitions, resolving ambiguities in spin assignments, and studying levels that are only weakly excited in the (He^3,d) reaction. The measurements were made possible by the availability of a large-volume, high-resolution Ge(Li) detector. Level energies were determined to within 1.5 keV, and limits on the life times of several bound levels could be deduced from the Doppler-shift attenuation.

II. EXPERIMENTAL PROCEDURE

The experiments were performed with the 2-MeV Van de Graaff accelerator of the Aerospace Research Laboratories. A proton beam of typically 25 μA was deflected onto the target by a 30° analyzing magnet. The beam spot at the target was about 0.25 in. in diam. Targets were prepared by evaporation of elemental titanium, enriched to 81.2% Ti^{46}, onto silver backings. The target thicknesses were determined by taking a yield curve over the 1127-keV resonance, and were typically about 2 keV at this energy. The targets were mounted at an angle of 45° to the beam direction.

A 40-cc Ge(Li) detector was placed about 1.3 in. from the target and spectra were observed at 0, 35, 55, and 90° relative to the beam direction. At the 1127.0- and 1285.7-keV resonances, spectra were also observed at 120° for improved Doppler-shift attenuation measurements. The asymmetry of the target chamber, detector system was determined by separate measurements of the isotropic 2.367-MeV γ ray from the reaction $C^{12}(p,\gamma)N^{13}$ at the $E_p = 459$-keV resonance.[9] For γ-ray energies less than 1.5 MeV, an additional correction for absorption in the target backing as a function of detector angle was calculated.

At $E_p = 1095.4$ keV, a triple-correlation measurement was made for the cascade through the first excited state. The 6.154-MeV primary transition was observed with an 8-in. by 8-in. NaI(Tl) detector, and the 0.087-MeV secondary transition with the Ge(Li) detector. Each transition was observed at 0, 35, 55, and 90° in coincidence with the other at 90°. The angle between the planes defined by the beam direction and the two detector axes was 180°.

The relative efficiency of the Ge(Li) detector as a function of γ-ray energy was calibrated with the accurately known decay schemes at the $E_p = 416$- and 731-keV resonances of the[10] reaction $Si^{29}(p,\gamma)P^{30}$. Spectra were recorded in one half of a 4096-channel analyzer, with a gain of about 3 keV per channel and a resolution of about 10-keV full width

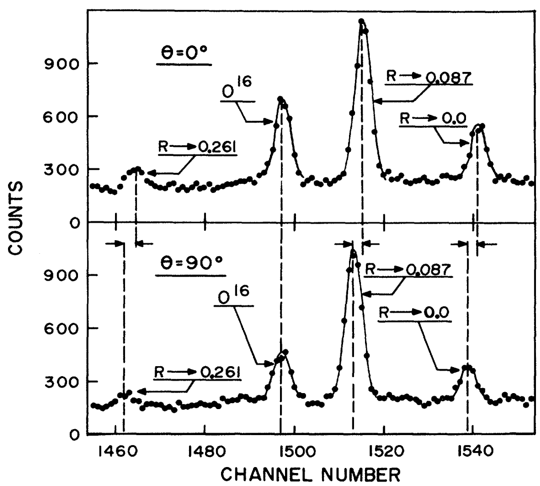

FIG. 1. A portion of the spectra at the $E_p = 1127.0$-keV resonance at 0 and 90°, showing the double-escape peaks of some primary transitions and of the O^{16} γ ray. The peaks have been fitted with Gaussian curves. The dashed lines indicate the centroids of the peaks, to emphasize the Doppler shifts at 0°.

at half maximum. Due to the large background in the low-energy end of the singles spectra, only peaks above 0.511 MeV were analyzed. A portion of the spectra at 0 and 90° for the 1127.0-keV resonance is shown in Fig. 1.

The energy calibration was based on the positions of the 511.0-keV annihilation-radiation peak and the double-escape peak of the 6129.3 ± 0.4-keV γ ray from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction.[11] The separations between the photopeaks and single- and double-escape peaks of prominent transitions in each spectrum were used as additional constraints. A least-squares fitting procedure was used to obtain the coefficients in a cubic equation relating energy to channel number. Level energies were based on the spectra at 90°, to eliminate Doppler-shift effects, and were corrected for nuclear recoil.

The centroids of the stronger γ-ray peaks exhibited clearly measurable Doppler shifts. These were used to find limits on the lifetimes of levels by the Doppler-shift attenuation method.[12] All primary γ rays exhibited the full Doppler shift. This fact was useful in deriving decay schemes.

Because of the high-energy resolution, the simple condition that energies of transitions in a cascade add up to the resonance-level energy was quite powerful in the determination of decay schemes. An additional requirement was that the intensities of primary transitions equal or exceed the sum of the intensities of observed secondary transitions. Intensities for the spectra at 55° were used in order to minimize angular-distribution effects.

The spectra were extremely complex as a result of the high level density of V^{47}. Identifiable transitions in V^{49} were also observed at all three resonances, stemming from a 14.5% content of Ti^{48} in the targets. Great care was taken to identify as many of the smaller peaks as possible, and to correct intensities for underlying unresolved peaks. All decay modes of the resonance levels with branching ratios greater than 3% were probably seen. But the decay schemes of a few weakly fed bound levels could not be determined satisfactorily.

III. RESULTS

The results of the measurements are summarized in Tables I and II, and in Figs. 2 and 4–9. In each table, the first two columns show the energy levels as determined in the present work. The agreement with previous work is excellent. Using the proton energies of Dubois[7] with our values for the excitation energies of the virtual levels, a Q value of 5167 ± 1.5 keV was obtained, which is slightly lower than the value of 5177 ± 5 keV reported by Albinsson and Dubois.[8] Part of the difference is due to our use of a more recent value of the O^{16} γ-ray calibration energy, which is 1.7 keV below the value used by Albinsson and Dubois.

The branching ratios in the third columns show fair agreement with those reported by Albinsson and Dubois[8] on the dominant decay modes, though there is some disagreement on the weaker transitions. At the 1095.4-keV resonance, they report a 10% branching to the 2.431-MeV level, while our data indicate an upper limit of 1%. In addition we see evidence of appreciable branching to the 2.211-,

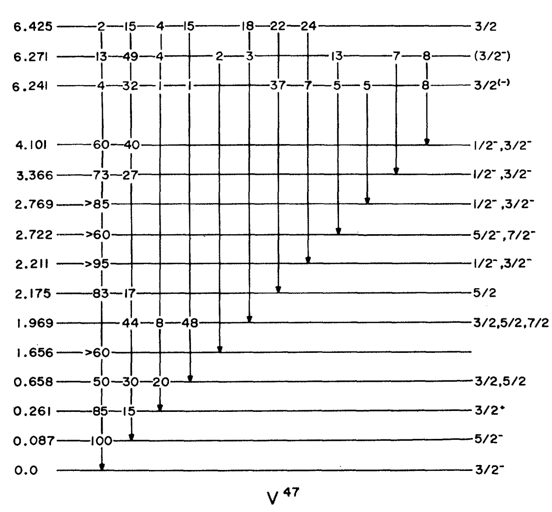

FIG. 2. The decay schemes of bound and virtual levels observed in the present work.

TABLE I. Primary transitions at the E_p = 1095.4-, 1127.0-, and 1285.7-keV resonances.

Initial-state energy (keV)	Final-state energy (keV)	Branching ratio (%)	Radiative width (eV)	J_i	$J_f^{\pi_f}$	δ
6240.9 ±1.5	0.0	4.2 ±0.7	0.005	3/2	$3/2^{-a,b}$	0.7 ±0.2 3.2 ±1.2
	87.0	31.7 ±3.3	0.04		$5/2^-$	−0.04 ±0.05
	260.8	1.0 ±0.7	0.001		$3/2^{+b}$	
	658.2	1.3 ±0.5	0.002		3/2, 5/2	
	2175.0	37.0 ±4.0	0.05		5/2	−0.10 ±0.06
	2211.0	7.2 ±1.2	0.009		$1/2^-$ $3/2^-$	0.36 ±0.11 0.84 ±0.18 1.4 ±0.5
	2768.8	4.5 ±1.0	0.006		$1/2^-$, $3/2^{-b}$	
	3366.1	5.0 ±1.6	0.006		$1/2^-$, $3/2^{-b}$	
	4101.5	8.2 ±1.3	0.01		$1/2^-$, $3/2^{-b}$	
6271.0 ±1.5	0.0	12.7 ±1.4	0.04	3/2	$3/2^{-a,b}$	0.03 ±0.09 −5.5 ±2.5
	87.0	49.3 ±5.0	0.1		$5/2^-$	0.09 ±0.03 3.1 ±0.7
	260.8	4.3 ±0.7	0.01		$3/2^{+b}$	−0.01 ±0.13 −4.7 ±2.3
	1656.4	2.4 ±0.7	0.007			
	1968.6	2.8 ±1.0	0.008		3/2, 5/2, 7/2	
	2721.7	13.2 ±1.6	0.04		$5/2^-$ $7/2^-$	−0.08 ±0.13 >3.2 −0.34 ±0.16 >1.6
	3366.1	7.0 ±1.9	0.02		$1/2^-$, $3/2^{-b}$	
	4101.5	8.3 ±1.3	0.02		$1/2^-$, $3/2^{-b}$	
6271.0 ±1.5	0.0	12.7 ±1.4	0.02	5/2	$3/2^{-a,b}$	−0.36 ±0.04
	87.0	49.3 ±5.0	0.09		$5/2^-$	0.36 ±0.04
	260.8	4.3 ±0.7	0.008		$3/2^{+b}$	−0.35 ±0.15
	1656.4	2.4 ±0.7	0.005			
	1968.6	2.8 ±1.0	0.005		3/2, 5/2, 7/2	
	2721.7	13.2 ±1.6	0.03		$5/2^-$ $7/2^-$	0.56 ±0.16 −0.04 ±0.12 >4.3
	3366.1	7.0 ±1.9	0.01		$1/2^-$, $3/2^{-b}$	
	4101.5	8.3 ±1.3	0.02		$1/2^-$, $3/2^{-b}$	
6425.3 ±1.5	0.0	2.0 ±0.5	0.004	3/2	$3/2^{-a,b}$	
	87.0	15.1 ±1.7	0.03		$5/2^-$	1.1 ±0.8
	260.8	3.5 ±0.7	0.007		$3/2^{+b}$	
	658.2	14.7 ±1.6	0.03		3/2 5/2	0.24 ±0.09 0.11 ±0.10
	1968.6	18.4 ±2.1	0.04		3/2 5/2 7/2	>4.7 −0.01 ±0.12 >3.1 −0.25 ±0.14
	2175.0	22.3 ±2.5	0.04		5/2	−0.08 ±0.10 >4.0
	2211.0	24.2 ±2.7	0.05		$1/2^-$ $3/2^-$	0.10 ±0.07 1.9 ±0.7 1.5 ±0.7

[a] See Refs. 17, 18.
[b] See Refs. 3–6.

2.769-, and 4.101-MeV levels. At the 1127.0-keV resonance we assigned an upper limit of 1% to the branching to the 2.081-MeV level, reported as 5% by Albinsson and Dubois. In the absence of a peak corresponding to the decay of the 2.175-MeV level to the 0.087-MeV level, we interpreted a peak at 2.169 MeV to be a primary transition to the 4.101-MeV level. This reversal between primary and

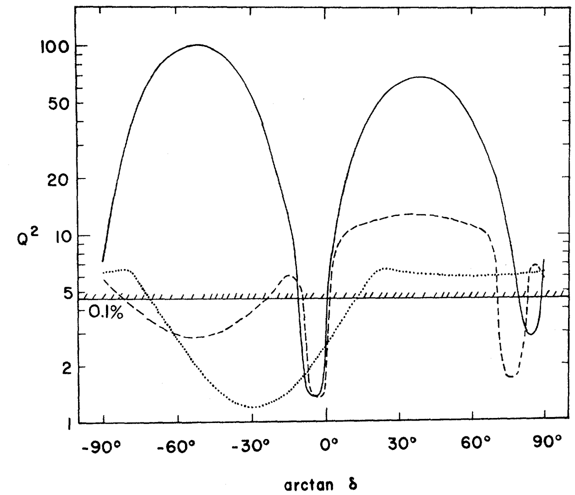

FIG. 3. Q^2 projections for the cascades $r \to 2.175 \to 0$ and $r \to 2.175 \to 0.087$ at the 1095.4-keV resonance. Varying the mixing ratio resulted in the solid curve for the primary transition, the dashed curve for the transition $2.175 \to 0$, and the dotted curve for the transition $2.175 \to 0.087$.

secondary transition compared with Albinsson and Dubois's work is also strongly supported by the exact energy values, and by the lower intensity and Doppler shift observed for the 4.101-MeV transition. We also saw a transition to the 3.596-MeV level. The decay of the 1285.7-keV resonance was not investigated by Albinsson and Dubois.

Since we did not attempt to analyze our spectra below 0.511 MeV, the branching ratios for the 0.261- and 0.658-MeV levels shown in Table II are those of Albinsson and Dubois. Our data indicated qualitative agreement. We obtained somewhat different decay schemes for the 1.969-, 2.175-, and 3.366-MeV levels.

Absolute values of 0.35 and 0.40 eV for the radiative width of the 1007.0-keV resonance in the $Ti^{48}(p,\gamma)V^{49}$ reaction have recently been obtained.[13,14] This information was combined with the results reported by Dubois[7] to estimate the radiative widths of the three Ti^{46} resonances studied in the present work. The results were $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma = 0.50$, 1.14, and 0.78 eV, respectively, for the 1095.4-, 1127.0-, and 1285.7-keV resonances. The radiative widths in Table I are based on these results, with the assumption that Γ_p is much larger than Γ_γ. Owing to the large uncertainty in the radiative width of the Ti^{48} 1007.0-keV resonance and in the comparison method used, the quoted values are only good to within a factor of 3 or so. The radiative widths in Table II are based on the lifetime limits resulting from the Doppler-shift attenuation, using the relationship

$$\Gamma_\gamma \tau = \hbar .$$

The last three columns show spins and parities available from other work, and spins and mixing ratios extracted from the present angular-corre-

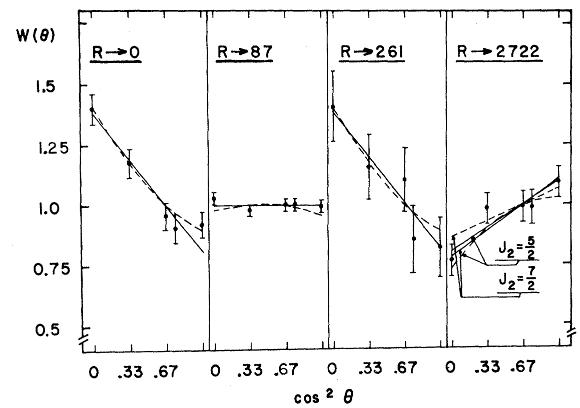

FIG. 5. Angular distributions of primary transitions at the 1127.0-keV resonance. The solid and dashed curves correspond, respectively, to a resonance spin of $\frac{3}{2}$ and $\frac{5}{2}$.

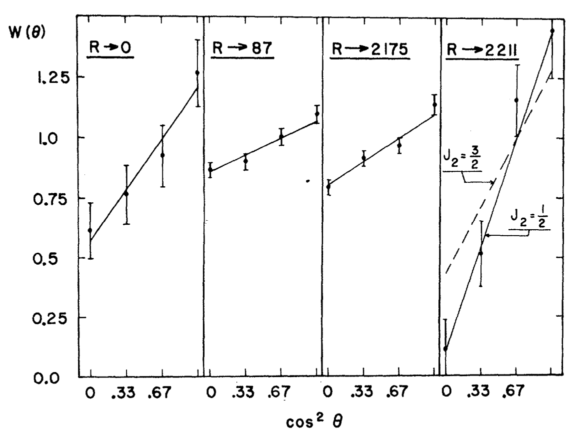

FIG. 4. Angular distributions of primary transitions at the 1095.4-keV resonance.

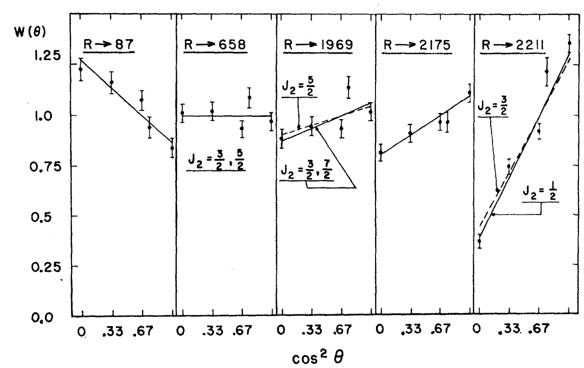

FIG. 6. Angular distributions of primary transitions at the 1285.7-keV resonance.

lation data. The formalism of Watson and Harris[15] was used. The details of the analysis were the same as those described by Harris and Breitenbecher.[16] Each level involved in a transition or cascade was assigned spin values of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ in turn, unless there were known restrictions on the possible spin values. Spin sequences involving a spin change larger than two were omitted. For all other spin sequences, searches over the multipolarity mixing ratios were made.

The goodness of fit was given by the parameter Q^2, defined as

$$Q^2 = [1/(A-q)] \sum_a (W_a - W_a^*)^2 \omega_a^2 ,$$

where W_a and W_a^* are experimental and calculated values of the correlations, ω_a is the inverse of the standard deviation of W_a, A is the number of observation points, and q is the number of mixing ratios varied. Projections showing the minimum Q^2 values obtainable for all possible values of the primary and secondary mixing ratios are shown in Fig. 3 for the cascades $r \to 2.175 \to 0$ and $r \to 2.175 \to 0.087$ at the 1095.4-keV resonance. The spin assignments shown in Tables I and II were used. Similar projections were made for all plausible spin sequences of all angular correlations that were analyzed. Spin sequences resulting in a minimum of Q^2 larger than the 0.1% confidence limit were discarded.

The experimental angular distributions of primary transitions at the three resonances are shown in Figs. 4–6. The distributions calculated with the mixing ratios yielding the lowest Q^2 values are also shown for the spin assignments shown in Tables I and II. All results are normalized to a calculated value of 1.0 for the angular distribution at 55°. Figures 7 and 8 show the angular distributions of the secondary transitions, and Fig. 9 shows the triple correlations for the cascade $r \to 0.087 \to 0$ at the 1095.4-keV resonance.

The $\frac{3}{2}^-$ assignment for the ground state has been firmly established.[3–6,17,18] The $\frac{5}{2}^-$ assignment for the first excited level has been based on systematics and theoretical predictions. Menti[19] has found the absolute value of the mixing ratio of the decay of this level to be 0.14 ± 0.02. Though the wrong spins were used in his analysis, the conclusions concerning the mixing ratio remain valid. It was our hope to experimentally verify the $\frac{5}{2}^-$ assignment using angular-distribution and triple-correlation measurements at the 1095.4-keV resonance. The triple-correlation measurements were made when the primary angular distribution failed to give a unique spin sequence. The analysis of the combined experimental results favored the $\frac{5}{2}^-$ assignment for the first excited state, but spin

TABLE II. Secondary transitions at the $E_p = 1095.4$-, 1127.0-, and 1285.7-keV resonances.

Initial-state energy (keV)	Final-state energy (keV)	Branching ratio (%)	Radiative width (eV)	$J_i^{\pi_i}$	$J_f^{\pi_f}$ [b,c]	δ
87.0 ± 1.0	0.0	100		5/2⁻	3/2⁻	−0.10 ± 0.06
260.8 ± 1.5	0.0	85[a]		3/2⁺ [c]	3/2⁻	
	87.0	15[a]			5/2⁻	
658.2 ± 1.0	0.0	50[a]		3/2, 5/2	3/2⁻	
	87.0	30[a]			5/2⁻	
	260.8	20[a]			3/2⁺	
1656.4 ± 3.0	0.0	> 60	< 0.05		3/2⁻	
1968.6 ± 1.5	87.0	44 ± 4	< 0.01	3/2, 5/2, 7/2	5/2⁻	
	260.8	8 ± 4	< 0.002		3/2⁺	
	658.2	48 ± 4	< 0.01		3/2, 5/2	
2175.0 ± 1.0	0.0	83 ± 5	0.02 to 0.1	5/2	3/2⁻	−0.06 ± 0.06
	87.0	17 ± 5	0.003 to 0.03		5/2⁻	− 0.8 ± 0.8
2211.0 ± 1.5	0.0	> 95	0.006 to 0.02	1/2⁻	3/2⁻	...
				3/2⁻	3/2⁻	1.4 ± 0.5
2721.7 ± 1.5	0.0	> 60	0.002 to 0.09	5/2⁻	3/2⁻	< −0.4
				7/2⁻	3/2⁻	< 0.0
2768.8 ± 4.0	0.0	> 85		1/2⁻, 3/2⁻ [c]	3/2⁻	
3366.1 ± 5.0	0.0	73 ± 10	> 0.01	1/2⁻, 3/2⁻ [c]	3/2⁻	
	87.0	27 ± 10	≥ 0.004		5/2⁻	
4101.5 ± 1.0	0.0	60 ± 20	0.001 to 0.04	1/2⁻, 3/2⁻ [c]	3/2⁻	
	87.0	40 ± 20	0.0006 to 0.03		5/2⁻	

[a] See Ref. 8.
[b] See Refs. 17, 18.
[c] See Refs. 3–6.

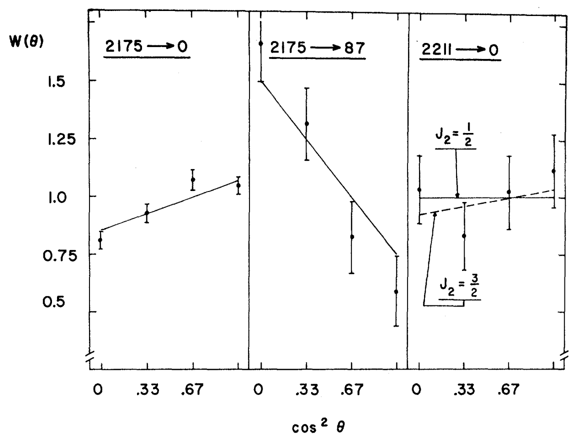

FIG. 7. Angular distributions of secondary transitions at the 1095.4-keV resonance.

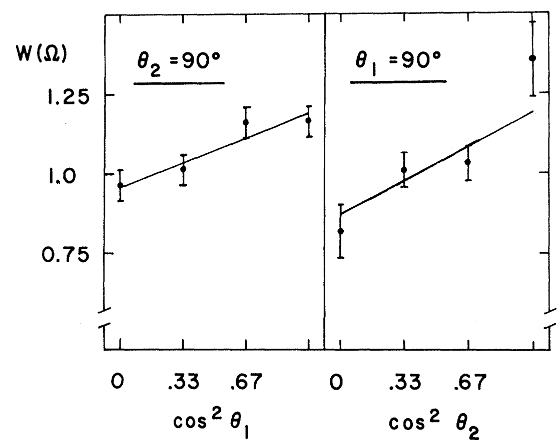

FIG. 9. Triple correlations for the cascade $r \to 0.087 \to 0$ at the 1095.4-keV resonance.

$\frac{3}{2}$ was ruled out with only a 4% confidence limit. Either solution requires a resonance spin of $\frac{3}{2}$. Spin $\frac{3}{2}$ or $\frac{5}{2}$ for each of the other two resonance levels is consistent with the observed angular distributions. At the 1285.7-keV resonance, spin $\frac{5}{2}$ resulted in an inconsistent mixing ratio for the 2.211-MeV γ ray compared with the result at the 1095.4-keV resonance, and was thus ruled out.

Roos, Ludemann, and Wesolowski[20] have found the Coulomb energy difference between Ti^{47} and V^{47} to be 7846 ± 18 keV. The 2.163-MeV level in Ti^{47}, which probably has $J^\pi = \frac{3}{2}^-$,[17,21] is thus expected to have an analog in V^{47} at about 6.30 MeV. The candidates for this level are the 1095.4-, 1127.0-, and 1158.2-keV resonances. The 1127.0-keV resonance is almost twice as strong as the other two. In addition it was observed in the (He^3, d) work.[4] This evidence warrants a tentative assignment of $J^\pi = \frac{3}{2}^-$ for this level.

On the basis of the angular distributions, the 2.175-MeV level was found to have spin $\frac{5}{2}$, and the spin of the 0.658-MeV level was limited to $\frac{3}{2}$ or $\frac{5}{2}$.

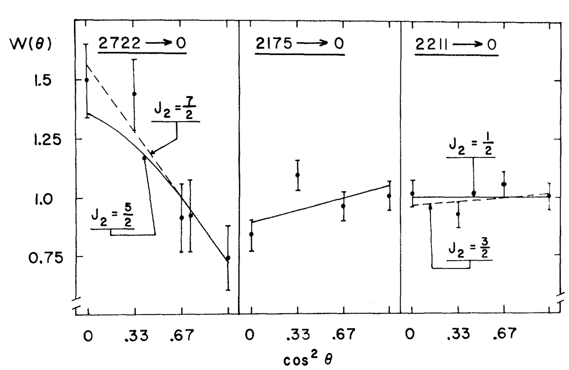

FIG. 8. Angular distributions of the transition $2722 \to 0$ at the 1127.0-keV resonance, and of the transitions $2175 \to 0$ and $2211 \to 0$ at the 1285.7-keV resonance.

Spin $\frac{1}{2}$ could be ruled out for the 1.969-MeV level. Our results are consistent with $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ for the 2.211-, 2.769-, 3.366-, and 4.101-MeV levels, all of which have been found to have $l = 1$ in (He^3, d) work.[3-6] $J^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$ is consistent with our results for the 2.722-MeV level, which has been found to have $l = 3$.[4,6]

Enhancement of electric quadrupole transitions beyond single-particle estimates by factors as large as 15 are not uncommon.[22] The largest $E2$ strength implied by the mixing ratios in Tables I and II was 14 Weisskopt units (Wu). None of the cases shown could therefore be ruled out because of excessive $E2$ strength. On the other hand, $M2$ strengths larger than 1 Wu are quite improbable.[22] We could tentatively assign negative parity to the 1095.4-MeV resonance level, since positive parity would lead to an $M2$ strength of at least 2.5 Wu for the transition to the 2.211-MeV level.

If the 2.722-MeV level had even parity, the $M2$ strength of its ground-state decay would at be least 10 Wu. This is also true if spin $\frac{3}{2}$ is assumed. This case is not shown in Table II. The $l = 2$ assignment of Dorenbusch, Rapaport, and Belote,[3] which disagrees with other (He^3, d) work,[4,6] is thus almost certainly erroneous.

IV. DISCUSSION

A $\frac{3}{2}^-$ assignment for the 2.211-MeV level is slightly preferred in the (He^3, d) work, since the $p_{3/2}$ centroid should be lower in energy than the $p_{1/2}$ centroid.[4] In the present work, $J^\pi = \frac{1}{2}^-$ resulted in a better fit at the 1095.4-keV resonance. The fit obtained for $J^\pi = \frac{3}{2}^-$ had $\chi^2 = 2.5$. Since there were four degrees fo freedom, so large a χ^2 value has only a 3.5% probability. $J^\pi = \frac{1}{2}^-$ is favored by the strong-coupling-model calculations of Malik and Scholz,[23] while the shell-model calculations of Ginocchio[24] require $J^{\pi} = \frac{3}{2}^-$.

A $\frac{5}{2}^-$ assignment for the 2.722-MeV level is preferred in the (He^3, d) work, since the 0.150-MeV level essentially exhausts the $T=\frac{1}{2}$, $1f_{7/2}$ strength.[4] No preference for either spin $\frac{5}{2}$ or $\frac{7}{2}$ was indicated by our results.

The 6.271-MeV virtual level is excited only weakly in the (He^3, d) work,[4] so that no l value could be deduced. This does not argue against the identification of this level as an isobaric analog state, however. The 2.163-MeV level in Ti^{47} is itself excited only weakly in (d,p) stripping.[21] It is of interest to note that we saw no evidence for decays of the 6.271-MeV level to the two strongest $l=1$ levels at 2.081- and 2.211-MeV. The predominant decay mode was to the $\frac{5}{2}^-$ state at 0.087 MeV. This behavior bears a striking resemblance[14] to the decay of the $\frac{3}{2}^-$ isobaric analog level at 7.784 MeV in V^{49}.

The reader is referred to the paper by Čujec and Szöghy[6] for some detailed comparison between experimental results and existing theoretical predictions for V^{47}. As more experimental information becomes available, theoretical predictions of branching ratios and multipolarity mixing ratios, and of even-parity states will be of increasing interest.

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