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Lifetime measurements and collective behavior in $^{49}V^{\dagger}$

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Lifetimes of levels in ^{49}V have been measured using the Doppler-shift attenuation method. States were populated with the ^{46}Ti(α, p)^{49}V reaction at a beam energy of 10 MeV. Protons were detected near 180° relative to the beam and most Doppler shifts were measured between γ spectra accumulated at θ_γ = 53 and 140°. Values or limits were obtained for the mean lifetimes of 25 levels in ^{49}V from 748 to 2812 keV in excitation energy. The positive parity levels appear to form two rotational bands with $K^\pi = \frac{3}{2}^+$ and $\frac{1}{2}^+$. The first 2 MeV of the negative parity level scheme is reproduced rather well with calculations using the strong coupling model. This model also predicts the transition strengths reasonably well. These results suggest strong collective behavior in the states of both parities.

[NUCLEAR REACTIONS ^{46}Ti(α, $p\gamma$), E_α=10 MeV; measured Doppler-shift attenuation. ^{49}V deduced levels, τ, J, π, $B(\Lambda)$, branching ratios. Enriched target.]

I. INTRODUCTION

There is some evidence of collective behavior in nuclei near the middle of the $f_{7/2}$ shell. The low lying levels in ^{47}Ti [1] and ^{49}Cr [2] form an increasing sequence of angular momenta, but the level spacing deviates considerably from the $I(I+1)$ dependence of an unperturbed rotational band. However, the $E2$ transitions between these levels are strongly enhanced and the level energies and transition strengths are reproduced fairly well with the strong coupling model which includes the effects of the Coriolis coupling term that tends to mix Nilsson bands. The present study of the mean lifetime and the decay scheme of levels in ^{49}V is motivated, in part, as a continued exploration of nuclear collectivity in the mid-$f_{7/2}$ shell.

The spectroscopy of ^{49}V has been studied with a variety of techniques. Particle spectra and angular distributions have been obtained from the ^{48}Ti(^{3}He, d)^{49}V reaction,[3–6] from the ^{50}Cr(t, α)^{49}V reaction,[5] and from the ^{52}Cr(p, α)^{49}V reaction.[7] γ spectra have been measured from resonant proton capture[8,9] in ^{48}Ti, from the ^{49}Ti(p, $n\gamma$)^{49}V reaction,[10] and from the ^{46}Ti(α, $p\gamma$)^{49}V reaction.[11,12] Recent measurements have been made of the lifetimes of the 91 keV[13] and of the 153 keV[14] levels. Lifetimes of some higher states were measured by Kiuru[9] from the proton capture experiment and recent lifetime measurements of a number of levels in ^{49}V have been reported in an abstract by Britz *et al.*[15] A lifetime measurement of the 1021 keV level has recently been reported by Brown *et al.*[16]

To further understand the level scheme in ^{49}V we have measured lifetimes using the Doppler-shift attenuation method with the ^{46}Ti(α, $p\gamma$)^{49}V reaction. Electromagnetic transition strengths have been calculated from these lifetimes and the level scheme and transition strengths are compared with predictions of the Coriolis coupling model.

II. EXPERIMENTAL PROCEDURE

The ^{46}Ti(α, p)^{49}V reaction was used to populate levels in ^{49}V. The α beam energy was 10 MeV and the target consisted of 1 mg/cm^2 of ^{46}Ti evaporated on an 0.8 mg/cm^2 backing of gold. The titanium was enriched to 81% with ^{46}Ti. Protons from the reaction were detected in a 1 mm thick silicon surface-barrier annular counter. A 42 mg/cm^2 tantalum foil was placed in front of the annular counter to stop α particles. γ rays were detected in coincidence with the protons using a 65 cm^3 Ge(Li) detector placed successively at angles of 53, 90 and 140° relative to the beam direction. The spectra at 53 and 140° were used to determine most of the Doppler shifts, while the 90° spectrum proved valuable in identifying spectral lines and in determining decay schemes.

For each coincident event, the proton energy, the γ-ray energy, and the time difference between the two detector signals were digitized and written on magnetic tape. γ-ray sources of ^{88}Y and ^{113}Sn were placed near the Ge(Li) detector during the run. The γ-ray singles spectrum was sampled and periodically written on magnetic tape. This provided an energy calibration accumulated simultaneously with the data and also monitored the energy calibration as a function of time. The gain of the system varied less than 0.1 keV during the accumulation of the three spectra.

The proton spectrum is shown in Fig. 1. Most of the peaks in the spectrum correspond to a number of levels in ^{49}V. The approximate excitation energy in ^{49}V is indicated in the figure. On analysis of the data tapes, γ rays were sorted into five separate spectra corresponding to the proton energy windows shown in Fig. 1.

III. EXPERIMENTAL RESULTS

Some examples of Doppler shifts are shown in Fig. 2 and Fig. 3. The γ rays in Fig. 1 result from the decay of the 748 keV level to the 91 and 153 keV levels. The Doppler shift is almost fully attenuated for this state. Figure 3(a) shows the lines from the ground state decays of the 1140 and 1155 keV levels. They exhibit about 20% of the full Doppler shift. Figure 3(b) shows the evidence for a closely spaced doublet of states. The spectra in Fig. 3(b) show the decays of the 1643 and 1646 keV levels to the 153 keV level. The γ ray from the 1643 keV level is almost fully shifted, while that from the 1646 keV level exhibits almost no Doppler shift.

The results of the Doppler-shift attenuation measurements are listed in Table I. Energy shifts were measured between the $\theta_\gamma = 53°$ and $\theta_\gamma = 140°$ spectra (except as noted in Table I) using peak centroid analysis. Mean lifetimes τ were determined from the ratio of observed to maximum possible Doppler shift $F(\tau)$ using the nuclear and electronic stopping power theory of Lindhard, Scharff, and Schiøtt[17] and the large-angle scattering consideration of Blaugrund.[18] Multiplicative adjustment factors of 1.16 ± 0.20 and 0.70 were used for the electronic and nuclear stopping power, respectively. The uncertainty in electronic stopping power has been added in quadrature to the uncertainty in τ arising from experimental uncertainty in measuring $F(\tau)$.

The lifetimes measured in this work for the 748 and 1140 keV levels are substantially longer than those reported by Kiuru.[9] Most of the other lifetimes in Ref. 9 are in reasonable agreement with the present measurements. The lifetimes reported here are also in reasonable agreement with the lifetime measurements reported in an abstract by Britz *et al.*[15] The lifetime of 5.1 ± 1.0 psec reported for the 1021 keV level in Ref. 16 agrees reasonably well with the value of $4.3^{+1.9}_{-1.1}$ psec measured in the present work.

Experimental branching ratios were determined by averaging those observed in each of the three spectra at $\theta_\gamma = 53$, 90, and 140°. This averaging improves statistics and reduces the effects of angular correlations on the measured branching ratio.

Experimental transition strengths have been calculated from the measured lifetimes. The branching ratios used in the calculation of the transition strengths were either measured in the present experiment or taken from Ref. 10 as indicated in Table II. Table II lists the electromagnetic transition strengths measured in the present work in both absolute units and single particle or Weisskopf units (W.u.). These are calculated under the hypothesis that the transition proceeds entirely by radiation of the indicated multipolarity. Thus the tabulated strength must be considered an upper limit for the weak $M1$ transitions. In cases where the spin restrictions do not uniquely determine the lowest allowed

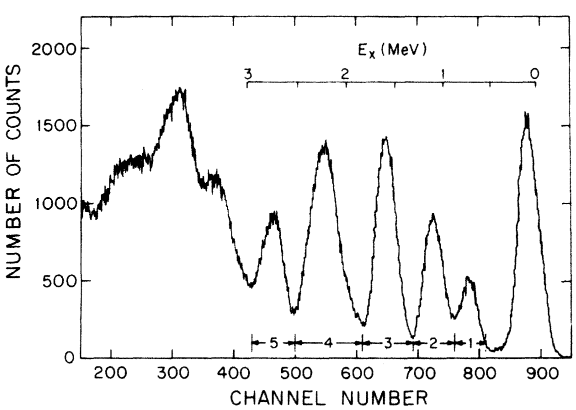

FIG. 1. The spectrum of protons from the $^{46}Ti(\alpha, p)^{49}V$ reaction. The numbers between arrows label proton energy windows used in sorting the γ spectra. Approximate excitation energy in ^{49}V is indicated on the scale above the spectrum.

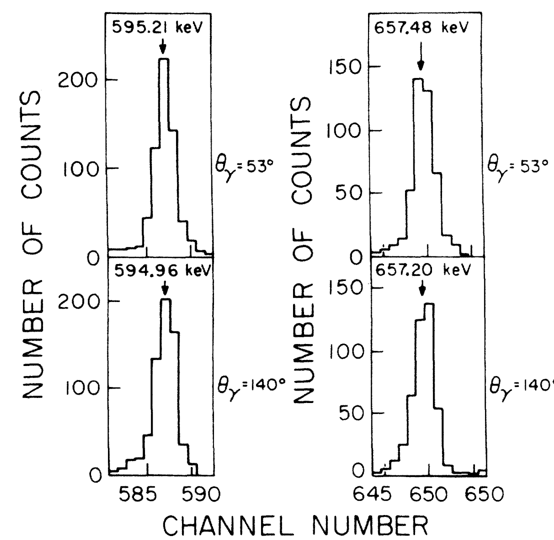

FIG. 2. Portions of the γ spectra in coincidence with protons in window 1. These γ rays come from the 748→153 keV and 748→91 keV transitions.

multipolarity, a value is assumed for the multipolarity. This assumed value and the resulting transition strengths are enclosed in parentheses. The spin and parity assignments or assumptions listed in Table II will be discussed subsequently.

IV. DISCUSSION OF INDIVIDUAL STATES

1021 keV level. There have been several suggestions[10–12] that $I^\pi = \frac{11}{2}^-$ for this state. Sawa *et al.*[12] find a pure $E2$ angular distribution for the ground state decay branch of this state. The measured lifetime implies an $E2$ strength of 16 W.u. for this transition. This is similar to $E2$ decay strengths of other low lying states. Accordingly, the lifetime measurement supports $\frac{11}{2}^-$ for this state.

1140 keV level. A state at 1148 keV is populated moderately strongly in the $^{50}Cr(t, \alpha)^{49}V$ pickup reaction[5] but very weakly in the $^{48}Ti(^3He, d)^{49}V$ stripping reaction.[5] This suggests a level of positive parity. Two states which could be identified with this state, the 1140 and 1155 keV levels, are seen in γ-ray studies. The assignment of $\frac{9}{2}^-$ to the 1155 keV level (see below) identifies the 1140 keV state with that seen in the pickup reaction. All spins except $\frac{5}{2}^+$ are ruled out by the presence of decay branches to the $\frac{7}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$ states, because a spin hypothesis of $\frac{3}{2}^+$ or $\frac{7}{2}^+$ for the 1140 keV level implies that one of these transitions has an $M2$ strength of about 1000 W.u. The assignment of this level into a rotational band is discussed in a following section.

1155 keV level. This state decays to the ground state and 91 and 1021 keV levels. The short lifetime of this level excludes multipolarities higher than quadrupole as the dominant decay mode for any of these branches. The decay to the $\frac{5}{2}^-$ 91 keV level then places an upper limit of $\frac{9}{2}$ on the spin of the 1155 keV state. The transition to the 1021 keV level has a strength of 0.36 W.u. for an $M1$ transition, but 48 000 W.u. for $E2$ radiation. The assignment of $\frac{11}{2}^-$ to the 1021 keV level fixes $I = \frac{9}{2}$ uniquely for the 1155 keV state. Positive parity is excluded by the unreasonably large $M2$ strength to the $\frac{5}{2}^-$ state that it would require. This is in agreement with Ref. 12 which reports a mixed $M1/E2$ transition for the $1155 \to 0$ keV branch and a pure $E2$ angular distribution for the $1155 \to 91$ keV transition.

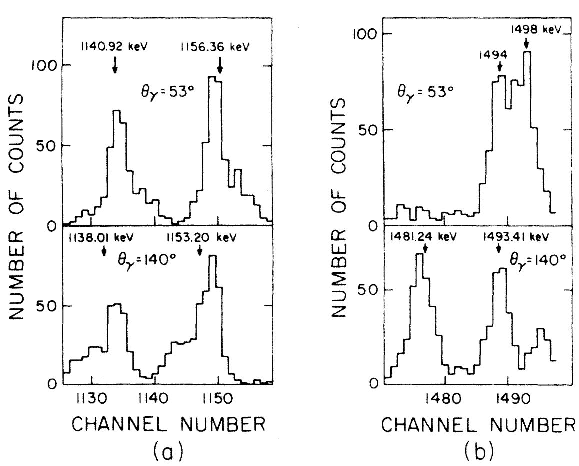

FIG. 3. (a) Portions of the γ spectra accumulated with window 2. These γ rays are produced by the ground state decays of the 1140 and 1155 keV levels. (b) Portions of the γ spectra accumulated with window 3. These γ rays are produced by the $1643 \to 153$ keV and $1646 \to 153$ keV transitions.

1514 keV level. The lifetime of this state and its decay to the $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ levels limit its possible spin to $\frac{5}{2}$, because the hypothesis of $I^\pi = \frac{3}{2}^-$ or $\frac{7}{2}^-$ implies an $E2$ transition strength of greater than 220 W.u. This is an order of magnitude larger than any other $E2$ strength in this nucleus. The hypothesis of $I^\pi = \frac{3}{2}^+$ or $\frac{7}{2}^+$ leads to an even more unreasonable $M2$ strength of about 1000 W.u. The observation[19] of an allowed β-decay branch to this state from the $\frac{5}{2}^-$ ground state of ^{49}Cr indicates negative parity. Hence $I^\pi = \frac{5}{2}^-$ for the 1514 keV level.

1602 keV level. The decay scheme and lifetime of this state favor $I^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$ over $\frac{3}{2}^-$ or $\frac{5}{2}^-$ and exclude all other spins. The existence of decay branches to the 748 keV $\frac{3}{2}^+$ and the 1140 keV $\frac{5}{2}^+$ states suggests positive parity for the 1602 keV state. The hypothesis $I^\pi = \frac{3}{2}^+$ leads to a ground state $M2$ transition strength of 80 W.u. and the hypothesis $\frac{7}{2}^-$ implies an $M2$ strength of 600 W.u. to the 748 keV level. These are unreasonably large. Spin hypotheses of $\frac{5}{2}^+$ and $\frac{7}{2}^+$ lead to quite reasonable transition strengths. Blasi *et al.*[10] conclude that the population of this level in the $^{50}Cr(t, \alpha)^{49}V$ reaction[5] and its absence from the $^{48}Ti(^3He, d)^{49}V$ spectrum[5] suggests positive parity while the flat $^{50}Cr(t, \alpha)^{49}V$ angular distribution indicates moderately high spin. A spin assignment of $\frac{7}{2}^+$ is also suggested by the possible inclusion of this state in the $K^\pi = \frac{3}{2}^+$ band.

1643 keV level. This is one member of the doublet shown in Fig. 3(b). The existence of two states near this excitation energy explains the discrepancy of γ energies reported Blasi *et al.*[10] Only an upper limit for this lifetime can be obtained because of the overlapping $1646 \to 153$ keV line. The absence of decay branches to positive parity levels suggests negative parity for this state. The hypothesis $I^\pi = \frac{7}{2}^-$ implies an unreasonably large $E2$ strength of greater than 300 W.u. to the 153 keV $\frac{3}{2}^-$ level. Spin hypotheses of $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$ imply a reasonable $M1$ strength of greater than 0.31 W.u. for the transition to the 153 keV level.

1646 keV level. This is the long-lived member of the doublet in Fig. 3(b). Its long lifetime and its decay branch to the 748 keV $\frac{3}{2}^+$ level are consistent with the assumption that this is the state which was seen as a very strong $l_p = 0$ transfer in the ^{50}Cr(t, α)^{49}V reaction[5] at a reported energy of 1652 keV. Hence $I^\pi = \frac{1}{2}^+$.

1661 keV level. The population of this level by $l_p = 1$ transfer in the ^{48}Ti(^{3}He, d)^{49}V reaction[3] restricts the possible spin-parity values to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The measured lifetime would imply an unreasonably large $E2$ strength of 220 W.u. to the 91 keV $\frac{5}{2}^-$ level if $I^\pi = \frac{1}{2}^-$. Therefore, $I^\pi = \frac{3}{2}^-$ for the 1661 keV level.

1995 keV level. Positive parity is suggested because this state is moderately strong in the ^{50}Cr(t, α)^{49}V spectrum[5] and not seen in the ^{48}Ti-(^{3}He, d)^{49}V reaction.[5] The observed lifetime is consistent with $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. Reference 5 indicates $l_p = 0$ for this state in the (t, α) reaction.

TABLE I. Doppler-shift attenuation results.

Level (keV)	Transition to (keV)	Full Doppler shift (keV)	Observed Doppler shift (keV)	$F(\tau)$	τ(fsec)
748	91	6.82	0.25 ± 0.09	0.037 ± 0.013	7700^{+3000}_{-1800}
	153	7.52	0.28 ± 0.11	0.037 ± 0.015	
1021	0	11.62	0.76 ± 0.22	0.065 ± 0.019	4300^{+1900}_{-1100}
1140	0	12.95	2.91 ± 0.29	0.225 ± 0.022	
	91	11.89	2.41 ± 0.31	0.203 ± 0.026	1150^{+170}_{-140}
	153	11.20	2.37 ± 0.50	0.212 ± 0.045	
1155	0	13.12	3.16 ± 0.21	0.241 ± 0.016	1060^{+150}_{-130}
	91	12.06	2.46 ± 0.36	0.204 ± 0.030	
1514	91	16.02	15.08 ± 0.56	0.941 ± 0.035	<14
	153	15.34	>14.98	>0.977	
1602	0	18.02	4.37 ± 0.60	0.243 ± 0.033	
	748	9.59	2.43 ± 0.60	0.253 ± 0.063	1040^{+220}_{-170}
	1140	5.19	0.98 ± 0.31	0.189 ± 0.060	
1643	153	16.72	>15.6	>0.933	<31
1646	748	10.08	0.87 ± 0.20	0.086 ± 0.020	3200^{+1100}_{-700}
1661	91	17.63	16.86 ± 0.30	0.956 ± 0.017	23 ± 10
1995	153	20.53	13.72 ± 1.50	0.668 ± 0.073	190^{+70}_{-50}
2178	1140	11.50	1.14 ± 0.70	0.099 ± 0.061	2700^{+4700}_{-1200}
2182	91	23.21	21.54 ± 0.70	0.928 ± 0.030	48 ± 17
	1155	5.01 [a]	4.10 [a] ± 0.70	0.818 ± 0.140	
2235	91	23.76	22.94 ± 0.50	0.965 ± 0.021	18 ± 11
2262	1021	13.74	<0.98	<0.071	>3840
2265	153	23.39	21.31 ± 0.50	0.911 ± 0.021	51 ± 13
	1643	5.94 [a]	4.91 [a] ± 1.00	0.827 ± 0.168	
2309	91	24.53	>23.19	>0.945	<26
2353	0	26.01	23.63 ± 0.75	0.909 ± 0.029	48 ± 17
2387	91	25.37	22.21 ± 1.50	0.875 ± 0.059	82^{+27}_{-24}
	748	18.10	14.87 ± 0.75	0.822 ± 0.042	
2408	0	26.57	>26.02	>0.979	<11
2671	1021	18.08	>17.54	>0.970	<16
2727	1021	18.66	15.39 ± 1.00	0.825 ± 0.054	138^{+58}_{-49}
	2262	5.08	3.03 ± 0.70	0.596 ± 0.138	
2742	1155	9.78 [a]	4.28 [a] ± 0.80	0.440 ± 0.082	560^{+520}_{-240}
	2178	6.16	1.45 ± 0.90	0.235 ± 0.146	
2787	0	30.48	>29.92	>0.982	<16
	1021	19.29	>18.41	>0.954	
2806	0	30.66	12.86 ± 1.00	0.419 ± 0.033	455^{+83}_{-70}
	748	12.67 [a]	5.81 [a] ± 1.50	0.459 ± 0.118	
2812	0	30.72	>27.83	>0.906	
	91	29.73	>28.79	>0.968	<18
	153	29.05	>26.51	>0.913	

[a] Shift measured between 53 and 90° or between 90 and 140°.

TABLE II. Experimental transition strengths in ^{49}V.

Level E_i(keV), I^{π}_i	Decay to E_f(keV), I^{π}_f, (%)	Multipole	Experimental strength [a] $B(\Lambda)$ [b]	Experimental strength [a] Weisskopf units
748, $\frac{3}{2}^+$	91, $\frac{5}{2}^-$, (44.6 ± 0.6) [c]	$E1$	$[1.28 \pm 0.39] \times 10^{-4}$	$[1.49 \pm 0.46] \times 10^{-4}$
	153, $\frac{3}{2}^-$, (55.4 ± 0.6) [c]	$E1$	$[2.15 \pm 0.66] \times 10^{-4}$	$[2.50 \pm 0.76] \times 10^{-4}$
1021, $\frac{11}{2}^-$	0, $\frac{7}{2}^-$, (100)	$E2$	172 ± 59	16.1 ± 5.5
1140, $\frac{5}{2}^+$	0, $\frac{7}{2}^-$, (51.8 ± 1.3) [c]	$E1$	$[1.92 \pm 0.28] \times 10^{-4}$	$[2.22 \pm 0.32] \times 10^{-4}$
	91, $\frac{5}{2}^-$, (26.4 ± 0.9) [c]	$E1$	$[1.25 \pm 0.18] \times 10^{-4}$	$[1.45 \pm 0.21] \times 10^{-4}$
	153, $\frac{3}{2}^-$, (16.6 ± 1.5) [c]	$E1$	$[9.4 \pm 1.6] \times 10^{-5}$	$[1.09 \pm 0.18] \times 10^{-4}$
	748, $\frac{3}{2}^+$, (5.2 ± 0.6) [c]	$M1$	0.043 ± 0.008	0.024 ± 0.004
1155, $\frac{9}{2}^-$	0, $\frac{7}{2}^-$, (74.7 ± 0.7) [c]	$M1$	0.026 ± 0.004	0.015 ± 0.002
	91, $\frac{5}{2}^-$, (22.4 ± 0.4) [c]	$E2$	126 ± 17	11.8 ± 1.6
	1021, $\frac{11}{2}^-$, (2.9 ± 0.6) [c]	$M1$	0.65 ± 0.16	0.36 ± 0.09
1514, $\frac{5}{2}^-$	0, $\frac{7}{2}^-$, (32.4 ± 0.7) [c]	$M1$	>0.38	>0.21
	91, $\frac{5}{2}^-$, (11.3 ± 0.4) [c]	$M1$	>0.16	>0.089
	153, $\frac{3}{2}^-$, (56.3 ± 1.0) [c]	$M1$	>0.90	>0.51
1602, ($\frac{5}{2}^+$, $\frac{7}{2}^+$)	0, $\frac{7}{2}^-$, (25.6 ± 0.6) [c]	$E1$	$[3.8 \pm 0.8] \times 10^{-5}$	$[4.4 \pm 0.9] \times 10^{-5}$
	91, $\frac{5}{2}^-$, (59.5 ± 1.3) [c]	$E1$	$[1.0 \pm 0.2] \times 10^{-4}$	$[1.2 \pm 0.2] \times 10^{-4}$
	748, $\frac{3}{2}^+$, (8.0 ± 0.8) [c]	($E2$)	(139 ± 31)	(13 ± 3)
	1140, $\frac{5}{2}^+$, (6.9 ± 0.6) [c]	$M1$	0.038 ± 0.008	0.021 ± 0.005
1643, ($\frac{1}{2}^- \cdots \frac{5}{2}^-$)	153, $\frac{3}{2}^-$, (100)	$M1$	>0.55	>0.31
1646, $\frac{1}{2}^+$	153, $\frac{3}{2}^-$, (69.0 ± 2.2)	$E1$	$[4.1 \pm 1.1] \times 10^{-5}$	$[4.7 \pm 1.3] \times 10^{-5}$
	748, $\frac{3}{2}^+$, (31.0 ± 2.2)	$M1$	$[7.6 \pm 2.2] \times 10^{-3}$	$[4.2 \pm 1.2] \times 10^{-3}$
1661, $\frac{3}{2}^-$	91, $\frac{5}{2}^-$, (64.0 ± 4.0) [c]	$M1$	$0.41^{+0.31}_{-0.13}$	$0.23^{+0.18}_{-0.07}$
	153, $\frac{3}{2}^-$, (36.0 ± 4.0) [c]	$M1$	$0.26^{+0.20}_{-0.08}$	$0.14^{+0.11}_{-0.05}$
1995, ($\frac{1}{2}^+ \cdots \frac{5}{2}^+$)	153, $\frac{3}{2}^-$, (100)	$E1$	$[5.2^{+2.0}_{-1.3}] \times 10^{-4}$	$[6.1^{+2.4}_{-1.5}] \times 10^{-4}$
2178, ($\frac{5}{2}^+ \cdots \frac{9}{2}^+$)	0, $\frac{7}{2}^-$, (46.9 ± 6.0)	$E1$	$[1.1^{+0.9}_{-0.7}] \times 10^{-5}$	$[1.2^{+1.0}_{-0.8}] \times 10^{-5}$
	1140, $\frac{5}{2}^+$, (39.7 ± 5.6)	($E2$)	(100^{+80}_{-65})	$(9.4^{+7.6}_{-6.1})$
	1602 (13.4 ± 3.8)	($M1$)	$(0.015^{+0.013}_{-0.010})$	$([8.2^{+7.0}_{-5.7}] \times 10^{-3})$
2182, $\frac{7}{2}^-$	0, $\frac{7}{2}^-$ (22.4 ± 6.6)	$M1$	$0.026^{+0.016}_{-0.010}$	$0.014^{+0.009}_{-0.006}$
	91, $\frac{5}{2}^-$, (57.2 ± 3.6)	$M1$	$0.074^{+0.041}_{-0.020}$	$0.041^{+0.023}_{-0.011}$
	1155, $\frac{9}{2}^-$, (20.4 ± 5.4)	$M1$	$0.22^{+0.14}_{-0.08}$	$0.12^{+0.08}_{-0.05}$
2235, ($\frac{3}{2}^- \cdots \frac{7}{2}^-$)	0, $\frac{7}{2}^-$, (22.4 ± 6.0)	($M1$)	$(0.064^{+0.100}_{-0.029})$	$(0.036^{+0.057}_{-0.016})$
	91, $\frac{5}{2}^-$, (77.6 ± 6.0)	$M1$	$0.25^{+0.39}_{-0.10}$	$0.14^{+0.22}_{-0.05}$
2262, $\frac{15}{2}^-$	1021, $\frac{11}{2}^-$, (100)	$E2$	<71	<6.7
2265, ($\frac{1}{2}^-$, $\frac{3}{2}^-$)	153, $\frac{3}{2}^-$, (92.8 ± 3.4)	$M1$	$0.11^{+0.04}_{-0.02}$	$0.061^{+0.021}_{-0.013}$
	1643(7.2 ± 3.4)	($M1$)	$(0.33^{+0.19}_{-0.17})$	$(0.19^{+0.11}_{-0.10})$
2309, $\frac{3}{2}^-$	91, $\frac{5}{2}^-$, (100)	$M1$	>0.20	>0.11
2353, ($\frac{9}{2}^-$, $\frac{11}{2}^-$)	0, $\frac{7}{2}^-$, (57.5 ± 4.8)	($M1$)	$(0.052^{+0.029}_{-0.014})$	$(0.029^{+0.016}_{-0.008})$
	1021, $\frac{11}{2}^-$, (42.5 ± 4.8)	$M1$	$0.21^{+0.12}_{-0.06}$	$0.12^{+0.07}_{-0.03}$
2387, ($\frac{3}{2}^+$, $\frac{5}{2}^+$)	91, $\frac{5}{2}^-$, (24.0 ± 7.0)	$E1$	$[1.5^{+0.8}_{-0.6}] \times 10^{-4}$	$[1.8^{+0.9}_{-0.7}] \times 10^{-4}$
	748, $\frac{3}{2}^+$, (76.0 ± 7.0)	$M1$	$0.12^{+0.05}_{-0.03}$	$0.067^{+0.028}_{-0.018}$

TABLE II *(Continued)*

Level E_i(keV), I^π_i	Decay to E_f(keV), I^π_f, (%)	Multipole	Experimental strength [a] $B(\Lambda)$ [b]	Weisskopf units
2408, $(\frac{7}{2}^-, \frac{9}{2}^-)$	0, $\frac{7}{2}^-$, (83.0 ± 4.0)	$M1$	>0.30	>0.16
	1155, $\frac{9}{2}^-$, (17.0 ± 4.0)	$M1$	>0.34	>0.19
2671, $(\frac{9}{2}^- \cdots \frac{13}{2}^-)$	1021, $\frac{11}{2}^-$, (100)	$M1$	>0.79	>0.44
2727, $(\frac{13}{2}^-, \frac{15}{2}^-)$	1021, $\frac{11}{2}^-$, (40.9 ± 2.4)	$(M1)$	$(0.034^{+0.019}_{-0.010})$	$(0.019^{+0.010}_{-0.006})$
	2262, $\frac{15}{2}^-$, (59.1 ± 2.4)	$M1$	$2.4^{+1.3}_{-0.7}$	$1.4^{+0.7}_{-0.4}$
2742, $(\frac{7}{2}^+ \cdots \frac{11}{2}^+)$	1155, $\frac{9}{2}^-$, (76.4 ± 9.6)	$E1$	$[2.1^{+1.6}_{-1.1}]\times 10^{-4}$	$[2.5^{+1.8}_{-1.2}]\times 10^{-4}$
	2178(23.6 ± 9.6)	$(M1)$	$(0.13^{+0.11}_{-0.08})$	$(0.075^{+0.062}_{-0.047})$
2787, $(\frac{9}{2}^-, \frac{11}{2}^-)$	0, $\frac{7}{2}^-$, (55.7 ± 5.8)	$(M1)$	(>0.082)	(>0.046)
	1021, $\frac{11}{2}^-$, (44.3 ± 5.8)	$M1$	>0.25	>0.14
2806, $\frac{5}{2}^+$	0, $\frac{7}{2}^-$, (64.9 ± 11.2)	$E1$	$[4.1 \pm 1.0]\times 10^{-5}$	$[4.7 \pm 1.2]\times 10^{-5}$
	748, $\frac{3}{2}^+$, (35.1 ± 11.2)	$M1$	$[5.0 \pm 1.8]\times 10^{-3}$	$[2.8 \pm 1.0]\times 10^{-3}$
2812, $(\frac{5}{2}^-, \frac{7}{2}^-)$	0, $\frac{7}{2}^-$, (63.2 ± 7.0)	$M1$	>0.081	>0.044
	91, $\frac{5}{2}^-$, (24.5 ± 6.2)	$M1$	>0.028	>0.016
	153, $\frac{3}{2}^-$, (12.3 ± 5.2)	$(M1)$	(>0.013)	(>0.007)

[a] These values attribute all the transition strength to the lowest allowed multipole.
[b] The units are μ_N^2 for $B(M1)$, $e^2\,\text{fm}^2$ for $B(E1)$ and $e^2\,\text{fm}^4$ for $B(E2)$.
[c] Reference 10.

However, $l_p = 2$ appears to fit the published angular distribution as well as $l_p = 0$. If $I^\pi = \frac{3}{2}^+$, this level may be the second member of the $K^\pi = \frac{1}{2}^+$ band.

2178 keV level. The existence of decay branches to other positive parity levels suggests positive parity for this level. The possibilities $I^\pi = \frac{3}{2}^+$ or $\frac{11}{2}^+$ can be rejected because the ground state transition would have an $M2$ strength of about 10 W.u. Accordingly $I^\pi = \frac{5}{2}^+$, $\frac{7}{2}^+$, or $\frac{9}{2}^+$ are the most probable spins. The excitation energy of this state and its decay to the $\frac{5}{2}^+$ and probable $\frac{7}{2}^+$ levels suggest that the 2178 keV level is the $\frac{9}{2}^+$ member of the $K^\pi = \frac{3}{2}^+$ band.

2182 keV level. The $l_p = 3$ angular distribution seen for this state in the ^{48}Ti(^{3}He, d)^{49}V reaction[3] limits the possible spin-parity values to $\frac{5}{2}^-$ or $\frac{7}{2}^-$. For $I^\pi = \frac{5}{2}^-$, the transition to the 1155 keV $\frac{9}{2}^-$ state would have an unreasonably large $E2$ strength of 275 W.u. Therefore, $I^\pi = \frac{7}{2}^-$ for this level.

2262 keV level. Sawa *et al.*[12] have suggested $I^\pi = \frac{15}{2}^-$ for this state based on an angular distribution indicating pure $E2$ radiation to the 1021 keV $\frac{11}{2}^-$ state. The lifetime limit implies a reasonable $E2$ strength of < 6.7 W.u. for $I^\pi = \frac{15}{2}^-$ and is consistent with the assignment of $I^\pi = \frac{15}{2}^-$.

2265 keV level. This state is seen with an $l_p = 1$ transfer in the ^{48}Ti(^{3}He, d)^{49}V reaction[3] and, consequently, the spin parity is restricted to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The lifetime and decay scheme of this state are consistent with both possible spins.

2309 keV level. A level at 2307 keV is populated very strongly by $l_p = 1$ transfer in the ^{48}Ti(^{3}He,d)^{49}V reaction.[3] Thus $I^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$. The short lifetime of this state would imply an unreasonably strong $E2$ transition of greater than 55 W.u. to the $\frac{5}{2}^-$ level at 91 keV if $I^\pi = \frac{1}{2}^-$. Therefore, $I^\pi = \frac{3}{2}^-$ for the 2309 keV level.

2387 keV level. The decay of this state to the 91 keV $\frac{5}{2}^-$ and the 748 keV $\frac{3}{2}^+$ levels and its measured lifetime limit the possible spin to $\frac{3}{2}$ or $\frac{5}{2}$. The existence of a strong decay branch to a positive parity level suggests positive parity for the 2387 keV state. Its excitation energy suggests that this state may be the $\frac{5}{2}^+$ member of the $K^\pi = \frac{1}{2}^+$ band.

2408 keV level. The short lifetime of this state would imply an $E2$ strength of > 70 W.u. for the ground state transition and > 380 W.u. for the transition to the 1155 keV $\frac{9}{2}^-$ level. Thus the lifetime and decay scheme of this state limit its possible spin to $\frac{7}{2}$ or $\frac{9}{2}$. It appears that this state can be identified with a level seen at 2388 keV in the ^{48}Ti(^{3}He, d)^{49}V reaction[3] for which no l value was assigned. Its presence in the stripping spectrum is an argument for negative parity.

2742 keV level. This state decays to the 1155 keV $\frac{9}{2}^-$ and the 2178 keV $(\frac{9}{2}^+)$ levels. The lifetime of this state would imply unreasonably large

(> 500 W.u.) $M2$ transitions to both final states and an unreasonably large $E2$ strength of 570 W.u. to the 2178 keV level. Hence these transitions are predominately dipole and $\frac{7}{2} \leq I \leq \frac{11}{2}$. The decay to a presumed positive parity level suggests positive parity. It is not possible to determine whether this state decays to the 1602 keV level because of the known presence of another γ ray of approximately the same energy from the 1140 → 0 keV transition. The excitation energy of this state suggests that it may be the $\frac{11}{2}^+$ member of the $K^\pi = \frac{3}{2}^+$ rotational band.

2806 and 2812 keV levels. A state at 2812 keV is populated with $l_p = 2$ in the $^{50}Cr(t, \alpha)^{49}V$ reaction[5] and a state at 2820 keV is reached by $l_p = 3$ stripping in the $^{48}Ti(^3He, d)^{49}V$ reaction.[3,5] The existence of a decay branch from the 2806 keV level to the 748 keV $\frac{3}{2}^+$ level suggests that the 2806 keV state is the one seen in the $^{50}Cr(t, \alpha)^{49}V$ reaction. Only spin-parity hypotheses of $\frac{3}{2}^+$ and $\frac{5}{2}^+$ are consistent with the l value, and the hypothesis of $I^\pi = \frac{3}{2}^+$ is ruled out by the unreasonably large $M2$ strength of 27 W.u. for the ground state transition which it would imply. Therefore, $I^\pi = \frac{5}{2}^+$ for the 2806 keV state. The 2812 keV state can presumably be identified with the state seen in the stripping reaction. This restricts its spin and parity to $\frac{5}{2}^-$ or $\frac{7}{2}^-$, and both of these possibilities are consistent with the decay scheme.

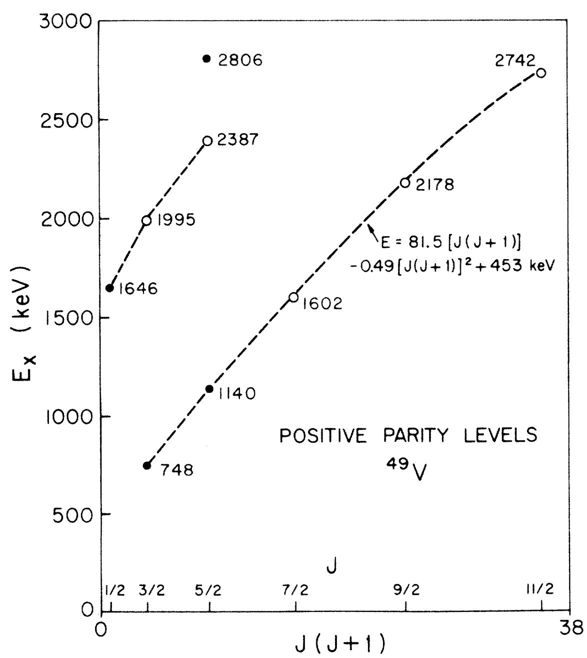

FIG. 4. The excitation energies of the positive parity levels in ^{49}V graphed as a function of $J(J+1)$. Open circles indicate states whose spin is not well determined. The dashed lines connect members of each rotational band.

2235, 2353, 2671, 2727, and 2787 keV levels. Some spin restrictions are possible for the remaining levels. The following transitions would have unreasonably large $E2$ strengths (in parentheses) if the transitions were purely quadrupole: 2235 → 91 keV (70 W.u.), 2353 → 1021 keV (160 W.u.), 2671 → 1021 keV (> 390 W.u.), 2727 → 2262 keV (> 15 000 W.u), 2787 → 1021 keV (> 100 W.u.). The possible spins which are consistent with these restrictions are indicated in Table II.

V. COLLECTIVE PROPERTIES

A. Positive parity rotational bands

The states which have been assigned or suggested to have positive parity are displayed on a graph of excitation energy vs $I(I+1)$ in Fig. 4. Two rotational bands and perhaps the head of a third are seen.

Every member of the $K^\pi = \frac{3}{2}^+$ band decays only to other members of the band and to members of the ground state triplet of negative parity levels. The decay schemes and lifetimes of all the states in this band are consistent with the spins indicated on Fig. 4. Spin assignments and suggestions are discussed in the preceding section. An earlier grouping of the first three levels into a rotational band was made in Ref. 10.

Strengths of $M1$ transitions within the $K^\pi = \frac{3}{2}^+$ band are typically a few hundredths of a single particle unit. The $E2$ transition strengths within the band are enhanced about a factor of 10 over the single particle estimate. This enhancement of $E2$ strengths is further evidence of collective behavior. The dashed curve drawn through the $K^\pi = \frac{3}{2}^+$ band in Fig. 4 is generated by the equation $E(\text{keV}) = 81.5\,[I(I+1)] - 0.49\,[I(I+1)]^2 + 453$ and represents a fit to the data using the variable moment of inertia model. The fit is excellent but, with three variable parameters, there are only two remaining degrees of freedom.

The $K^\pi = \frac{1}{2}^+$ band is somewhat less well established. Electromagnetic transitions within the presumed band have not been observed. This may be a consequence of the higher excitation energy of this band which increases the energy and probability of decays to low lying negative parity states. Even without the evidence of decays within the band, the sequence of excitation energies provides reasonable evidence for existence of the $K^\pi = \frac{1}{2}^+$ band. The deviations of the level positions from an $I(I+1)$ dependence may be a result of the decoupling term for $K = \frac{1}{2}$ rotational bands. The observed level spacing can be fitted by $E(\text{keV}) = 97.4\,[I(I+1) + 0.20(-1)^{I+1/2}(I+\frac{1}{2})] + 1592$. The parameters in this formula appear reasonable, but not enough levels are known in this band to test the equation.

The $E1$ strengths of the transitions from positive to negative parity levels are retarded by about 10^{-4} compared to the single particle estimate. Retardations of this order of magnitude have been observed for the $E1$ transitions from the lowest $\frac{3}{2}^+$ levels in ^{49}Cr[2] and ^{47}Ti.[1] These retardations are probably indicative of poor overlap between the wave functions for predominantly $f_{7/2}$ particle states and predominantly s-d hole states.

B. Negative parity levels and the strong coupling model

An examination of the negative parity levels in ^{49}V which are shown in Fig. 5 does not reveal obvious rotational bands. Angular momenta of the lower levels do not even increase monotonically as in the case of ^{47}Ti and ^{49}Cr. However, the Coriolis term in the Hamiltonian is known to be effective in mixing Nilsson bands[20] in nuclei in the $f_{7/2}$ shell.

We have performed calculations in ^{49}V using the strong coupling model. Earlier calculations of the level scheme in this nucleus using a somewhat similar model were made by Malik and Scholz.[21]

In contrast to the earlier work, the present model yields states of definite isospin and includes the full effect of the Coriolis term

$$-\frac{\hbar^2}{2\mathcal{I}}\vec{I}\cdot\vec{j}$$

in the Hamiltonian, which couples rotation and particle motion (RPC) and mixes Nilsson bands. The band mixing calculation involves diagonaliza-

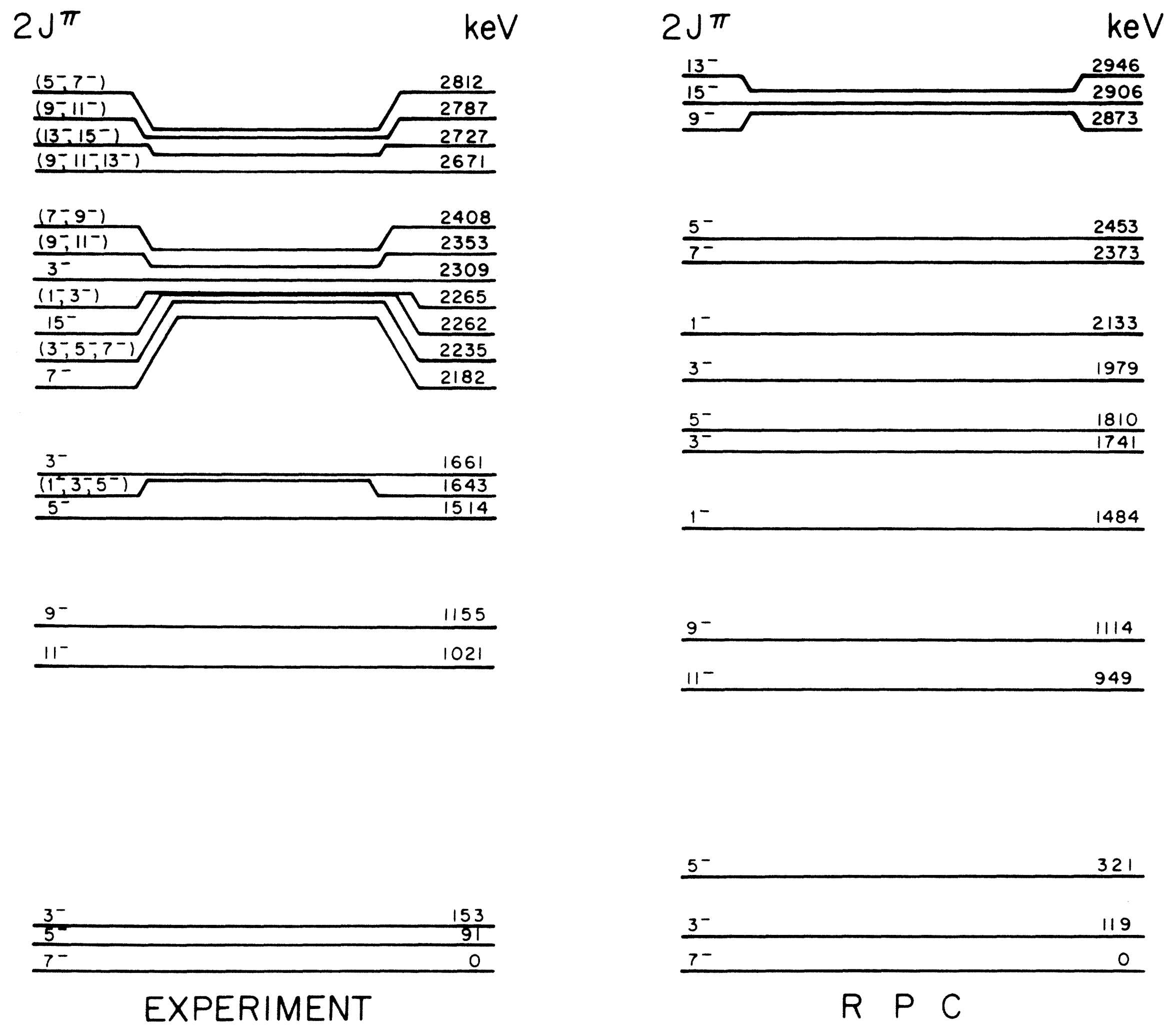

FIG. 5. Energy level diagrams of the experimentally determined levels in ^{49}V for which positive parity is not favored and of the levels predicted by the strong coupling model (RPC).

tion of the total Hamiltonian

$$H=\frac{\hbar^2}{2\mathscr{I}}[I^2+j^2-2(\vec{I}\cdot\vec{j})]$$
$$-\frac{\hbar^2}{2M}\Delta+\frac{M}{2}(\omega_x{}^2x^2+\omega_y{}^2y^2+\omega_z{}^2z^2)$$
$$-\hbar\,\mathring{\omega}_0\chi(2\vec{l}\cdot\vec{s}+\mu\vec{l}\cdot\vec{l}),$$

where $\hbar\,\mathring{\omega}_0$ is the oscillator energy with the deformation $\delta=0$. The model is described in more detail in Ref. 2.

The level scheme of Fig. 5 was calculated using the following parameters:

$$\frac{\hbar^2}{2\mathscr{I}}=125\text{ keV},\quad \delta=0.20$$

$$\chi=0.040,\quad \mu=0.45\ .$$

The moment of inertia parameter is in good agreement with the value deduced from the excitation energy of the lowest 2^+ state in ^{50}Cr. The value of μ is identical to that used for calculations in ^{47}Ti and ^{49}Cr, and the deformation parameter δ does not differ greatly from that used for ^{47}Ti ($\delta=0.22$) or ^{49}Cr ($\delta=0.24$).

The experimental level scheme can be compared with the RPC model calculation in Fig. 5. The agreement in excitation energies up through the $\frac{9}{2}^-$ state is good. The ground state spin in correctly predicted although the $\frac{5}{2}^-$ state is predicted 230 keV too high. If the 1643 keV level has spin $\frac{1}{2}^-$, then the model works fairly well through the $\frac{3}{2}^-$ state at 1661 keV. The RPC model predicts the $\frac{15}{2}^-$ and $\frac{13}{2}^-$ levels to be rather close in excitation energy. The $\frac{15}{2}^-$ level is observed about 600 keV below the predicted energy and the nearest candidates for the $\frac{13}{2}^-$ state are 400 keV above the experimental $\frac{15}{2}^-$ state.

Some predictions of transition strengths using the RPC model are compared with the experimental strengths in Table III. Lifetimes of the first two levels and the ground state magnetic moment are taken from the literature. The agreement of $E2$ strengths is rather good although the model tends to slightly over-predict the strengths. There is also reasonable agreement with the $M1$ strengths. The model does not predict very well the ratios of strengths among the decay branches of the 1514 keV level. Prediction of the ground state magnetic moment is reasonably good.

The wave function of the ground state calculated in the RPC model has the following principle components in a basis of Nilsson model states

TABLE III. Comparison of experimental transition strengths with RPC calculations.

Transition E_i(keV), $I^\pi{}_i$	$\rightarrow E_f$ (keV), $I^\pi{}_f$	Multipole	$B(\Lambda)$ Experiment [a]	RPC	
91, $\frac{5}{2}^-$	0, $\frac{7}{2}^-$	$M1$	0.12 ± 0.01 [b]	0.57	μ_N^2
153, $\frac{3}{2}^-$	0, $\frac{7}{2}^-$	$E2$	197 ± 3 [c]	254	$e^2\,\text{fm}^4$
	91, $\frac{5}{2}^-$	$M1$	0.0035 ± 0.0001 [c]	0.036	μ_N^2
1021, $\frac{11}{2}^-$	0, $\frac{7}{2}^-$	$E2$	172 ± 59	211	$e^2\,\text{fm}^4$
1155, $\frac{9}{2}^-$	0, $\frac{7}{2}^-$	$M1$	0.016 ± 0.004 [d]	0.004	μ_N^2
	0, $\frac{7}{2}^-$	$E2$	106 ± 28 [d]	111	$e^2\,\text{fm}^4$
	91, $\frac{5}{2}^-$	$E2$	126 ± 17	173	$e^2\,\text{fm}^4$
	1021, $\frac{11}{2}^-$	$M1$	0.65 ± 0.16	0.87	μ_N^2
1514, $\frac{5}{2}^-$	0, $\frac{7}{2}^-$	$M1$	>0.38	1.50	μ_N^2
	91, $\frac{5}{2}^-$	$M1$	>0.16	0.81	μ_N^2
	153, $\frac{3}{2}^-$	$M1$	>0.90	0.08	μ_N^2
1643, ($\frac{1}{2}^-$)	153, $\frac{3}{2}^-$	$M1$	>0.55	2.34	μ_N^2
1661, $\frac{3}{2}^-$	91, $\frac{5}{2}^-$	$M1$	$0.41^{+0.31}_{-0.13}$	0.40	μ_N^2
	153, $\frac{3}{2}^-$	$M1$	$0.26^{+0.20}_{-0.08}$	0.12	μ_N^2
g.s.	Magnetic moment		4.5 [e]	5.45	μ_N

[a] Assuming the mixing ratio $\delta=0$ except as noted.
[b] Using $\tau=620\pm29$ psec from Ref. 13.
[c] Using $\tau=28.7\pm0.5$ nsec from Ref. 14.
[d] Using $\delta=-0.78^{+0.18}_{-0.22}$ from Ref. 12.
[e] Reference 22.

$|K^{\pi}[Nn_3\Lambda]\rangle$:

$$(0.35)^{1/2}|\tfrac{1}{2}^-[330]\rangle+(0.52)^{1/2}|\tfrac{3}{2}^-[321]\rangle+(0.12)^{1/2}|\tfrac{5}{2}^-[312]\rangle.$$

The composition of the lowest $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^-$ states is fairly similar except that the $\frac{3}{2}^-$ state cannot contain any admixture of the $|\frac{5}{2}^-[312]\rangle$ state. The strong admixture of three Nilsson bands probably accounts for the even poorer resemblence of these levels in ^{49}V to a rotational band than of the lower levels in ^{47}Ti or ^{49}Cr.

The success of the strong coupling model in reproducing the transition strengths and level energies below 2 MeV and the enhancement of $E2$ transition strengths indicate the importance of collective effects among the negative parity levels of ^{49}V.

The strong coupling model appears to describe the ^{49}V spectrum better than the shell model with configurations limited to the $f_{7/2}$ shell.[23] The shell model predicts only a ground state doublet ($\frac{5}{2}^-$, $\frac{7}{2}^-$) and the $\frac{3}{2}^-$ and $\frac{9}{2}^-$ states are predicted 400 to 600 keV too high. A more complete shell model calculation including additional configurations would be interesting.

C. Comparison with ^{45}Ti

Since the spectrum predicted by the strong coupling model depends mainly on the odd particles outside the core, it is instructive to compare the excitation spectrum of ^{45}Ti (with three neutrons outside the ^{40}Ca core) with that of ^{49}V (with three protons outside the ^{40}Ca core). It should be noted, however, that the RPC model used in the present calculations does not predict identical spectra for these two nuclei even with the same choice of parameters because of the effect of generating states of good isospin.

The low energy spectrum of ^{45}Ti does resemble that of ^{49}V. ^{45}Ti has an almost degenerate triplet of levels[24] near the ground state ($\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$). The $\frac{9}{2}^-$ (1354 keV) and the $\frac{11}{2}^-$ (1468 keV) levels[25] are closely spaced but come about 500 keV higher in ^{45}Ti than in ^{49}V.

A $K^{\pi}=\frac{3}{2}^+$ band consisting of the 329, 744, 1227, 1882, and 2475 keV states is also seen[25,26] in ^{45}Ti. This band begins about 400 keV below that in ^{49}V but has a similar moment of inertia.

The fact that the spectrum of ^{49}V resembles that of ^{45}Ti more than the spectrum of the cross-conjugate nucleus ^{47}Ti indicates the limitations of the pure $f_{7/2}$ shell model in describing ^{49}V.

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[1]J. J. Weaver, M. A. Grace, D. F. H. Start, R. W. Zurmühle, D. P. Balamuth, and J. W. Noé, Nucl. Phys. A196, 269 (1972).
[2]R. W. Zurmühle, D. A. Hutcheon, and J. J. Weaver, Nucl. Phys. A180, 417 (1972).
[3]D. J. Pullen, B. Rosner, and O. Hansen, Phys. Rev. 166, 1142 (1968).
[4]B. Čujec and I. M. Szöghy, Phys. Rev. 179, 1060 (1969).
[5]D. Bachner, R. Santo. H. H. Duhm, R. Bock, and S. Hinds, Nucl. Phys. A106, 577 (1968).
[6]C. St. Pierre, P. N. Maheshwari, D. Doutriaux, and L. LaMarche, Nucl. Phys. A102, 433 (1967).
[7]G. Brown, A. MacGregor, and R. Middleton, Nucl. Phys. 77, 385 (1966).
[8]J. C. Legg, D. G. Megli, D. R. Abraham, L. D. Ellsworth, and S. Hechtl, Phys. Rev. 186, 1138 (1969).
[9]A. Kiuru, Z. Phys. 251, 93 (1972).
[10]P. Blasi, M. Mandò, P. R. Maurenzig, and N. Taccetti, Nuovo Cimento 4, 61 (1971).
[11]J. N. Mo, B. Čujec, R. Dayras, I. M. Szöghy, and M. Toulemonde, Nucl. Phys. A147, 129 (1970).
[12]Z. P. Sawa, J. Blomqvist, and W. Gullholmer, Nucl. Phys. A205, 257 (1973).
[13]H. C. Cheung and S. K. Mark, Nucl. Phys. A176, 219 (1971).
[14]G. B. Vingiani, C. Rossi-Alvarez, A. Boscemi, F. Brandolini, and F. Cervellera, Phys. Lett. 40B, 638 (1972).
[15]J. Britz, J. Chevallier, B. Haas, and J. Styczen, in *Proceedings of the International Conference on Nuclear Physics, Munich, 1973,* edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam/American Elsevier, New York, 1973).
[16]B. A. Brown, D. B. Fossan, J. M. McDonald, and K. A. Snover, Phys. Rev. C 9, 1033 (1974).
[17]J. Lindhard, M. Scharff, and H. E. Schiøtt, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 33, No. 14 (1963).
[18]A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[19]S. L. Tabor, L. K. Fifield, K. Young, and R. Zurmühle, to be published.
[20]S. G. Nilsson, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 29, No. 16 (1955).
[21]F. B. Malik and W. Scholz, Phys. Rev. 150, 919 (1966).
[22]G. H. Fuller and V. W. Cohen, Nucl. Data A 5, 433 (1969).
[23]J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. 134, B515 (1964).
[24]J. H. Jett, G. D. Jones, and R. A. Ristinen, Phys. Lett. 28B, 111 (1968).
[25]K. V. K. Iyengar and B. C. Robertson, Nucl. Phys. A171, 73 (1971).
[26]J. Kownacki, L. Harms-Ringdahl, J. Sztarkier, and Z. P. Sawa, Phys. Scr. 8, 135 (1973).