Properties of excited states of ^{49}V

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Excitation energies, spins and lifetimes have been measured in ^{49}V employing the reaction ^{46}Ti$(\alpha, p\gamma)^{49}$V at a bombarding energy of 10.6 MeV. Reaction-produced protons were detected in an annular Si counter at an average angle of 171°. Coincident γ-ray spectra were measured with a Ge(Li) detector at angles $120° \geq \theta \geq 0°$. Two Ge(Li) detectors were used in a γ-γ coincidence experiment. The half-life of the 90.7 keV excited state, $T_{1/2} = 0.45(3)$ ns, was measured by time-delayed n-γ coincidences employing the reaction ^{49}Ti$(p, n\gamma)^{49}$V at a proton bombarding energy of 2.1 MeV. The results obtained for excitation energies, spins, parities, and lifetimes (ps) are: 748.3, $\frac{3}{2}^+$, >5, <1000; 1021.6, $\frac{11}{2}^-$, $6.3^{+3.9}_{-2.5}$; 1140.9, $\frac{5}{2}^+$, $1.8^{+0.9}_{-0.5}$; 1155.4, $\frac{9}{2}^-$, $1.65^{+0.48}_{-0.34}$; 1514.4, $\frac{5}{2}^-$, $0.045^{+0.021}_{-0.018}$; 1603.1, $\frac{7}{2}^+$, $0.68^{+0.31}_{-0.18}$; 1643.1, $\frac{1}{2}^{(-)}$, $\frac{3}{2}^{(-)}$, $\frac{5}{2}^{(-)}$, $0.050^{+0.017}_{-0.014}$; 1646.4, $\frac{1}{2}^{(+)}$, $\frac{3}{2}^{(+)}$, $\frac{5}{2}^{(+)}$, >7.5, <1000; 1661.4, $\frac{3}{2}^-$, <0.04; 1994.9, $\frac{3}{2}^+$, $1.34^{+0.80}_{-0.43}$; 2178.5, $\frac{9}{2}^+$, $0.80^{+0.70}_{-0.40}$; 2182.7, $\frac{7}{2}^-$, <0.08; 2235.3, $\frac{5}{2}^-$, <0.05; 2263.3, $\frac{15}{2}^-$, $0.93^{+0.55}_{-0.28}$; 2265.2, $\frac{3}{2}^-$, <0.06; 2309.7, $\frac{3}{2}^-$, <0.07; 2353.3, $\frac{9}{2}^-$, <0.07; 2388.2, $\frac{5}{2}^+$, $0.09^{+0.04}_{-0.02}$; 2408.4, $\frac{7}{2}^\pm$, $\frac{9}{2}^-$, $\frac{11}{2}^-$, <0.03; 2670.8, $\frac{9}{2}^-$, $\frac{11}{2}^-$, $\frac{13}{2}^-$, <0.03; 2727.8, $\frac{15}{2}^{(-)}$, $0.35^{+0.15}_{-0.11}$; 2741.1, $\frac{7}{2}^-$, $\frac{9}{2}^\pm$, $\frac{11}{2}^+$, $0.70^{+0.80}_{-0.50}$; 2786.3, $\frac{9}{2}^-$, $\frac{11}{2}^-$, <0.04; 2810.7, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, $\frac{9}{2}^-$, <0.06; 2860.8, $\frac{13}{2}^-$, $0.15^{+0.08}_{-0.06}$; 3017.3, $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, <0.06; 3133.4, $(\frac{7}{2}^-)$, $\frac{9}{2}^{(+)}$, $(\frac{11}{2}^-)$, <0.06; 3133.7, $\frac{9}{2}^{(-)}$, $\frac{11}{2}^{(-)}$, $\frac{13}{2}^{(-)}$, $0.32^{+0.11}_{-0.06}$; 3259.4, undetermined, >3, <1000; 3341.6, $\frac{9}{2}^\pm$, $\frac{11}{2}^\pm$, $\frac{13}{2}^+$, >5, <1000. γ-ray branching ratios and multipole mixing ratios were also obtained from the data, and reduced electromagnetic transition matrix elements have been extracted for a number of observed transitions. The positive parity states of ^{49}V were organized into two rotational bands with $K^\pi = \frac{1}{2}^+$ and $K^\pi = \frac{3}{2}^+$. Calculations have been performed for negative parity states based on the strong-coupling model of Bohr and Mottelson with correctly treated phases in particle-hole excitations and the $(\Sigma_i j_i)^2$ term in the Hamiltonian. The results are compared with experiment.

NUCLEAR REACTIONS ^{46}Ti$(\alpha, p\gamma)$, $E_\alpha = 10.6$ MeV and ^{49}Ti$(p, n\gamma)$, $E_p = 2.1$ MeV; measured $\gamma\gamma$, $p\gamma$, $n\gamma$, E_γ, $T_{1/2}$, δ for transitions in ^{49}V. Deduced J, π for levels.

I. INTRODUCTION

The growing interest in studying properties of $f_{7/2}$ nuclei seems to be prompted by the possibility of observing different aspects of their complex phenomena through different modes of excitation. Gross features of negative parity states in some of these nuclei have been described by the model of McCullen, Bayman, and Zamick[1] considering n particles coupled in the $f_{7/2}$ major shell. Allowing these particles to occupy the $p_{3/2}$ and $f_{5/2}$ shells improves the calculations.[2] On the other hand, properties of some odd $f_{7/2}$ nuclei have been successfully described by the model of Malik and Scholz[3] in which a nucleus is considered to be deformed and an unpaired particle is Coriolis coupled to the even-even core.

Much experimental data exists on positive parity states of odd $f_{7/2}$ nuclei and their properties can be reproduced by assuming them to be members of $K^\pi = \frac{1}{2}^+$ and $K^\pi = \frac{3}{2}^+$ bands built on the $s_{1/2}$ and $d_{3/2}$ hole states.[4] Recently Kownacki *et al.*[5] have derived $|g_K - g_R|$ and β for the $K^\pi = \frac{3}{2}^+$ positive parity bands in ^{45}Sc and ^{45}Ti. They found a deformation parameter $\beta = 0.26$ for ^{45}Ti and a consistency of $|g_K - g_R|$ values for the in-band transitions observed in ^{45}Sc and ^{45}Ti.

The ^{49}V nucleus having three protons and six neutrons beyond the $Z = N = 20$ closed shells and thus lying in the middle of the $f_{7/2}$ shell may provide some evidence as to whether its excited states can be described by shell model configurations of the $(fp)^n$ type or by deformed model wave functions. The energy levels below 2.6 MeV and their properties have been investigated by many authors using the reactions (p, γ), $(p, n\gamma)$, $(\alpha, p\gamma)$[6-11] and $(^3$He$, d)$, (t, α), and (p, α).[12-18] Still, however, many ambiguities concerning spin and parity assignments existed and the electromagnetic properties had scarcely been investigated. Recently, during the course of the present work, lifetimes for some excited states measured by the Doppler shift attenuation method (DSAM) were reported and some high spin states observed.[19]

After this paper was submitted for publication, an article on lifetime measurements and collective behavior in ^{49}V appeared in the literature.[20]

In the present work, preliminary results of which have been reported earlier,[21] excited states up to 3.34 MeV were investigated using the ^{46}Ti$(\alpha, p\gamma)^{49}$V reaction. Lifetimes were measured both by DSAM and delayed-coincidence. Proton-γ angular correlations provided mixing ratios for some transitions and, combined with the lifetimes, furnished information on spins and parities of excited states in ^{49}V.

Calculations have been performed using the strong-coupling model with a correct treatment of particle-hole excitations and a $(\sum_i j_i)^2$ term in the Hamiltonian which gives rise to a coupling between orbitals of active particles. The results of these calculations are compared with the experimental data in Sec. IV B.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experiments were carried out on the 5.5 MV Van de Graaff accelerator in Strasbourg. A 500 μg/cm^2 target of ^{46}Ti enriched to 84% evaporated on a Ag backing was bombarded with doubly ionized ^{4}He particles at 10.6 MeV. Protons from the ^{46}Ti$(\alpha, p)^{49}$V reaction were detected with an annular Si surface barrier detector of 16 mm o.d. and 700 μm depletion depth placed at 180° with respect to the beam direction and 25 mm from the target. To eliminate the backscattered α particles, the detector was covered with an 18 mg/cm^2 Al foil. The energy resolution of the particle detection system was 130 keV.

Ge(Li) detectors of 60 and 80 cm^3 were employed in the γ-γ coincidence experiment; the 80 cm^3 detector was used for the lifetime and p-γ angular correlation measurements. The energy resolution of these detectors at $E_\gamma = 1.33$ MeV was 2.5 and 2.1 keV, respectively.

The p-γ and γ-γ coincidences were detected with constant fraction timing discriminators and time-to-amplitude converters (TAC). During the lifetime measurements, ^{56}Co γ rays coincident in the Ge(Li) counter and in a 5×5 cm NaI(Tl) crystal were simultaneously recorded. This served for the energy calibration and as a check on possible gain shifts in the Ge(Li) system. Pulse-height information from the particle and γ-ray channels as well as from the time channels was converted by analog-to-digital converters directly interfaced with an on-line IBM1800 computer system. Data were stored event by event on disks and in the subsequent analysis individual coincidence spectra as well as random coincident spectra were generated and analyzed using the computer program MEGACA[22] which permits the setting of gates on the two-parameter spectra and yields intensities and centroids of lines of interest in one-parameter spectra. An example of a generated proton spectrum is shown in Fig. 1.

In the γ-γ coincidence measurement the Ge(Li) detectors were placed at target-detector distance of 4 cm while in the lifetime and angular correlation experiments this distance was 10 cm.

A. Delayed-coincidence experiment

A delayed-coincidence method was used to measure (or to define upper limits of) lifetimes of ^{49}V excited states in the nanosecond region. In these measurements, γ rays were detected by a 5×3 cm diam NE102 plastic scintillator coupled to an XP1021 photomultiplier and protons by the annular surface-barrier Si detector. The 124×60 channel two-dimensional proton-(p, γ) time spectra were stored in a Tridac multichannel analyzer. The slopes of the prompt curves for γ-ray energies

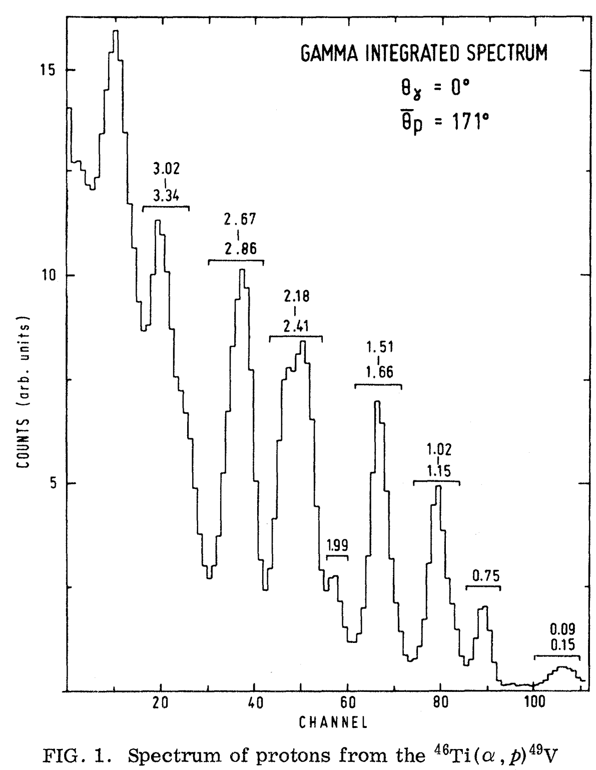

FIG. 1. Spectrum of protons from the ^{46}Ti$(\alpha, p)^{49}$V reaction. This spectrum was projected from a two-dimensional p-γ coincidence spectrum with an integral γ gate ranging from 0.05 to 3.5 MeV. The energies of the proton groups are in MeV.

between 0.4 and 3 MeV were less than 1 ns.

The lifetime of the 90.7 keV first excited state in ^{49}V was measured in the $^{49}Ti(p,n)^{49}V$ reaction via the n-γ delayed-coincidence method. Protons of 2.1 MeV from a 3 MV Van de Graaff accelerator were used to bombard a ^{49}Ti target of 100 $\mu g/cm^2$ evaporated on a Au backing. Two NE102 plastic scintillators of 0.5×2 cm diam with XP1021 photomultipliers were used to detect γ rays and neutrons. The "γ" counter was placed 1.5 cm from the target while the "neutron" counter was placed at a distance of 5 cm. This neutron counter was shielded, in order, from the target by 2 cm of Pb, 1 mm of Cd, and 1 mm of Cu, so as to reduce the γ-γ coincidence prompt peak which was separated from the n-γ peak by 5 ns owing to the time-of-flight of the neutrons. Fast electronics and antipileup circuits were used in conjunction with a TAC. Energy selection channels were set to accept 20% of the Compton spectrum below the Compton edge of the 90.7 keV γ ray. For the neutron counter, the selected pulses corresponded to 30% (below the edge) of the spectrum of 630 keV neutrons which were released in the reaction leading to the first excited state in ^{49}V. The neutron energy spectrum was found by gating the spectrum of the neutron counter with the n-γ prompt coincidence peak. Coincidences between these two channels mainly selected out the coincidence between 90.7 keV γ rays and 630 keV neutrons and were used to gate a multichannel analyzer whose input was the TAC spectrum. The delayed-time n-γ spectrum is shown in Fig. 2. The measured half-life for the 90.7 keV state is 0.45 ±0.03 ns and agrees within the limits of error with the value $T_{1/2} = 0.43 \pm 0.02$ ns quoted by Cheung and Mark[23] but is higher than the value measured by Okon *et al.*[24] which is 0.33±0.02 ns.

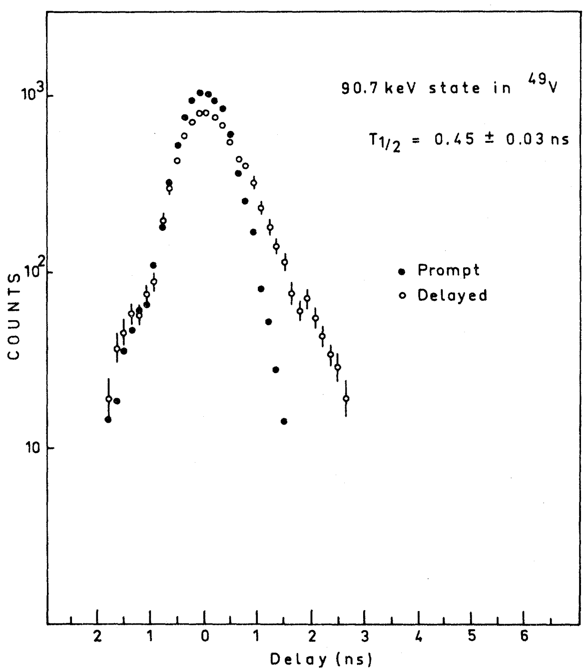

FIG. 2. Neutron-γ coincidence (delayed) TAC spectrum obtained with two plastic scintillators for the 90.7 keV state in ^{49}V with the $^{49}Ti(p,n\gamma)^{49}V$ reaction. The prompt curve was measured employing the 377 keV transition in ^{53}Mn with the $^{53}Cr(p,n\gamma)^{53}Mn$ reaction. The same energy-gate settings as in the $^{49}Ti(p,n\gamma)^{49}V$ reaction were used.

B. Angular correlations

The analysis of the particle-γ angular correlations was done by the method outlined by Poletti and Warburton.[25] Since the outgoing protons were detected at $\bar{\theta}_p = 171°$, magnetic substates $m = \pm\frac{1}{2}$ were populated. However, due to the finite size of the proton detector a population of $m = \pm\frac{3}{2}$ substates could be possible. Following the arguments given by Ball *et al.*[26] for a similar study involving the $^{40}Ca(\alpha,p)^{43}Sc$ reaction, the contribution from $m = \pm\frac{3}{2}$ substates can be neglected in this experiment. This population was estimated[27] to be $p(\pm\frac{3}{2}) = 0.07\ p(\pm\frac{1}{2})$. Inclusion of the $p(\frac{3}{2})$ contribution was found not to alter the results. In the analysis, spin sequences were discarded if the corresponding χ^2_{min} was not within the 0.1% confidence limit. Signs of δ are given according to the convention of Rose and Brink.[28] An example of the χ^2 plot for different spin sequences for the

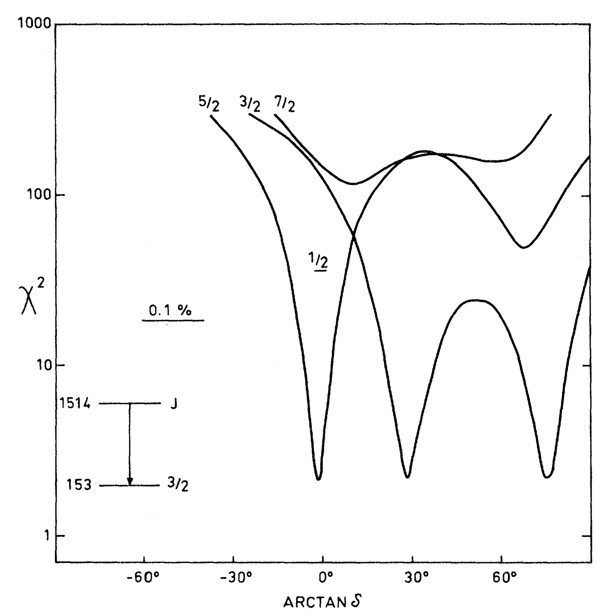

FIG. 3. Example of a χ^2 analysis. This one is for the p-γ angular correlation of the 1361.5 keV γ transition.

1361.5 keV transition is shown in Fig. 3. The estimates of errors associated with the mixing ratios δ were obtained at a χ^2 value corresponding to one standard deviation from χ^2_{min}. Possible spin sequences and mixing ratios were additionally restricted on the basis of unacceptable transition strengths.[29] For this purpose the transition strength Γ_γ was computed from the mean life, branching ratio, and mixing ratio and their independent errors. If Γ_γ minus its error exceeded 0.03 Weisskopf units (W.u.) for $E1$, 100 W. u. for $E2$ or $E3$, 3 W. u. for $M2$, and 10 W. u. for $M3$, a solution possible from a χ^2 analysis was rejected.

C. Lifetimes by DSAM

Peak positions measured at five angles, $\theta_\gamma = 0°$, 30°, 45°, 90°, and 120°, were determined from first-moment calculations. For several cases in the analysis, in order to minimize the interference of γ transitions of similar energies, the generated coincident γ spectra corresponded to upper halves of proton peaks observed in the coincident proton spectra generated previously from these γ transitions. No statistically significant electronic shifts were observed in the source calibration spectra. Each coincident γ spectrum was calibrated and errors of the calibration were quadratically added to the errors found in the first-moment calculations.

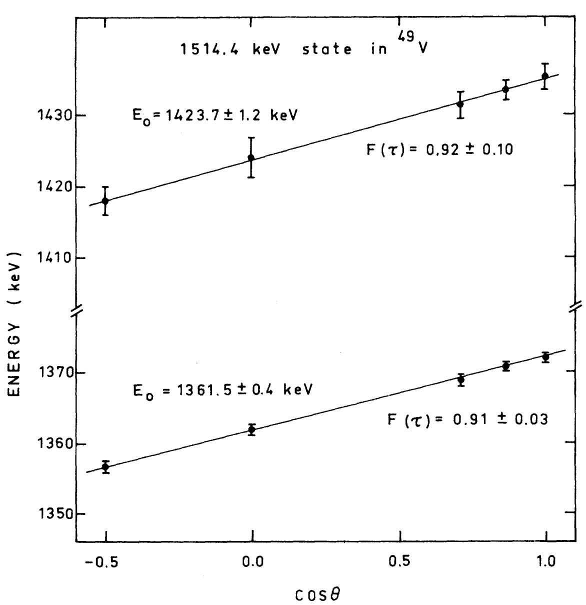

FIG. 4. γ-ray energies obtained from DSAM spectra measured at five angles (see Sec. II D) for two transitions deexciting the 1514.4 keV level.

The full Doppler shifts were computed from the kinematics. Effects due to the finite solid angle subtended by the particle and γ-ray detectors were smaller than 1% and could be thus neglected. The experimental attenuation factors $F(\tau)$ and unshifted γ-ray energies were computed from least-squares fits to the experimental points versus $\cos\theta_\gamma$ (Fig. 4).

The attenuation factor $F(\tau)$ was computed as a function of τ with the stopping theory of Lindhard, Scharff, and Schiøtt[30] including the Blaugrund approximation.[31] In these computations the target was assumed to consist of ten layers of equal thickness, each with identical reaction yield. Then, slowing down in the successive Ti layers and in the Ag backing was taken into account. Due to the target thickness (500 $\mu g/cm^2$) most of the recoils were slowed down in the Ti. As follows from Ref. 32, lifetimes measured with Ti as a stopping material agree with results obtained in recoil distance experiments. Therefore, no correction factors f_e and f_n were applied to the nuclear and electronic stopping powers. Errors assigned to the mean lives were obtained by quadratic addition of the statistical errors in the measured F values and an assumed 20% uncertainty in the stopping powers.

D. γ-ray decay

Accurate excitation energies of ^{49}V were known for several low-lying levels below 1.7 MeV.[8,9,11] However, there were some ambiguities, as for example, with the 1643.1 keV level. The 897.4 keV transition feeding the 748.2 keV level did not fit the energy sum of the 1490.4 keV transition going to the 152.8 keV level.[8] In the present analysis, the γ-ray energies were obtained from accurately calibrated spectra measured at five angles including 90° (see Sec. II C) and then nonshifted energies E_0 were obtained by the least-squares fit defined in Sec. II C. A great help in finding the energies of excited states was furnished by the calibrated proton spectra generated with different γ transitions and by γ-γ coincidences. In the final analysis, the majority of strong γ rays were observed to cascade through the 90.7, 152.9, 748.3, 1021.6, 1140.9, 1155.4, 2263.3, and 2670.8 keV levels. An example of a γ-γ coincidence spectra obtained with the 1021.6 keV transition as a gate is shown in Fig. 5.

The γ-ray branching ratios of ^{49}V levels below 3.4 MeV excitation energy were obtained from the intensities in the coincident p-γ spectra measured at $\theta_\gamma = 0°$, 30°, 45°, 60°, and 90°. The level energies and branching ratios are given in Table I.

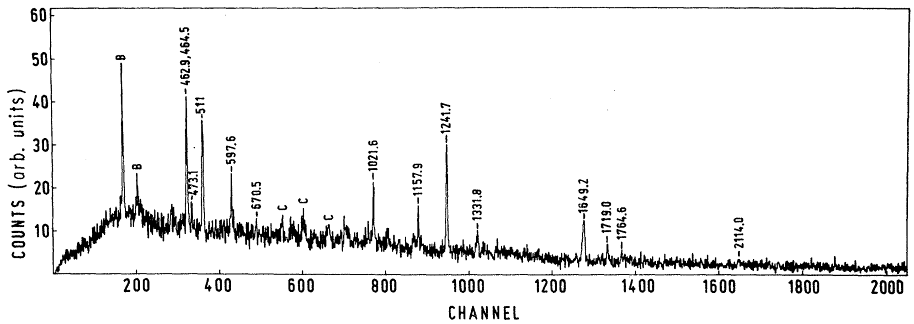

FIG. 5. Coincident γ-ray spectrum obtained in the γ-γ coincidence experiment with the energy gate set on the 1021.6 keV transition. The peaks labeled B come from background, while those with C come from excited states lying at energies higher than 3.5 MeV. γ-ray energies are in keV.

III. RESULTS

A summary of all experimental results obtained in the present work and a comparison with previous data are given in Tables I, II, and III. In this section, some observed states of ^{49}V will be discussed individually. Since no new information was obtained for the $\frac{3}{2}^-$, 152.9 keV, the $\frac{11}{2}^-$, 1021.6 keV, the $\frac{9}{2}^-$, 1155.4 keV, and the $\frac{15}{2}^-$, 2263.3 keV levels, except lifetimes of the latter three, they will not be discussed individually here. The present angular correlation and lifetime results confirm the spin and parity assignments $J^\pi = \frac{11}{2}^-$, $\frac{9}{2}^-$, and $\frac{15}{2}^-$ and multipole mixing ratios measured recently in Ref. 19 for the 1021.6, 1155.4, and 2263.3 keV levels, respectively. The lifetime measurement of the 90.7 keV level has been discussed in Sec. II A. Recently, Tabor and Zurmühle[20] measured lifetimes in a DSAM coincidence experiment at two angles, in the ^{46}Ti$(\alpha, p\gamma)^{49}$V reaction at 10 MeV. The over-all agreement between our lifetime measurements and those of Ref. 20 is good. Discrepancies exist for the 1646.4, 1994.9, and 2263.3 keV levels. Our τ values for these levels are based on at least two transitions except in the case of the 2263.3 keV level where only one transition was seen.

748.3 keV level. In both stripping and pickup reactions[15-18] evidence was found for an $l = 2$ transition to this level, allowing $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$. From the present angular correlation measurements and the upper and lower limits for the lifetime of this level ($5 < \tau < 1000$ ps), the $J^\pi = \frac{5}{2}^+$ assignment is improbable since it would require an enhanced $M2$ component in the transitions to the first and second excited states, the values being $3 < \Gamma_{M2} < 400$ W. u. This corroborates the $J^\pi = \frac{3}{2}^+$ assignment proposed in Ref. 9 on the basis of the measured excitation strength to this level in the ^{49}Ti(p, n) reaction.

1140.9 keV level. The spin values $J = \frac{5}{2}$ or $\frac{7}{2}$ have been proposed for this level from (p, γ) experiments.[6] Moreover, this state was strongly populated in the ^{50}Cr(t, α) reaction[15] and was not seen in the ^{48}Ti$(^3$He$, d)$ reaction.[15,18] This would suggest a proton-hole configuration and favor positive parity for this state. The present angular correlation measurements for the 393.9 keV γ transition to the $\frac{3}{2}^+$, 748.3 keV state are consistent with $J = \frac{3}{2}$ and $\frac{5}{2}$, while the $J = \frac{1}{2}$ and $\frac{7}{2}$ possibilities are ruled out, χ^2_{min} being 28 and 37, respectively. The value $J = \frac{3}{2}$ was rejected by the angular correlation of the 1050.0 keV transition to the $J^\pi = \frac{5}{2}^-$, first excited state. On the basis of the measured lifetime of the 1140.9 keV level $\tau = 1.8^{+0.9}_{-0.5}$ps, negative parity can be discarded because it would imply an enhanced $M2$ component in the 393.9 keV transition ($\delta = 0.26 \pm 0.12$ or 1.2 ± 0.3). The $J^\pi = \frac{5}{2}^+$ spin and parity corroborates the previous tentative assignment proposed for the 1140.9 keV level.[8]

1514.4 keV level. The present angular correlation measurements for the 1361.5 keV transition feeding the $\frac{3}{2}^-$, 152.9 keV level eliminated the values $J = \frac{1}{2}$ and $\frac{7}{2}$. The $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$ assignments are not probable because the δ values from the angular correlations of the 1361.5 and 1423.7 keV transitions (Table I), and the lifetime $\tau = 0.045^{+0.021}_{-0.018}$ ps, would imply $M2$ components in the two transitions in the range $1350 < \Gamma_{M2} < 5030$ and $3 < \Gamma_{M2} < 1280$ W. u. for $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$, respectively. The spin and parity $J^\pi = \frac{5}{2}^-$ are in agreement with the relative excitation strength measured by Malan *et al.*[9] and it is proposed here for the 1514.4 keV level.

1603.1 keV level. This level was found to decay 31% to the $\frac{7}{2}^-$ ground state, 42% to the $\frac{5}{2}^-$, 90.7 keV, 13% to the $\frac{3}{2}^+$, 748.3 keV, and 14% to the $\frac{5}{2}^+$, 1140.9 keV levels in slight disagreement with the results of Blasi *et al.*[8] The angular correlation results for the 1602.8 keV γ transition and the measured lifetime $\tau = 0.68^{+0.31}_{-0.18}$ ps yield unrealistic enhancements for $M2$, $M3$, or $E3$ components for spin and parity assignments $J^\pi = \frac{3}{2}^\pm$ or $\frac{5}{2}^+$ ($\delta = 0.53^{+0.31}_{-0.26}$ and $0.7^{+0.8}_{-0.3}$,

TABLE I. Energies and branching ratios for γ-ray transitions in ^{49}V.

E_i (keV)	E_f (keV)	γ-ray energy (keV)	Branching [a] (%)	γ-ray energy [b] (keV)	Branching [b] (%)
90.7 (1) [c]	0	90.7 (1) [c]	100	90.5 (1) [c]	100
152.9 (1)	0	152.9 (1)	58	152.8 (1)	57.8 (10)
	90.7	62.2 (3)	42	62.2 (3)	42.2 (10)
748.3 (2)	90.7	657.7 (2)	52	657.6 (2)	44.6 (6)
	152.9	595.3 (2)	48	595.4 (2)	55.4 (6)
1021.6 (2)	0	1021.6 (2)	100	1021.4 (2)	100
1140.9 (3)	0	1141.0 (3)	55	1140.2 (2)	51.8 (13)
	90.7	1050.0 (6)	23	1049.5 (2)	26.4 (9)
	152.9	987.9 (5)	15	987.4 (2)	16.6 (15)
	748.3	393.9 (9)	7	392.1 (2)	5.2 (6)
1155.4 (3)	0	1155.4 (3)	77	1154.9 (2)	74.7 (7)
	90.7	1064.8 (5)	23	1064.3 (2)	22.4 (4)
	1021.6	133.8 (3)	<5	133.8 (2)	2.9 (6)
1514.4 (4)	0	1514.4 (10)	31	1514.4 (2)	32.4 (7)
	90.7	1423.7 (12)	9	1423.8 (2)	11.3 (4)
	152.9	1361.5 (4)	60	1361.6 (2)	56.3 (10)
1603.1 (6)	0	1602.8 (10)	31	1602.2 (2)	25.6 (6)
	90.7	1511.8 (12)	42	1511.8 (3)	59.5 (13)
	748.3	853.7 (22)	13	854.1 (2)	8.0 (8)
	1140.9	463.3 (8)	14	462.1 (2)	6.9 (6)
1643.1 (3)	152.9	1490.2 (2)	100	1490.4 (3)	[79.0 (70)]
				[897.4 (5)]	[21.0 (70)]
1646.4 (4)	152.9	1493.6 (3)	47		
	748.3	898.0 (3)	53		
1661.4 (5)	90.7	1570.7 (4)	64	1571.0 (2)	64.0 (40)
	152.9	1508.7 (10)	36	1508.7 (5)	36.0 (40)
1994.9 (6)	90.7	1904.1 (20)	24		
	152.9	1840.3 (14)	39		
	1140.9	854.5 (5)	37		
2178.5 (6)	0	2179.0 (15)	62		
	1021.6	1157.9 (10)	10		
	1140.9	1037.0 (7)	21		
	1603.1	576.5 (16)	7		
2182.7 (8)	0	2183.0 (20)	<5		
	90.7	2092.0 (10)	79		
	1155.4	1027.2 (12)	21		
2235.3 (10)	0	2235.7 (19)	30		
	90.7	2144.4 (10)	70		
2263.3 (3)	1021.6	1241.7 (2)	100		
2265.2 (6)	152.9	2112.3 (5)	100		
2309.7 (11)	90.7	2219.3 (14)	54		
	152.9	2156.4 (15)	46		
2353.3 (6)	0	2353.2 (7)	53		
	1021.6	1331.8 (9)	26		
	1155.4	1200.0 (15)	21		
2388.2 (6)	0	2388.2 (20)	7		
	90.7	2299.2 (22)	17		
	152.9	2235.3 (25)	<5		
	748.3	1639.6 (7)	59		
	1140.9	1247.8 (12)	7		
	1994.9	393.6 (15)	10		
2408.4 (4)	0	2408.4 (4)	79		
	1155.4	1253.5 (13)	21		
	2178.5	229.2 (20)	<5		
2670.8 (4)	1021.6	1649.2 (3)	100		
2727.8 (5)	2263.3	464.5 (3)	100		
2741.1 (8)	1021.6	1719.0 (15)	<5		
	1155.4	1585.0 (20)	39		
	1603.1	1139.7 (14)	48		

TABLE I *(Continued)*

E_i (keV)	E_f (keV)	γ-ray energy (keV)	Branching[a] (%)	γ-ray energy[b] (keV)	Branching[b] (%)
	2178.5	562.0 (10)	13		
2786.3 (4)	0	2786.4 (5)	46		
	1021.6	1764.6 (4)	26		
	1155.4	1630.9 (5)	28		
2810.7 (5)	0	2810.9 (5)	61		
	90.7	2720.3 (19)	25		
	2182.7	625.0 (20)	14		
2860.8 (7)	1155.4	1705.0 (20)	78		
	2263.3	597.6 (6)	22		
3017.3 (12)	0	3017.9 (20)	18		
	90.7	2926.1 (16)	45		
	152.9	2864.6 (24)	37		
3133.4 (9)	0	3133.0 (11)	64		
	1021.6	2114.0 (25)	9		
	1155.4	1978.0 (15)	27		
3133.7 (5)	2670.8	462.9 (3)	100		
3259.4 (4)	2786.3	473.1 (2)	100		
3341.6 (7)	2178.5	1163.0 (10)	40		
	2670.8	670.5 (8)	31		
	2741.1	601.0 (8)	29		

[a] Absolute errors of 5% on the values given are taken for the measured branching ratios.
[b] Transition energies and branching ratios taken from Ref. 8.
[c] Uncertainties (in parentheses) refer to the last given significant figures.

TABLE II. Spins and multipole-mixing ratios derived from angular-correlation measurements in ^{49}V. Lifetime and other arguments limiting J^π values are included (see text).

E_i (keV)	E_f (keV)	J_i^π	J_f^π	δ [a]
90.7	0	$\frac{5}{2}^-$	$\frac{7}{2}^-$	b
152.9	0	$\frac{3}{2}^-$	$\frac{7}{2}^-$	b
	90.7		$\frac{5}{2}^-$	b
748.3	90.7	$\frac{3}{2}^+$	$\frac{5}{2}^-$	0.01 ± 0.02
	152.9		$\frac{3}{2}^-$	0.02 ± 0.02
1021.6	0	$\frac{11}{2}^-$	$\frac{7}{2}^-$	0.03 ± 0.03
1140.9	0	$\frac{5}{2}^+$	$\frac{7}{2}^-$	0.05 ± 0.06
	90.7		$\frac{5}{2}^-$	$> -1.40, < -0.05$
	152.9		$\frac{3}{2}^-$	0.02 ± 0.09
	748.3		$\frac{3}{2}^+$	0.26 ± 0.12; 1.2 ± 0.3
1155.4	0	$\frac{9}{2}^-$	$\frac{7}{2}^-$	-0.68 ± 0.08
	90.7		$\frac{5}{2}^-$	0.03 ± 0.05
	1021.6		$\frac{11}{2}^-$	0.15 ± 0.15
1514.4	0	$\frac{5}{2}^-$	$\frac{7}{2}^-$	b
	90.7		$\frac{5}{2}^-$	$>0.06, <1.23$
	152.9		$\frac{3}{2}^-$	0.57 ± 0.05

TABLE II *(Continued)*

E_i (keV)	E_f (keV)	J_i^π	J_f^π	δ [a]
1603.1	0	$\frac{7}{2}^+$	$\frac{7}{2}^-$	>-1.15, <-0.05
	90.7		$\frac{5}{2}^-$	b
	748.3		$\frac{3}{2}^+$	b
	1140.9		$\frac{5}{2}^+$	0.05 ± 0.21
1643.1	152.9	$\frac{1}{2}^{(-)}, \frac{3}{2}^{(-)}, \frac{5}{2}^{(-)}$	$\frac{3}{2}^-$	b
1646.4	152.9	$\frac{1}{2}^{(+)}, \frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	$\frac{3}{2}^-$	b
	748.3	$\frac{1}{2}^{(+)}$	$\frac{3}{2}^+$	
		$\frac{3}{2}^{(+)}$		0.15 ± 0.06
		$\frac{5}{2}^{(+)}$		-0.26 ± 0.05
1661.4	90.7	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.04 ± 0.09
	152.9		$\frac{3}{2}^-$	b
1994.9	90.7	$\frac{3}{2}^+$	$\frac{5}{2}^-$	b
	152.9		$\frac{3}{2}^-$	0.17 ± 0.09
	1140.9		$\frac{5}{2}^+$	0.22 ± 0.16; 2.2 ± 1.0
2178.5	0	$\frac{9}{2}^+$	$\frac{7}{2}^-$	0.02 ± 0.05
	1021.6		$\frac{11}{2}^-$	b
	1140.9		$\frac{5}{2}^+$	b
	1603.1		$\frac{7}{2}^+$	0.07 ± 0.15
2182.7	0	$\frac{7}{2}^-$	$\frac{7}{2}^-$	b
	90.7		$\frac{5}{2}^-$	0.09 ± 0.04
	1155.4		$\frac{9}{2}^-$	b
2235.3	0	$\frac{5}{2}^-$	$\frac{7}{2}^-$	-0.17 ± 0.12; >23; <-6.3
	90.7		$\frac{5}{2}^-$	-0.04 ± 0.14
2263.3	1021.6	$\frac{15}{2}^-$	$\frac{11}{2}^-$	-0.05 ± 0.05
2265.2	152.9	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.18 ± 0.08; 11 ± 6; >31
2309.7	90.7	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.12 ± 0.15; >1.5, <7.1
	152.9		$\frac{3}{2}^-$	0.02 ± 0.20; >-11.4, <-2.3; $+\infty$
2353.3	0	$\frac{9}{2}^-$	$\frac{7}{2}^-$	0.54 ± 0.23
	1021.6		$\frac{11}{2}^-$	0.19 ± 0.16
	1155.4		$\frac{9}{2}^-$	b
2388.2	0	$\frac{5}{2}^+$	$\frac{7}{2}^-$	b
	90.7		$\frac{5}{2}^-$	b
	152.9		$\frac{3}{2}^-$	b
	748.3		$\frac{3}{2}^+$	0.36 ± 0.15
	1140.9		$\frac{5}{2}^+$	b
	1994.9		$\frac{3}{2}^+$	0.04 ± 0.11

TABLE II *(Continued)*

E_i (keV)	E_f (keV)	J_i^π	J_f^π	δ [a]
2408.4	0	$\frac{7}{2}^{\pm}$	$\frac{7}{2}^{-}$	-0.02 ± 0.15
		$\frac{9}{2}^{-}$		-0.42 ± 0.05
		$\frac{11}{2}^{-}$		-0.05 ± 0.15
	1155.4		$\frac{9}{2}^{-}$	b
	2178.5		$\frac{9}{2}^{+}$	b
2670.8	1021.6	$\frac{9}{2}^{-}$	$\frac{11}{2}^{-}$	0.41 ± 0.06
		$\frac{11}{2}^{-}$		0.16 ± 0.08; -0.73 ± 0.13
		$\frac{13}{2}^{-}$		0.36 ± 0.03
2727.8	2263.3	$\frac{15}{2}^{(-)}$	$\frac{15}{2}^{-}$	>-0.10, <0.04
2741.1	1021.6	$\frac{7}{2}^{-}, \frac{9}{2}^{\pm}, \frac{11}{2}^{+}$	$\frac{11}{2}^{-}$	b
	1155.4		$\frac{9}{2}^{-}$	b
	1603.1		$\frac{7}{2}^{+}$	b
	2178.5		$\frac{9}{2}^{+}$	b
2786.3	0	$\frac{9}{2}^{-}$	$\frac{7}{2}^{-}$	-0.35 ± 0.08
		$\frac{11}{2}^{-}$		-0.02 ± 0.06
	1021.6	$\frac{9}{2}^{-}$	$\frac{11}{2}^{-}$	0.02 ± 0.15; $+\infty$
		$\frac{11}{2}^{-}$		0.78 ± 0.20; 2.14 ± 0.50
	1155.4	$\frac{9}{2}^{-}$	$\frac{9}{2}^{-}$	0.90 ± 0.35
		$\frac{11}{2}^{-}$		-0.02 ± 0.09; >2.0, <6.8
2810.7	0	$\frac{5}{2}^{\pm}, \frac{7}{2}^{\pm}, \frac{9}{2}^{-}$	$\frac{7}{2}^{-}$	b
	90.7		$\frac{5}{2}^{-}$	b
	2182.7		$\frac{7}{2}^{-}$	b
2860.8	1155.4	$\frac{13}{2}^{-}$	$\frac{9}{2}^{-}$	-0.09 ± 0.17
	2263.3		$\frac{15}{2}^{-}$	b
3017.3	0	$\frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}, \frac{7}{2}^{\pm}$	$\frac{7}{2}^{-}$	b
	90.7		$\frac{5}{2}^{-}$	b
	152.9		$\frac{3}{2}^{-}$	b
3133.4	0	$(\frac{7}{2}^{-})$	$\frac{7}{2}^{-}$	0.22 ± 0.22; -1.3 ± 0.7
		$\frac{9}{2}^{(+)}$		-0.26 ± 0.12
		$(\frac{11}{2}^{-})$		0.01 ± 0.10
	1021.6		$\frac{11}{2}^{-}$	b
	1155.4		$\frac{9}{2}^{-}$	b
3133.7	2670.8	$\frac{9}{2}^{(-)}$	$\frac{9}{2}^{-}$	>-1.00, <0.10
		or $\frac{11}{2}^{(-)}$	$\frac{11}{2}^{-}$	>-0.90, <0.10
		or $\frac{13}{2}^{(-)}$	$\frac{13}{2}^{-}$	>-0.80, <0.10
3259.4	2786.3		$\frac{9}{2}^{-}, \frac{11}{2}^{-}$	b
3341.6	2178.5	$\frac{9}{2}^{\pm}, \frac{11}{2}^{\pm}, \frac{13}{2}^{+}$	$\frac{9}{2}^{+}$	b
	2670.8		$\frac{9}{2}^{-}, \frac{11}{2}^{-}, \frac{13}{2}^{-}$	b
	2741.1		$\frac{7}{2}^{-}, \frac{9}{2}^{\pm}, \frac{11}{2}^{+}$	b

[a] Rose and Brink convention (Ref. 28). [b] All values possible.

TABLE III. Mean lifetimes from DSAM.

Energy level (keV)	$F(\tau)$ [a]	τ (ps) This work	Ref. 19	Ref. 33	Ref. 20
748.3	0.02 ± 0.02	>5 [b]		$0.2^{+0.4}_{-0.1}$	$7.7^{+3.0}_{-1.8}$
1021.2	0.04 ± 0.02	$6.3^{+3.9}_{-2.5}$	>5		$4.3^{+1.9}_{-1.1}$
1140.9	0.13 ± 0.03	$1.8^{+0.9}_{-0.5}$	$4.6^{+7.4}_{-2.5}$	$0.25^{+0.50}_{-0.10}$	$1.15^{+0.17}_{-0.14}$
1155.4	0.14 ± 0.02	$1.65^{+0.48}_{-0.34}$	$4.3^{+5.6}_{-2.1}$	>0.4	$1.06^{+0.15}_{-0.13}$
1514.4	0.91 ± 0.03	$0.045^{+0.021}_{-0.018}$		$0.45^{+0.030}_{-0.020}$	<0.014
1603.1	0.30 ± 0.06	$0.68^{+0.31}_{-0.18}$			$1.04^{+0.22}_{-0.17}$
1643.1	0.90 ± 0.02	$0.050^{+0.017}_{-0.014}$		$0.055^{+0.030}_{-0.020}$	<0.031
1646.4	0.01 ± 0.02	>7.5 [b]			$3.2^{+1.1}_{-0.7}$
1661.4	0.95 ± 0.03	<0.04	$0.016^{+0.012}_{-0.008}$	0.025 ± 0.005	0.023 ± 0.010
1994.9	0.17 ± 0.05	$1.34^{+0.80}_{-0.43}$		>0.4	$0.19^{+0.07}_{-0.05}$
2178.5	0.26 ± 0.09	$0.80^{+0.70}_{-0.40}$			$2.7^{+4.7}_{-1.2}$
2182.7	0.91 ± 0.06	<0.08	$0.031^{+0.011}_{-0.009}$		0.048 ± 0.017
2235.3	0.95 ± 0.04	<0.05	$0.021^{+0.008}_{-0.007}$	$0.030^{+0.030}_{-0.015}$	0.018 ± 0.011
2263.3	0.23 ± 0.06	$0.93^{+0.55}_{-0.28}$	$0.064^{+0.025}_{-0.016}$	$0.045^{+0.030}_{-0.015}$	>3.84
2265.2	0.93 ± 0.04	<0.06			0.051 ± 0.013
2309.7	0.94 ± 0.07	<0.07		0.020 ± 0.010	<0.026
2353.3	0.94 ± 0.07	<0.07			0.048 ± 0.017
2388.2	0.82 ± 0.05	$0.09^{+0.04}_{-0.02}$	$0.27^{+0.09}_{-0.06}$		$0.082^{+0.027}_{-0.024}$
2408.4	1.00 ± 0.04	<0.03	<0.01		<0.011
2670.8	0.97 ± 0.02	<0.03			<0.016
2727.8	0.48 ± 0.08	$0.35^{+0.15}_{-0.11}$			$0.138^{+0.058}_{-0.049}$
2741.1	0.36 ± 0.20	$0.70^{+0.80}_{-0.50}$			$0.56^{+0.52}_{-0.24}$
2786.3	0.99 ± 0.04	<0.04			<0.016
2810.7	0.94 ± 0.04	<0.06			<0.018
2860.8	0.71 ± 0.09	$0.15^{+0.08}_{-0.06}$			
3017.3	0.96 ± 0.06	<0.06			
3133.4	0.94 ± 0.05	<0.06			
3133.7	0.49 ± 0.04	$0.32^{+0.11}_{-0.06}$			
3259.4	0.04 ± 0.05	>3 [b]			
3341.6	0.01 ± 0.03	>5 [b]			

[a] If more than one $F(\tau)$ value was obtained for transitions depopulating an excited state, the weighted average is given.

[b] An upper limit of 1 ns was determined in a delayed-coincidence experiment (see Sec. I A).

respectively). The $J^\pi = \frac{5}{2}^-$ value is also improbable since it would imply an enhanced $M2$ component in the 463.3 keV transition ($\delta = 0.83 \pm 0.40$) while the $J^\pi = \frac{7}{2}^-$ possibility would require $1116 < \Gamma_{M2} < 2207$ W.u. in the 853.7 keV transition. The present experiment thus corroborates the previous tentative spin and parity $J^\pi = \frac{7}{2}^+$ assigned to the 1603. 1 keV level.[8]

1643. 1 and 1646. 4 keV doublet. The $J^\pi = \frac{1}{2}^+$ assignment was generally adopted for a state at 1644 keV excitation energy. This assignment was based on the angular momentum transfer $l_p = 0$ in the $^{50}Cr(t, \alpha)$ reaction.[15] Blasi *et al.*[8] found a transition 897.4 keV which was tentatively placed between the 1643.4 and 748.2 keV states, but it differed by 2 keV from the energy expected in the

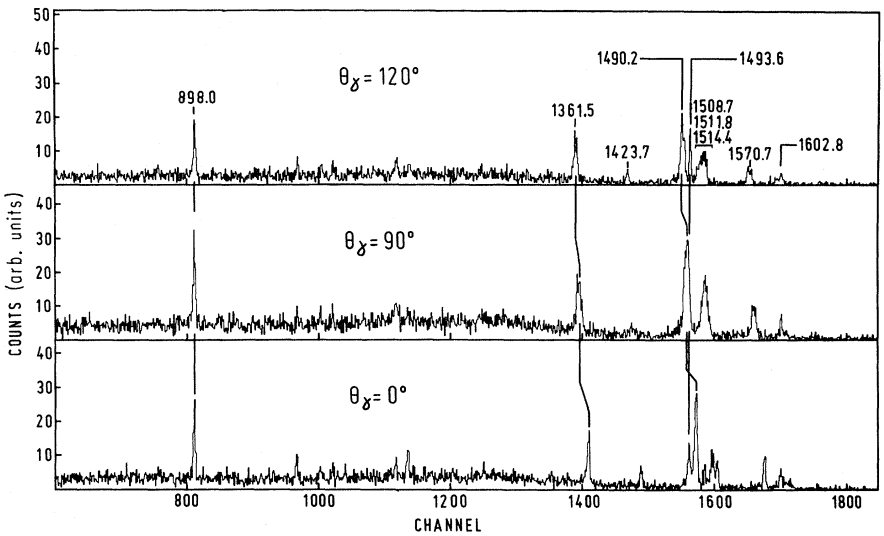

FIG. 6. Portions of coincident γ spectra corresponding to three angles $\theta_\gamma = 0°$, 90°, and 120°. These spectra were obtained in a DSAM experiment with the ^{46}Ti$(\alpha, p\gamma)^{49}$V reaction. They display different energy shifts for the 1490.2 and 1493.6 keV transitions from the 1643.1 and 1646.4 keV doublet state. The energies (keV) given in the spectrum for $\theta = 120°$ refer to the unshifted γ-ray energies.

proposed scheme. In the present experiment two transitions were found 1490.2 and 1493.6 keV which were differently shifted in the DSAM spectra (see Fig. 6). No energy shift was found for the latter one nor for the 898.0 keV transition which was found in the γ-γ coincidence measurement to cascade through the 748.3 keV level. The energy balance of the corresponding γ transitions and the excited state energies are consistent with a proposed level at 1646.4 keV. The angular correlation of the 898.0 keV transition and the lifetime $7.5 < \tau < 1000$ ps of the 1646.4 keV state indicates that most probably $J = \frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. As the 1646.4 keV level is assumed to be the one which was strongly excited in the ^{50}Cr(t, α) reaction its spin and parity assignment is probably $J^\pi = \frac{1}{2}^+$.

The 1490.2 keV γ transition is proposed to deexcite the 1643.1 keV state which was not found to decay by any other γ transition. Its decay mode and the lifetime $\tau = 0.050^{+0.017}_{-0.014}$ ps favor a $J^\pi = \frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$ assignment. However, positive parity cannot be definitely excluded.

1661.4 keV level. The assignment of $J^\pi = \frac{3}{2}^-$ was made for this level on the basis of the observed $l_p = 1$ transition in the ^{48}Ti(^{3}He, d) reaction.[15,16] The present angular correlation measurements for the 1570.7 keV transition and the lifetime of the 1661.4 keV level leads to either $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ for spin and parity values. As a result, the previous $J^\pi = \frac{3}{2}^-$ assignment is adopted for this level.

1994.9 keV level. An $l_p = 0$ angular distribution was observed for this state in ^{50}Cr(t, α) reaction and the spin-parity assignment $J^\pi = \frac{1}{2}^+$ was proposed.[15] However, the present value of the lifetime $\tau = 1.34^{+0.80}_{-0.43}$ ps and the observed decay to the $J^\pi = \frac{5}{2}^-$ first excited state would require an $M2$ transition of at least 17 W.u. and challenges this assignment. Moreover, the angular correlation for the 393.6 keV transition from the $J^\pi = \frac{5}{2}^+$, 2388.2 keV level (see the discussion of this level) has no solution for the $\frac{5}{2} \to \frac{1}{2}$ spin sequence. Similar arguments for the 854.5 and 1840.3 keV transitions limit the probable spin and parity values to $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$. The latter assignment would, however, imply an enhanced $E2$ component in the 393.6 keV transition ($\delta = 0.8 \pm 0.2$) of at least 1660 W.u. As a result, the $J^\pi = \frac{3}{2}^+$ assignment is proposed for the 1994.9 keV level.

2178.5 keV level. In the present p-γ and γ-γ coincidence experiments this level was found to decay 62% to the ground state, 10% to the 1021.6 keV, 21% to the 1140.9 keV, and 7% to the 1603.1 keV levels. The measured lifetime $\tau = 0.80^{+0.70}_{-0.40}$ ps and the angular correlations for the 576.5 and 2179.0 keV transitions limit the spin and parity values to $J^\pi = \frac{9}{2}^+$. Any other assignment would yield enhanced $M2$ ($E3$) transitions from this level. The enhancement factor would be at least 1150 for a $\frac{7}{2}^- \to \frac{7}{2}^+$, $M2$ component [$\delta(576\text{ keV}) = 1.1 \pm 0.2$], 64 for the $\frac{7}{2}^+ \to \frac{11}{2}^-$, $M2$ transition, and 367 for the $\frac{9}{2}^- \to \frac{5}{2}^+$, $M2$ transition.

2182.7 keV level. In the ^{48}Ti(^{3}He, d) reaction a 2190 keV level was strongly excited with an $l_p = 3$

transition.[15,16,18] In the present experiment the 2182.7 keV state was found to decay 21% to the 1155.4 keV level, 79% to the 90.7 keV level, and less than 5% to the ground state. On the basis of the angular correlation measurement for the 2092.0 keV transition, the only possibilities for the spin of this level are $J=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. The $J=\frac{3}{2}$ assignment can be ruled out due to the improbable existence of the $\frac{3}{2}\rightarrow\frac{9}{2}^-$, 1027.2 keV transition. Also, the $J^\pi=\frac{5}{2}^+$ and $\frac{7}{2}^+$ assignments would yield improbable $M2$ components in the 2092.0 keV transition ($\delta=1.1\pm0.04$ and 0.09 ± 0.04, respectively) enhanced over single particle Weisskopf estimates, while the $J^\pi=\frac{5}{2}^-$ spin and parity would imply an $E2$, 1027.2 keV transition with $\Gamma_{E2}>240$ W. u. As a result, the $J^\pi=\frac{7}{2}^-$ assignment is proposed for the 2182.7 keV level.

2235.3 keV level. This level was observed in the ^{48}Ti(p,γ) reaction and its spin was assigned as $\frac{5}{2}$.[33] In the present experiment the 2235.3 keV level was found to decay 70% to the 90.7 keV level and 30% to the ground state in disagreement with the decay proposed in Ref. 11. From the angular correlations of the two observed transitions and the upper limit for the lifetime $\tau<0.05$ ps, realistic transition rates are obtained only for the spin-parity assignments $J^\pi=\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$. As a result, the value $J^\pi=\frac{5}{2}^-$ may be adopted for the 2235.3 keV level.

2265.2 keV level. It is unlikely that the assigned $J^\pi=\frac{15}{2}^-$, 2263.3 keV level (see introduction of Sec. III) was excited in the ^{48}Ti(^{3}He, d) reaction[15,16,18] with the $l_p=1$ transition but instead it could be the present level proposed at 2265.2 keV which was found to decay only to the 152.9 keV level. The upper limit for the lifetime was determined to be $\tau<0.06$ ps. The present angular correlation measurements and the lifetime result in $J^\pi=\frac{1}{2}^\pm$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ possibilities. This level was also observed in the ^{48}Ti(p,γ) reaction and its spin was assigned as $\frac{3}{2}$ or $\frac{5}{2}$.[33] As a result, the $J^\pi=\frac{3}{2}^-$ is proposed for this level.

2309.7 keV level. A level corresponding to this excitation energy was observed in the ^{48}Ti(^{3}He, d) reaction with an angular momentum transfer $l_p=1$[15,16,18] and in the ^{48}Ti(p,γ) reaction for which its γ-ray distribution was measured.[33] Consequently, the $J^\pi=\frac{3}{2}^-$ assignment has previously been proposed for this state. The present angular correlation and lifetime measurements ($\tau<0.07$ ps) do not result in a definite J^π value. They give $J^\pi=(\frac{1}{2}^-)$, $\frac{3}{2}^\pm$, $\frac{5}{2}^-$, and $(\frac{7}{2}^-)$. The values given in parentheses correspond to solutions between the 0.1 and the 10% confidence levels. In this case, the $J^\pi=\frac{3}{2}^-$ assignment will be adopted.

2353.3 keV level. In the present p-γ and γ-γ coincidence measurements this level was found to decay 21% to the 1155.4 keV level, 26% to the 1021.6 keV level, and 53% to the ground state. The angular correlation of the 2353.2 keV transition is consistent with spin values $J=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{9}{2}$. The first two spins are quite improbable because of the 1331.8 keV transition to the $J^\pi=\frac{11}{2}^-$, 1021.6 keV level, consideration being given to the fact that the measured lifetime of the 2353.3 keV level is shorter than 0.07 ps. For the measured mixing ratio $\delta=0.54\pm0.23$, positive parity would yield an enhanced $M2$ component in the 2353.2 keV transition. As a result, the $J^\pi=\frac{9}{2}^-$ assignment is proposed for the 2353.3 keV level.

2388.2 keV level. This level was observed in the ^{48}Ti(^{3}He, d) reaction with the proton transfer $l_p=2$.[15] In the present experiment, it was found to decay 10% to the 1994.9 keV, 7% to the 1140.9 keV, 59% to the 748.3 keV, 17% to the 90.7 keV levels, 7% to the ground state level, and less than 5% to the 152.9 keV level. The angular correlation measurement for the 1639.6 keV transition to the $J^\pi=\frac{3}{2}^+$ state resulted in the $J=\frac{5}{2}$ spin value and $\delta=0.36\pm0.15$. A negative parity is quite improbable as it would yield an unrealistically large $M2$ component in this transition ($\tau=0.09^{+0.04}_{-0.02}$ ps). The $J^\pi=\frac{5}{2}^+$ assignment is also consistent with the observed decay mode of this level and the quoted $l_p=2$ angular momentum transfer.

2408.4 keV level. This level was found to decay less than 5% to the 2178.5 keV level, 21% to the 1155.4 keV level, and 79% to the ground state. The angular correlation measurement for the ground state transition resulted in possible spin values $J=\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}$, and $\frac{11}{2}$. The $J^\pi=\frac{5}{2}^\pm$ assignment is quite unlikely as it would yield an unrealistic $E2$ or $M2$, 229.2 keV transition, since the upper limit of the lifetime of the 2408.4 keV level was measured to be $\tau<0.03$ ps. The probable assignment for this level is $J^\pi=\frac{7}{2}^\pm$, $\frac{9}{2}^-$, or $\frac{11}{2}^-$, so as to have realistic transition rates.

2670.8 keV level. In the p-γ and γ-γ coincidence experiments this level was found to decay only to the $J^\pi=\frac{11}{2}^-$, 1021.6 keV level. The angular correlation results gave possible spins $J=\frac{7}{2}$, $\frac{9}{2}$, $\frac{11}{2}$, $\frac{13}{2}$, or $\frac{15}{2}$. With the upper limit of the lifetime of this level which was measured to be $\tau<0.03$ ps, it can be seen that the first and the last of the given values are improbable as they would give rise to $E2$ and $M3$ components enhanced by factors at least 210 and 3.10^6, respectively. None of the three other values can be rigorously discounted. The $J=\frac{11}{2}$ assignment may be favored by the 56% confidence level on δ obtained from the angular correlation fit. The confidence levels were less than 10% for $J=\frac{9}{2}$ and $\frac{13}{2}$. It should be added that from consideration of the γ-ray yield of the 1649.2 keV transition in the ^{46}Ti(α,p) reaction, a spin assignment $J=\frac{9}{2}$

or $\frac{11}{2}$ was inferred for the 2670.8 keV state.[19] Finally, realistic transition rates require a negative parity.

2727.8 keV level. In the p-γ and γ-γ coincidence measurements, this level was found to decay 100% to the $J^\pi=\frac{15}{2}^-$, 2263.3 keV level. The lifetime $\tau=0.35^{+0.15}_{-0.11}$ ps and the angular correlation results yield only one probable assignment $J^\pi=\frac{15}{2}^{(-)}$ for this level, since for the positive parity, the $E1$ transition strenth Γ_{E1} would be $0.021^{+0.009}_{-0.008}$ W.u. This corroborates the higher of two tentative spin values $J^\pi=\frac{13}{2}^-$ and $\frac{15}{2}^-$ inferred in Ref. 19.

2741.1 keV level. A level at about this energy was observed in the ^{50}Cr(t,α) reaction but no l_p value was given.[15] In the present p-γ and γ-γ coincidence experiments this level was found to decay 13% to the 2178.5 keV, 48% to the 1603.1 keV, 39% to the 1155.4 keV, and less than 5% to the 1021.6 keV levels. Its lifetime was measured to be $\tau=0.70^{+0.80}_{-0.50}$ ps. Because of poor statistics on the transitions involved in angular correlation measurement it was not possible to make a definite J^π assignment. However it is possible to limit spin parity values to $J^\pi=\frac{7}{2}^-$, $\frac{9}{2}^\pm$, and $\frac{11}{2}^+$ on the basis of decay modes and lower limits on mixing ratios. Of these assignments the $J^\pi=\frac{11}{2}^+$ value is tentatively favored, providing that the 2741.1 keV state is a member of a rotational band built on the $K^\pi=\frac{3}{2}^+$, 748.3 keV state (see Sec. IV).

2786.3 keV level. In the p-γ and γ-γ experiments this level was found to decay 28% to the 1155.4 keV level, 26% to the 1021.6 keV level, and 46% to the ground state. From consideration of its decay mode, the angular correlation results for the three transitions and the upper limit of the lifetime ($\tau<0.04$ ps), the spin and parity values are limited to $J^\pi=\frac{9}{2}^-$ and $\frac{11}{2}^-$.

2810.7 keV level. Near this energy, two levels at 2812 and 2820 keV excitation energy were, respectively, observed in the ^{50}Cr(t,α) reaction with an $l_p=2$ orbital momentum transfer[15] and in the ^{48}Ti(^{3}He, d) reaction with an $l_p=3$ orbital momentum transfer.[16] Considering the decay mode of the present level, 14% to the 2182.7 keV level, 25% to the 90.7 keV level, and 61% to the ground state, and the upper limit of its lifetime ($\tau<0.06$ ps), the spin and parity assignments were limited to $J^\pi=\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, and $\frac{9}{2}^-$.

2860.8 keV level. In the p-γ and γ-γ coincidence experiments this level was found to decay 22% to the 2263.3 keV and 78% to the 1155.4 keV level. The decay mode and the lifetime which was measured to be $\tau=0.15^{+0.08}_{-0.06}$ ps, as well as mixing ratios obtained from the fit to the angular correlation of the 1705.0 keV transition, result in realistic transition rates only for $J^\pi=\frac{13}{2}^-$.

3017.3 keV level. This level was found to decay 37% to the 152.9 keV level, 45% to 90.7 keV level, and 18% to the ground state. The fit to the angular correlation data did not result in a definite spin assignment. On the basis of the observed decay mode and the upper limit of the lifetime ($\tau<0.06$ ps), the probable J values can be limited to $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ for this level.

3134.0 keV doublet. In the p-γ and γ-γ coincidence experiments, a transition of 462.9 keV was observed to deexcite a level at 3134 keV with the lifetime $\tau=0.32^{+0.11}_{-0.06}$ ps. On the other hand, a transition of 3133.0 keV energy was observed to exhibit the full energy shift in the DSAM spectra ($\tau<0.06$ ps). Other transitions of 1978.0 and 2114.0 keV, also fully shifted, were recognized in coincidence spectra as deexciting a level at 3134 keV. These facts can be explained by assuming a doublet of states at 3134 keV and differing in energy by less than 1 keV. The long-lived member of the proposed doublet, found to decay 100% to the 2670.8 keV level ($J^\pi=\frac{9}{2}^-$, $\frac{11}{2}^-$, or $\frac{13}{2}^-$) is very probably a high-spin state. Angular correlation results for the deexciting 462.9 keV transition and the lifetime give spins $J=\frac{9}{2}$, $\frac{11}{2}$, or $\frac{13}{2}$ if $J^\pi=\frac{9}{2}^-$, $\frac{11}{2}^-$, or $\frac{13}{2}^-$ is considered for the 2670.8 keV level. Negative parity is preferred since for a positive one the $E1$ transition strength Γ_{E1} is $0.023^{+0.007}_{-0.015}$. This high-spin member was suggested in Ref. 19 with possible spin assignment $J=\frac{9}{2}$, $\frac{11}{2}$, $\frac{13}{2}$.

The short-lived state was probably observed in the ^{50}Cr(t,α) and ^{48}Ti(^{3}He, d) reactions.[15] The angular distribution of deuterons was fitted with $l=4$. The observed decay modes, lifetime, and angular correlation results furnish the four possible values $J^\pi=\frac{7}{2}^-$, $\frac{9}{2}^\pm$, and $\frac{11}{2}^-$. For the $J^\pi=\frac{9}{2}^+$ assignment, the measured mixing ratio $\delta=-0.26\pm0.12$ and the upper limit of the lifetime yield an $M2$ admixture in the ground state 3133.0 keV transition of $\Gamma_{M2}\geq 2$ W.u. which does not rigorously contradict the $J^\pi=\frac{9}{2}^+$ assignment proposed previously.[15]

3259.4 keV level. The lifetime of this level was measured to be longer than 3 ps but shorter than 1000 ps. In the p-γ coincidences this level was observed to decay only to the 2786.3 keV level which has the possible assignments $J^\pi=\frac{9}{2}^-$ and $\frac{11}{2}^-$. In the ^{50}Cr(t,α) and ^{48}Ti(^{3}He, d) reactions a state at 3248 keV was observed with an $l=0$ angular momentum transfer,[15] and a $J^\pi=\frac{1}{2}^+$ value was proposed. Due to the unknown J^π of the 2786.3 keV level, one cannot make definite suggestions concerning the J^π of the 3259.4 keV level observed in the present work. However, it is unlikely that it is a $J^\pi=\frac{1}{2}^+$ state.

3341.6 keV level. In the p-γ coincidence runs this level was observed to decay 29% to the 2741.1

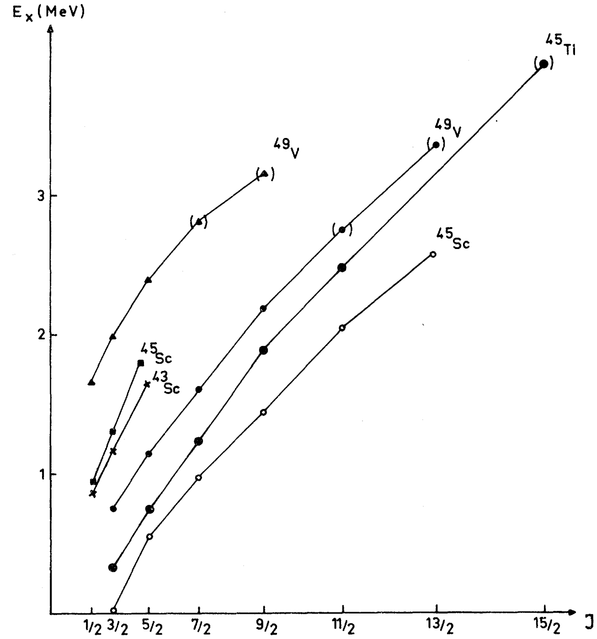

FIG. 7. Energy of ^{49}V positive parity levels versus $J(J+1)$. The proposed $K^{\pi}=\frac{1}{2}^{+}$ in ^{43}Sc and ^{45}Sc and $K^{\pi}=\frac{3}{2}^{+}$ bands in ^{45}Sc and ^{45}Ti (Refs. 4 and 5) are shown for comparison.

keV, 31% to the 2670.8 keV, and 40% to the 2178.5 keV levels. Due to poor statistics, the angular correlations did not furnish definite solutions for the spin of this level or for mixing ratios of the deexciting transitions. From consideration of its decay modes, and estimated limits on the lifetime ($5<\tau<1000$ ps) and the possibility of regarding this level as a member of the $K^{\pi}=\frac{3}{2}^{+}$ rotational band (see Sec. IV) a spin and parity assignment $J^{\pi}=\frac{13}{2}^{+}$ is tentatively favored.

IV. DISCUSSION

A. Positive parity states

The $\frac{3}{2}^{+}$, 748.3 keV, $\frac{5}{2}^{+}$, 1140.9 keV, and $\frac{7}{2}^{+}$, 1603.1 keV states have already been organized into a rotational band built on the first $\frac{3}{2}^{+}$ state.[4] However, the spins and parities had been only tentatively assigned to the 1140.9 and 1603.1 keV states.[8] In the present study, these J^{π} assignments are confirmed and moreover a $\frac{9}{2}^{+}$, 2178.5 keV state was found which lies on the $J(J+1)$ line (Fig. 7) and can thus be attributed to the $K^{\pi}=\frac{3}{2}^{+}$ band. The 2741.1 keV state follows this $J(J+1)$ line and is tentatively assigned as the $J^{\pi}=\frac{11}{2}^{+}$ member of the rotational band. A possible $J^{\pi}=\frac{13}{2}^{+}$ assignment may be given to the 3341.6 keV state which, along with the 2741.1 keV state, seems to follow the same $J(J+1)$ dependence.

As has already been discussed (Sec. III), the 1646.4 keV level probably has a $J^{\pi}=\frac{1}{2}^{+}$ assignment and it would be the $s_{1/2}$ hole state[15] like the $J^{\pi}=\frac{1}{2}^{+}$ states in the 43, 45, and 47 scandium isotopes. The $\frac{3}{2}^{+}$, 1994.9 keV and $\frac{5}{2}^{+}$, 2388.2 keV states would then form a $K^{\pi}=\frac{1}{2}^{+}$ rotational band in ^{49}V with the decoupling factor close to zero as in the $K^{\pi}=\frac{1}{2}^{+}$ bands in ^{43}Sc and ^{45}Sc. The candidates for the next members of this band would be the 2810.7 keV state which was assigned $J^{\pi}=\frac{5}{2}^{\pm}$, $\frac{7}{2}^{\pm}$, or $\frac{9}{2}^{-}$ and the 3133.4 keV state having possibly the $J^{\pi}=\frac{9}{2}^{+}$ assignment.

The experimental $B(M1)$ and $B(E2)$ reduced transition probabilities for transitions within the $K^{\pi}=\frac{3}{2}^{+}$ band are given in Table IV. Unfortunately, the uncertainties on the mixing ratios are relatively large and consequently the $B(E2)$ values for the $E2$ transitions between two successive members are imprecise. In any case it is observed that the

TABLE IV. Experimental transition strengths for the $K^{\pi}=\frac{3}{2}^{+}$ rotational band in ^{49}V.

E_i (keV)	E_f (keV)	J_i^{π}	J_f^{π}	$B(E2)$ (e^2 fm^4)	$B(M1)$ (μ_N^2)
1140.9	748.3	$\frac{5}{2}^{+}$	$\frac{3}{2}^{+}$	212^{+790}_{-199}	$0.03^{+0.05}_{-0.02}$
1603.1	1140.9	$\frac{7}{2}^{+}$	$\frac{5}{2}^{+}$	>0, <920	$0.12^{+0.10}_{-0.07}$
	748.3		$\frac{3}{2}^{+}$	343^{+305}_{-198}	
2178.5	1603.1	$\frac{9}{2}^{+}$	$\frac{7}{2}^{+}$	>0, <177	$0.03^{+0.06}_{-0.03}$
	1140.9		$\frac{5}{2}^{+}$	177^{+265}_{-105}	
2741.1	2178.5	$(\frac{11}{2}^{+})$	$\frac{9}{2}^{+}$		$0.06^{+0.23}_{-0.04}$ [a]
	1603.1		$\frac{7}{2}^{+}$	291^{+834}_{-171}	
3341.6	2741.1	$(\frac{13}{2}^{+})$	$(\frac{11}{2}^{+})$		>0.000 06, <0.02 [a]
	2178.5		$\frac{9}{2}^{+}$	>0.1, <34	

[a]Mixing ratio $\delta=0$ was used in the $B(M1)$ calculation.

$E2$ transitions between the positive parity states are enhanced over single-particle Weisskopf estimates and thus would lend support to the rotational character of these states.

B. Negative parity states

Properties of low-lying negative parity states in ^{49}V have been calculated by McCullen, Bayman, and Zamick[1] and more recently by Brut[34] within the framework of the shell model using an $(f_{7/2})^n$ configuration for n nucleons outside a ^{40}Ca core. This approach fails, however, to reproduce even the energy of the low-lying $J^\pi = \frac{3}{2}^-$ state. As can be seen from proton transfer reactions[14-18] the inclusion of the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbits in the calculations is necessary and is expected to improve the results.[2]

On the other hand, the strong-coupling model calculations of Scholz and Malik[3] furnished more correct energy spacings for the first five negative states of ^{49}V but the agreement between experimental and theoretical transition probabilities is poor.

Calculations performed in the present study are also based on the strong-coupling model of Bohr and Mottelson.[35] Due to the interaction between a collective rotational motion and the single-particle motion of a certain number of extra-core nucleons, the total angular momentum I of the nucleus is:

$$I = R + j, \tag{1}$$

where R is the rotational angular momentum of the whole nucleus and $j = \sum_i j_i$ is the total angular momentum of the extra-core nucleons, expressed in the body-fixed coordinates. A correct treatment of the $\sum_i j_i$ term in the Hamiltonian requires the sum to extend over all open shell nucleons. However, such a calculation is quite complicated and we therefore confined the sum to the three extra-core protons. Earlier calculations[3,20] considered only the contribution of the unpaired nucleon. Details of the calculations are given in Ref. 36.

The Nilsson model Hamiltonian was used to describe the single particle motion. The unpaired proton was allowed to occupy any orbit in the $N = 3$ oscillator shell above the filled orbit No. 14. Furthermore, hole states were included which were obtained by promoting one nucleon from orbit 14 to orbit 13. Care has been taken to treat correctly the hole excitations. Such hole excitations were treated essentially as particle excitations in the calculations of Ref. 3. The parameters χ and μ appearing in the Nilsson Hamiltonian are consistent with the single-particle energies, as deduced from ^{41}Sc and ^{49}Sc, and are equal to 0.075 and 0.25, respectively. They also give the best fit to the experimental energy spectrum. The value of the deformation parameter $\delta = 0.17$ corresponds to a minimum of the total ground state energy. The rotational constant $\hbar^2/2J$ was the only adjustable parameter. Even then the value $\hbar^2/2J = 90$ keV giving the best fit between the calculated and observed energy spectrum is in agreement with the values determined from the energy of the first $J^\pi = 2^+$ state in ^{48}Cr and deduced from the $\frac{3}{2}^+$ positive parity band in ^{49}V. In the band-mixing calculations, the same parameters were used for the ten Nilsson orbits occuring in the $1f$-$2p$ shell. Furthermore, the bandhead energies were computed and not treated as parameters. In Fig. 8, the experimental energy level scheme is compared with the calculated one. The agreement is fairly good. The exception is the $\frac{5}{2}^-$ state found experimentally at 1514.4 keV which is calculated to be relatively high in energy. The same is observed for the $B(M1)$ and $B(E2)$ reduced transition

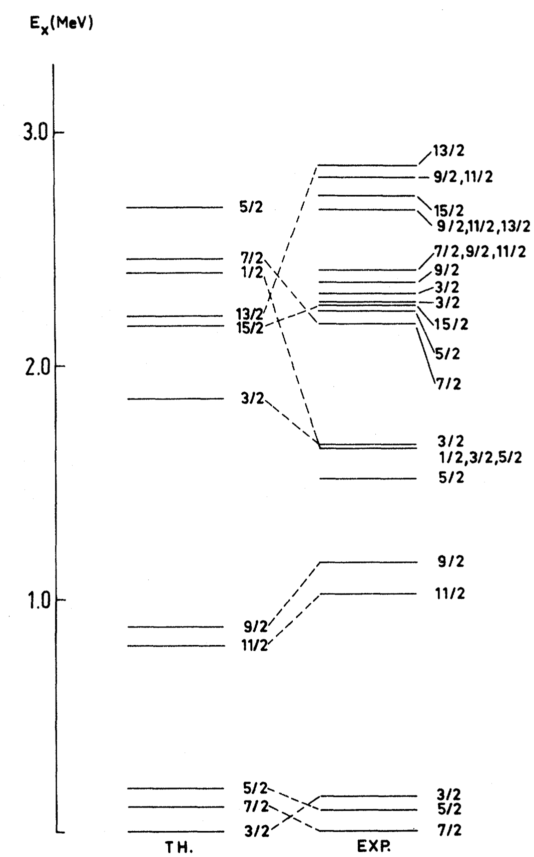

FIG. 8. Comparison of the calculated negative parity energy levels in ^{49}V with the experimentally observed values. The calculated spectrum was obtained with the following parameters (see Sec. IV B): $\delta = 0.17$, $\hbar^2/2J = 90$ keV, $\chi = 0.075$, and $\mu = 0.25$.

TABLE V. $B(M1)$ and $B(E2)$ reduced matrix elements for transitions between negative parity states and magnetic moments μ in ^{49}V. [Ground state magnetic moment (μ_N): $\mu_{exp}=4.46 \pm 0.05$ (Ref. 38), $\mu_{th}=5.09$. Second excited state magnetic moment (μ_N): $\mu_{exp}=2.37\pm0.12$ (Ref. 10), $\mu_{th}=3.00$.]

E_i (keV)	E_f (keV)	J_i^π	J_f^π	$B(M1)$ (μ_N^2) Exp.	Th.	$B(E2)$ ($e^2\,\mathrm{fm}^4$) Exp.	Th.
90.7	0	$\frac{5}{2}^-$	$\frac{7}{2}^-$	0.12 ± 0.01 [a]	0.37		136
152.9	90.7	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.004 ± 0.0005 [a,b]	0.001		220
	0		$\frac{7}{2}^-$			197 ± 20	146
1021.6	0	$\frac{11}{2}^-$	$\frac{7}{2}^-$			144 ± 28 [c]	123
1155.4	1021.6	$\frac{9}{2}^-$	$\frac{11}{2}^-$	<0.90 [a]	0.67		55
	90.7		$\frac{5}{2}^-$			83 ± 44	96
	0		$\frac{7}{2}^-$	0.012 ± 0.005	0.003	58 ± 33	49
1514.4	152.9	$\frac{5}{2}^-$	$\frac{3}{2}^-$	$0.23^{+0.20}_{-0.09}$	1.09	570^{+595}_{-260}	1.9
	90.7		$\frac{5}{2}^-$	>0.004, <0.10	0.37	>0.3, <435	4.1
	0		$\frac{7}{2}^-$	$0.11^{+0.11}_{-0.05}$ [a]	0.08		0.65
1643.1	152.9	$(\frac{1}{2}^-)$	$\frac{3}{2}^-$	$0.34^{+0.14}_{-0.08}$ [a]	0.70		25
1661.4	152.9	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$0.37^{+0.48}_{-0.19}$ [a,d]	0.72		8.9
	90.7		$\frac{5}{2}^-$	$0.59^{+0.68}_{-0.30}$ [d]	1.37	<122	22
2182.7	1155.4	$\frac{7}{2}^-$	$\frac{9}{2}^-$	$0.36^{+0.26}_{-0.16}$ [a,d]	1.29		14.5
	90.7		$\frac{5}{2}^-$	$0.16^{+0.10}_{-0.05}$ [d]	0.71	$4.2^{+8.8}_{-3.7}$	5.5
	0		$\frac{7}{2}^-$	<0.01 [a]	0.03		0.06
2263.3	1021.6	$\frac{15}{2}^-$	$\frac{11}{2}^-$			297 ± 128	137
2860.8	2263.3	$\frac{13}{2}^-$	$\frac{15}{2}^-$	$0.39^{+0.41}_{-0.19}$	0.85		29
	1155.4		$\frac{9}{2}^-$			295^{+230}_{-125}	120

[a] Mixing ratio $\delta=0$ was used in the $B(M1)$ calculation.
[b] The $B(M1)$ value was calculated with $\tau=28.7\pm0.5$ ns taken from Ref. 10.
[c] The $B(E2)$ value was calculated with $\tau=5.1\pm1.0$ ps taken from Ref. 37.
[d] The $B(M1)$ value was calculated with mean lifetimes taken from Ref. 19.

probabilities for this level (see Table V). It should be pointed out that the sign of the deformation parameter was found to be positive, opposite to that of Scholz and Malik[3] ($\delta=-0.37$).

Table V compares the calculated reduced transition probabilities $B(M1)$ and $B(E2)$ with those obtained from experiment. As can be seen, the predicted $M1$ and $E2$ transition rates are in fair agreement with the measured values. In the same table are listed the experimental and theoretical values of the ground and second excited state magnetic moments. The trend is reproduced but the calculated magnetic moments are higher than the ones experimentally observed. In the calculations, the free nucleon charge and gyromagnetic ratios were used, while, for the rotational gyromagnetic ratio the value of $g_R=Z/A$ was used.

To summarize, it appears that low-lying negative parity states in ^{49}V show collective behavior. The level energies as well as electromagnetic properties are in fairly good agreement with the predictions of the strong-coupling model if one takes into account the two-body part of the j^2 term and uses a correct treatment of particle-hole excitations. The disagreement in the case of the 1514.4 keV state may be due to another type of excitation or may be explained with another set of parameters. However, the advantage of simple band-mixing calculations would be lost.

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