High-spin $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration, two-particle—one-hole states in ^{49}Ti

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(Received 23 July 1984)

The ^{51}V($\vec{d}$,α)^{49}Ti reaction has been studied with 79.4-MeV vector polarized deuterons. Angular distributions of the differential cross section and vector analyzing power have been measured for strongly-populated states up to an excitation energy of 5 MeV. Two-particle—one-hole states of the $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration were identified from the characteristic $L=6$ shapes of the differential cross section and $J=7$ patterns of the vector analyzing power. These states lie at 0.00, 1.54, 1.62, 2.26, 2.72, 2.98, 3.05, 3.29, 3.46, 3.97, 4.22, and 4.39 MeV in ^{49}Ti. The relative $(f_{7/2})^2_{J=7}$ pickup strength to these states is compared to predictions of the $(f_{7/2})^n$ model of Kutschera, Brown, and Ogawa. The identification in this work of $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration states at 4.39 and 3.97 MeV tends to confirm the suggestion that states found at 4.4 and 4.0 MeV in the ^{48}Ca(p,π^-)^{49}Ti reaction are the $\frac{19}{2}^-$ and $\frac{15}{2}^-$ members of that configuration.

I. INTRODUCTION

Previous (d,α) studies[1-3] at 80 MeV bombarding energy for $1f$-shell nuclei have shown preferential excitation of states in the residual nucleus formed by picking up proton-neutron pairs in the completely aligned $(f_{7/2})^2_{J=7}$ configuration. Such $(f_{7/2})^2_{J=7}$ transitions are characterized by pure $L=6$ differential cross section angular distributions and distinct $J=7$ patterns of the vector analyzing powers.[3] This selectivity was used in the present study of the ^{51}V(d,α)^{49}Ti reaction in order to locate $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration two-particle—one-hole states relative to ^{48}Ca as a core, since the ground state wave function of ^{51}V can be described as predominantly $(\pi f_{7/2})^3$ with respect to ^{48}Ca.

The high-spin states of this configuration are of interest in the context of interpreting the selective and strong population of discrete final states observed in the ^{48}Ca(p,π^-)^{49}Ti reaction.[4] From the point of view of a simple two-nucleon mechanism for the (p,π^-) reaction, it was conjectured[4] that the transitions to these strongly excited states involve the effective capture of the incident proton plus charge exchange of a target neutron to form 2p-1h $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration high-spin states with respect to the ^{48}Ca ground state configuration. Due to the inherently large momentum mismatch of the (p,π) reaction, maximal or near maximal spin couplings of the highest j orbitals available are preferred.

Experimentally, the level scheme of ^{49}Ti has been fairly well established[5-7] up to about 6.3 MeV of excitation. High-spin states have in fact been observed in the ^{50}V(t,α)^{49}Ti work of Andersen *et al.*[8] and the ^{48}Ca(α,3nγ)^{49}Ti work of Behar *et al.*[9] Still, information about the 2p-1h high-spin states above 3 MeV of excitation has remained somewhat incomplete.

Several shell-model calculations have been performed for $1f_{7/2}$ nuclei. The most recent and comprehensive calculations by Kutschera *et al.*,[10] applying the $(1f_{7/2})^n$ model to all the $42 \le A \le 54$ nuclei, were quite successful in reproducing electromagnetic transition probabilities and spectroscopic factors for transfer reactions. This simple $(1f_{7/2})^n$ model should also do well in reproducing the relative $L=6$, $J=7$ transition strengths in the ^{51}V(d,α)^{49}Ti reaction, since nearby orbitals outside this configuration space cannot contribute to these high spin transitions.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A 79.4-MeV vector polarized deuteron beam from the Indiana University Cyclotron Facility was used for the ^{51}V(d,α)^{49}Ti reaction studies. The target consisted of a self-supporting vanadium foil with a thickness of about 0.50 mg/cm^2. For reasons of comparison, the ^{50}Ti(d,α)^{48}Sc reaction was also studied using an enriched (76.4%), 0.51-mg/cm^2 thick, self-supporting ^{50}Ti foil. The reaction products were momentum analyzed in a quadrupole-dipole-dipole-multipole magnetic spectrometer and detected in the focal plane by a position-sensitive helical proportional counter followed by two plastic scintillator detectors for particle identification.

Typical vector beam polarizations were 0.55 and -0.59, measured before and after each run by inserting a ^{3}He polarimeter into the beam directly after the injector cyclotron.[3] At all times the tensor component in the beam polarization was less than 0.04 in magnitude. The spin orientation was changed every 60 s during the data acquisition in order to reduce systematic errors associated with any slow change of beam properties on target.

A typical alpha-particle spectrum is shown in Fig. 1.

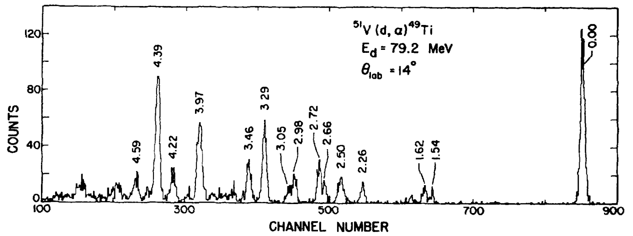

FIG. 1. Alpha-particle spectrum from the ^{51}V(d,α)^{49}Ti reaction. Peaks are labeled by the excitation energy (in MeV) of the state populated in the residual nucleus.

By means of dispersion matching an overall resolution between 50 and 60 keV (FWHM) was obtained. Most of the stronger peaks in the spectrum belong to transitions of a predominantly $L=6$ character which are momentum matched at about 80-MeV bombarding energy. The spectra were analyzed with a conventional peak-fitting program.

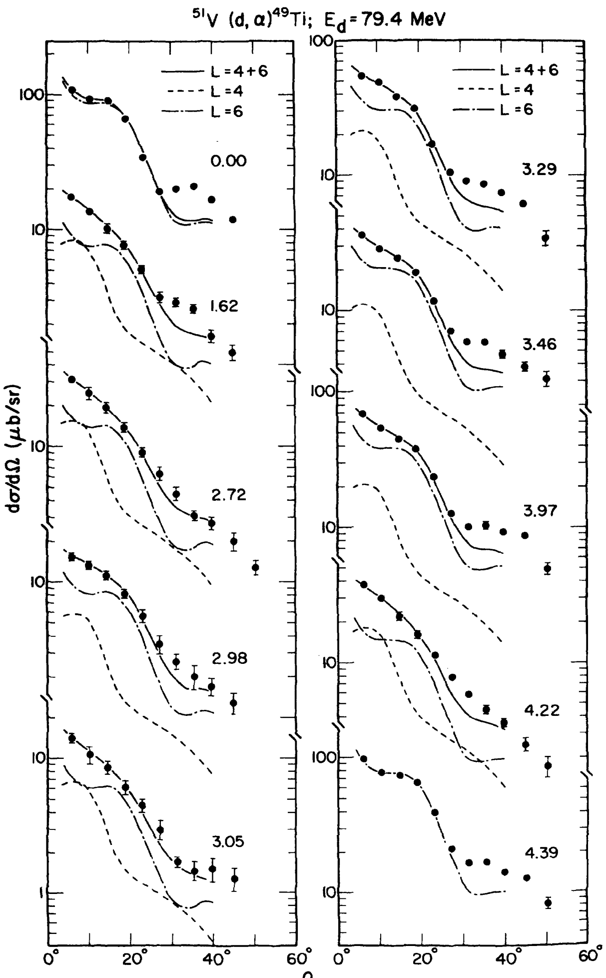

FIG. 2. Differential cross section angular distributions for predominant $L=6$ transitions. The dashed and dash-dotted curves represent empirical $L=4$ and $L=6$ shapes, respectively, whereas the full curve represents the best fit of these two components to the data.

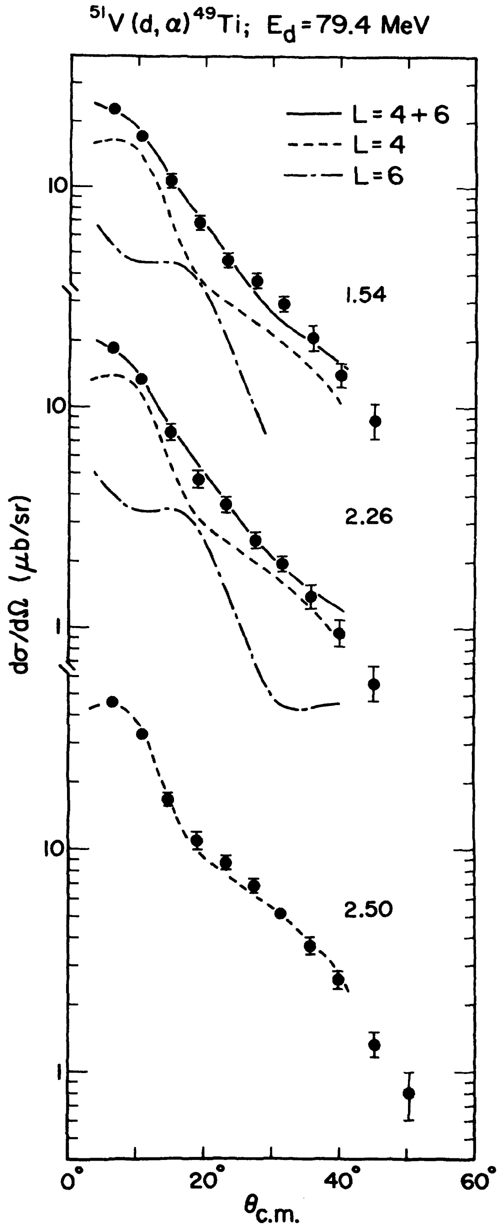

FIG. 3. Differential cross section angular distributions for predominant $L=4$ transitions. See caption of Fig. 2 for details.

Angular distributions extracted for the differential cross section are shown in Figs. 2 and 3, with the corresponding vector analyzing powers presented in Figs. 4 and 5. The error bars shown in the figures reflect statistical errors as well as the uncertainties associated with background subtraction and, in some cases, with unfolding close-lying peaks. Absolute cross sections were determined from the extracted peak area, areal density of the target (determined by weighing), spectrometer solid angle, and integrated charge. The overall normalization in the differential cross section is estimated to be accurate to better than $\pm 15\%$, with the largest contribution coming from the uncertainty in the target thickness.

A summary of the present results is given in Table I.

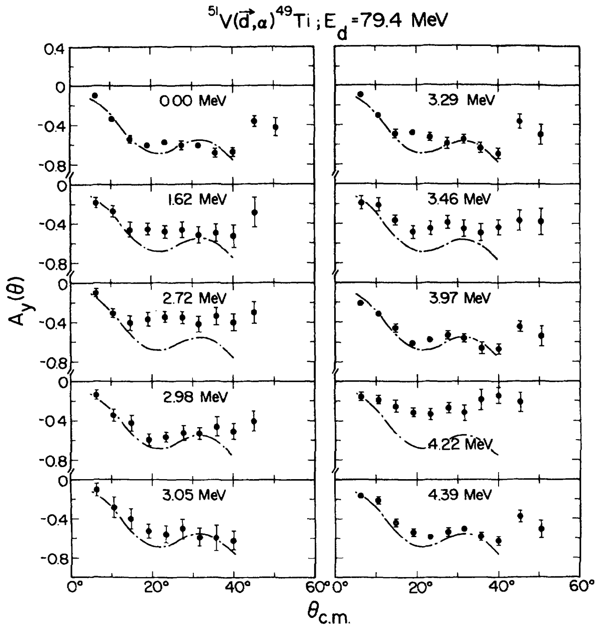

FIG. 4. Measured vector analyzing power angular distributions for the predominant $L=6$ transitions presented in Fig. 2. The dash-dotted curves represent an empirically determined $J=7$ vector analyzing power shape.

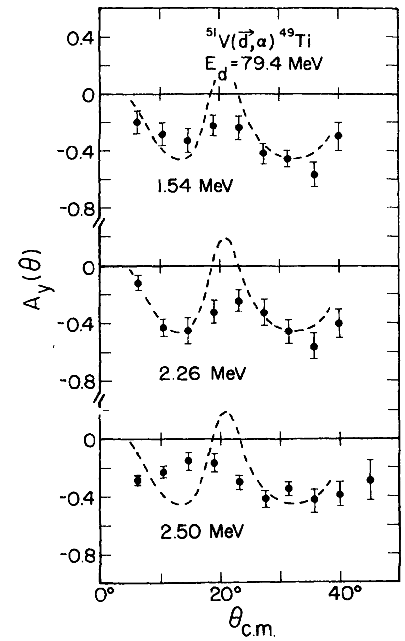

FIG. 5. Vector analyzing power angular distributions for the predominant $L=4$ transitions. The dashed curves represent an empirically determined $J=5$ vector analyzing power shape.

Excitation energies of the observed levels are listed along with the contributing L transfers and corresponding partial differential cross sections at 10°. Also tabulated are the data from the compilation of Halbert,[5] as well as excitation energies derived from a recent high-resolution $^{51}V(d,\alpha)^{49}Ti$ experiment by Sherr *et al.*[11] at 28-MeV bombarding energy. The present excitation energies were calibrated against well-known residual states populated in the

TABLE I. Results of the $^{51}V(\vec{d},\alpha)^{49}Ti$ reaction.

Present work			Compilation (Ref. 5)		Ref. 11
	$\sigma(10°)$ (μb/sr)		E_x (MeV)	J^π	E_x (MeV)
E_x (MeV)	$L=4$	$L=6$			
0.0	8.0	86.0	0.0	$\frac{7}{2}^-$	
1.543	14.8	4.5	1.542	$\frac{11}{2}^{-\,a}$	1.543
1.623	7.3	7.6	1.623	$\frac{9}{2}^{-\,b}$	1.623
2.264	12.0	3.4	2.262	$\frac{7}{2}^-,\frac{5}{2}^-$	2.264
2.504	37.5		2.470	$\frac{7}{2}^-,\frac{5}{2}^-$	2.470
			2.504	$\frac{1}{2}^+$	
			2.506	$\frac{15}{2}^{-\,a}$	2.504
2.664			2.663	$\frac{3}{2}^+$	2.665
2.722	12.8	14.0	2.720	$\frac{13}{2}^-,\frac{15}{2}^{-\,b}$	2.722
2.984	5.2	8.2	2.981	$\frac{11}{2}^+,\frac{13}{2}^{-\,b}$	2.980
3.048	5.7	6.0	3.043		3.048
3.291	18.3	30.5	3.291[a]	$\frac{17}{2}^{-\,a}$	3.295
3.460	9.5	26.7	3.456		3.461
3.967	18.0	38.5	not reported		3.968
4.223	16.0	14.8	correspondence unclear		4.225
4.386		78.0	4.383[a]	$\frac{19}{2}^{-\,a}$	4.388
4.593			(4.621)		4.593

[a]Reference 9.
[b]Reference 6.

^{50}Ti(d,α)^{48}Sc reaction by using the same (undisturbed mechanically and magnetically) setting of the spectrometer. The resulting uncertainties for the excitation energies quoted in the table are estimated to be about ± 5 keV.

III. DISCUSSION

The preferential pickup of the proton-neutron pair in a completely aligned configuration in the (d,α) reaction on 1f-shell target nuclei at 80 MeV bombarding energy has been reported previously.[1–3] The enhancement effects are such that, for example, the pickup in the $(f_{7/2})^2_{J=7,T=0}$ and $(f_{7/2},p_{3/2})_{5,0}$ couplings are about one order of magnitude stronger than for the other couplings. Accordingly, high-spin states belonging to the $[{}^{51}\mathrm{V}(\frac{7}{2}^-)\times(f_{7/2})^{-2}_{7,0}]$ configurations are expected to be strongly excited, exhibiting characteristic $L=6$ angular distributions of the differential cross section and $J=7$ distribution shapes for the vector analyzing power. Since the ground state wave function of ^{51}V can be described predominantly as $(\pi f_{7/2})^3_{7/2}$ with respect to ^{48}Ca as a core, where the neutron $f_{7/2}$ orbital is completely filled, this strong selectivity allows the location of $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration 2p-1h high-spin states in the residual nucleus ^{49}Ti. Such states are not only of interest from the shell model point of view but also provide further evidence for the nuclear structure selectivity of the (p,π^-) reaction,[4,12] which can populate 2p-1h states of the same high-spin configuration via the ^{48}Ca(p,π^-)^{49}Ti reaction.

In order to experimentally determine shapes for the expected $L=6$ angular distributions of the cross section and the characteristic $J=7$ vector analyzing powers (VAP), the ^{50}Ti($\vec{\mathrm{d}}$,α)^{48}Sc reaction leading to the known 7^+ state in ^{48}Sc at 1.10 MeV (Ref. 13) was also studied. This reaction also yields the typical $L=4$ differential cross section and $J=5$ VAP patterns from the transition to the 5^+ state at 0.31 MeV. The measured angular distributions are displayed in Fig. 6. The dashed and dash-dotted lines are smooth curves drawn through the data points indicating the characteristic patterns taken for the $L=4$ and $L=6$ transitions, respectively. The full curves shown are results from DWBA calculations which will be discussed in more detail later. Although these DWBA calculations reproduce the main features of the data, they are less reliable than experimentally determined shapes for identifying and disentangling mixtures of $L=4$ and $L=6$ transfers in neighboring nuclei.[3] For the ^{51}V(d,α)^{49}Ti transitions of interest in the present work the relative contribution of these $L=4$ and $L=6$ patterns were determined by best fit to the cross section angular distributions. For the predominantly $L=6$ transitions, the data points at angles larger than 30° could not be reproduced. The resulting curves are plotted along with the measured differential cross sections in Figs. 2 and 3, and their individual contributions are given in Table I.

The transitions to the states at 0.00, 1.62, 2.72, 2.98, 3.05, 3.29, 3.46, 3.97, 4.22, and 4.39 MeV exhibit predominantly $L=6$ shapes (see Fig. 2) with some $L=4$ admixtures. The corresponding vector analyzing powers in Fig. 4 show a clear $J=7$ signature as indicated by their similarity to the $J=7$ VAP shape from the ^{50}Ti(d,α)^{48}Sc reaction. Thus these transitions proceed most likely by picking up a proton-neutron pair in the stretched $(f_{7/2})^2_{7,0}$ configuration since other configurations with the same quantum numbers, e.g., $(g_{9/2},d_{5/2})_{7,0}$, are highly improbable. This suggests that the wave functions of these residual ^{49}Ti states have significant 2p-1h components of the type $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ with respect to ^{48}Ca as a core. Their possible spin-parity values could range from $\frac{7}{2}^-$ to $\frac{19}{2}^-$, since the ground state of ^{51}V has $J^\pi=\frac{7}{2}^-$.

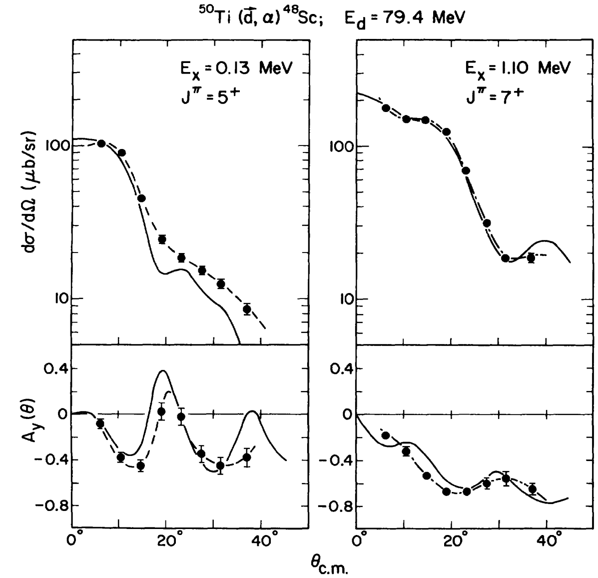

FIG. 6. Differential cross section and vector analyzing power angular distributions of the ^{50}Ti(d,α)^{48}Sc reaction leading to the 5^+ state at 0.13 MeV and the 7^+ state at 1.10 MeV. The dashed and dash-dotted curves were drawn to provide empirical $L=4$, $J=5$ and $L=6$, $J=7$ shapes, respectively. The solid curves are the results of DWBA calculations as described in the text.

Similarly, the states at 1.54, 2.26, and 2.50 MeV are observed to be excited predominantly by $L=4$ angular distributions of the differential cross section (see Fig. 3), with the first two states having small $L=6$ admixtures. The corresponding vector analyzing powers are displayed in Fig. 5 along with $J=5$ VAP shape from the ^{50}Ti(d,α)^{48}Sc reaction. The 1.54- and 2.26-MeV transitions clearly exhibit a mixture of $J=7$ and $J=5$ patterns with the $J=7$ contribution being reflected by a filling in of the positive going $J=5$ analyzing power pattern near 21° (see Fig. 6 for comparison). Although the differential cross section of the 2.50-MeV transition shows a pure $L=4$ shape, its vector analyzing power angular distribution bears no resemblance to the $J=5$ pattern presented in Fig. 6. Since it has been shown previously[3] that the VAP "J patterns" are independent of the configuration of the transferred proton-neutron pair, this suggests that more than one member of the triplet of states near 2.50 MeV contribute to the observed cross section and vector analyzing power angular distributions.

The present results are in good agreement (see Table I) with the results of the ^{50}V(t,α)^{49}Ti work of Andersen *et al.*,[8] the ^{48}Ca(α,3nγ)^{49}Ti work of Behar *et al.*,[9] and the ^{49}Ti(p,p$'\gamma$)^{49}Ti work of Mando *et al.*,[6] all of whom

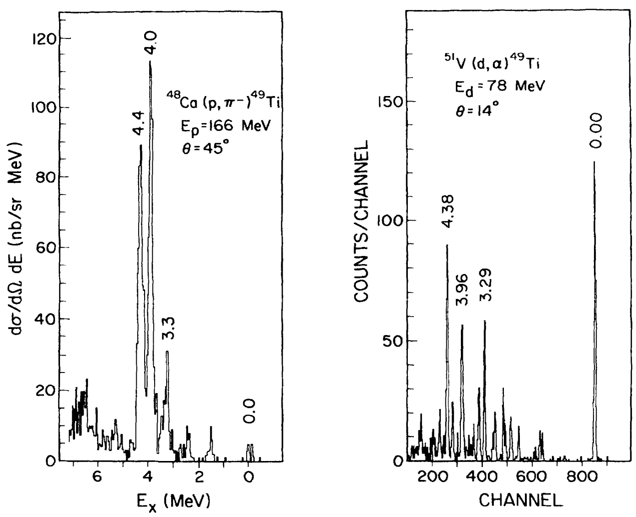

FIG. 7. Comparison of ^{51}V(d,α) and ^{48}Ca(p,π^-) (from Ref. 15) spectra, showing selective excitation of 2p-1h high-spin states in the common residual nucleus ^{49}Ti.

identified several high-spin states. However, the state at 3.967 MeV was not observed in Ref. 6, 8, or 12.

It is interesting to compare these results to those from the ^{48}Ca(p,π^-)^{49}Ti reaction[4] (see Fig. 7), where two states at about 4.0 and 4.4 MeV excitation energy are observed to be strongly populated. In addition, a weaker transition is observed to a state at 3.3 MeV. It was surmised that the (p,π^-) transitions to these states, viewed in a two-nucleon model, would effectively involve capture of the incident proton into the $f_{7/2}$ orbital plus charge exchange of a $f_{7/2}$ target neutron into a $f_{7/2}$ proton to form 2p-1h states with $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configurations with respect to the ^{48}Ca ground state. These 2p-1h configurations will be preferentially coupled to maximal or near maximal angular momentum in order to accommodate the inherently large (linear and angular) momentum mismatch of the (p,π) reaction.[4] The results of the present ^{51}V($\vec{d}$,α)^{49}Ti reaction show that the very same states appear also to be very strongly excited, although not as selectively as in the (p,π^-) reaction, in the pickup of a proton-neutron pair in the completely aligned $(f_{7/2})^2_{7,0}$ configuration. The similarity in excitation energy for the observed residual states and demonstrated high J-transfer selectivity by the (d,α) reaction would thus seem to confirm the conjectures about the structural nature of these states excited in the ^{48}Ca(p,π^-)^{49}Ti reaction.

IV. DWBA ANALYSIS

Microscopic DWBA calculations have been performed with the code DWUCK4 for the ^{50}Ti(d,α)^{48}Sc and ^{51}V(d,α)^{49}Ti reactions using spectroscopic amplitudes calculated from the $(1f_{7/2})^n$ model wave functions of Kutschera *et al.*[10] The deuteron and alpha-particle optical model parameters were taken from the literature[14] and are listed in Table II. Standard nonlocality corrections have been applied.

The results of these DWBA calculations for the transitions to the well established 5^+ state at 0.13 MeV and 7^+ state at 1.10 MeV in the ^{50}Ti($\vec{d}$,α)^{48}Sc reaction are compared in Fig. 6 (full curves) to the experimental data. For both transitions, the agreement in shape for the differential cross sections and analyzing powers is quite good. However, the strength of the transition to the 5^+ state is underestimated by a factor of 3.4 relative to the strength for the 7^+ state. This stems mainly from the omission of the $2p_{3/2}$ orbital from the shell model configuration space used in the calculations. Since the pickup of the proton-neutron pair in the $(f_{7/2},p_{3/2})_{5,0}$ configuration is an order of magnitude larger than pickup in the $(f_{7/2})^2_{5,0}$ configuration, a relatively small amount of $(f_{7/2},p_{3/2})_{5,0}$ admixture to the 5^+ transition can account for this underestimation. This means, of course, that the $(1f_{7/2})^n$ model cannot be expected to accurately predict even the relative $L=4$, $J=5$ transition strengths.

A comparison can be made, however, between $L=6$, $J=7$ transitions and the $(1f_{7/2})^n$ model predictions, since nearby orbitals lying outside this configuration space cannot contribute to these transitions. Figure 8 shows this comparison, where the strengths of the $L=6$ component of the experimental and DWBA differential cross section, at $\theta_{\mathrm{c.m.}}=10°$, are plotted versus excitation energy. Overall, the agreement is reasonable. However, except for a few states, for which spins and parities are known, no clear correspondence between experimental and theoretical levels can be made on the basis of their $L=6$ transition strength. Modifications to the input parameters for the $(1f_{7/2})^n$ shell model calculations can result in interchange of the predicted level orderings, but only small changes in the $(f_{7/2})^2_{7,0}$ transition strengths for the individual transitions. On the other hand, the summed $L=6$ transition strength for the ^{51}V(d,α)^{49}Ti reaction as deduced from this analysis, corrected for the Q-value dependence, agrees very well with that of the $L=6$, $J=7$ transition strength of the 1.10-MeV transition in the ^{50}Ti(d,α)^{48}Sc reaction, which is believed to be relatively unfragmented.

There are candidates in the experimental spectrum for

TABLE II. Optical model parameters[a] used in DWBA calculations. Nonlocality parameters: $\beta_p=\beta_n=0.85$, $\beta_d=0.54$, $\beta_\alpha=0.2$.

	V (MeV)	r (fm)	a (fm)	W_v (MeV)	$4W_s$ (MeV)	r' (fm)	a' (fm)	r_c (fm)
d	84.0	1.20	0.75		84.1	1.26	0.68	1.2
α	198.1	1.20	0.75	14.5		1.73	0.56	1.3
p,n		1.20	0.75	$\lambda=25$				1.2

[a]Reference 14.

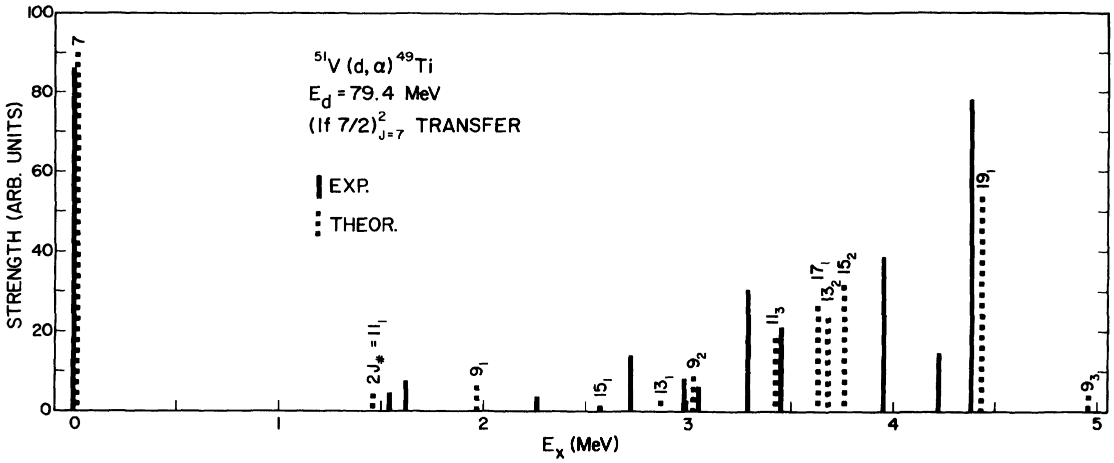

FIG. 8. Comparison of the $L=6$, $J=7$ transition strengths from the present ^{51}V(d,α)^{49}Ti experiment (solid lines) with those predicted from the $(1f_{7/2})^n$ model of Kutschera *et al.* (broken lines).

the third $\frac{11}{2}^-$, the second $\frac{13}{2}^-$, and $\frac{15}{2}^-$ theoretical states, but further information is clearly needed to make a one-to-one correspondence between the experimentally observed and theoretical states. We gain some information from a comparison of different reaction probes, since the selectivity of the (p,π^-) reaction is such that only a few states of the highest spin configurations will be excited strongly[12] (refer to Fig. 7). The association of the 4.4-MeV state in the (p,π^-) spectrum with the $\frac{19}{2}^-$ state at 4.38 MeV (Ref. 9) and predicted at 4.43 MeV in the $(1f_{7/2})^n$ model now seems certain, given the confirmed structural nature of these states deduced from the present (d,α) results. Similarly, the state at 3.3 MeV can be associated with the $\frac{17}{2}^-$ state at 3.29 MeV (Ref. 9) (predicted at 3.63 MeV). In the (p,π^-) spectrum this state should be suppressed (as observed) by the *jj* to *LS* transformation coupling coefficients.[12] The systematics suggest that the remaining strong state in the (p,π^-) spectrum at 4.0 MeV and the corresponding state in the (d,α) spectrum at 3.97 MeV is $\frac{15}{2}^-$, and hence should be associated with the second $\frac{15}{2}^-$ state predicted at 3.76 MeV (the location of the lower-lying $\frac{15}{2}^-$ state is known[6]).

V. SUMMARY

The ^{51}V(d,α)^{49}Ti reaction has been studied using 79.4-MeV vector polarized deuterons in order to locate transitions in which the proton-neutron pair is picked up in the stretched $(1f_{7/2})^2_{7,0}$ configuration. Such transitions are characterized by strong $L=6$ and $J=7$ admixtures in the angular distributions of the differential cross section and vector analyzing power. Since the ground state wave function of ^{51}V is predominantly $(\pi f_{7/2})^3$ with respect to ^{48}Ca as a core, states in ^{49}Ti reached by this $(1f_{7/2})^2_{7,0}$ pickup have large components of the 2p-1h $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration.

In our experimental analysis, ten strong, predominant $L=6$, $J=7$ transitions were identified leading to states at 0.00, 1.62, 2.72, 2.98, 3.05, 3.29, 3.46, 3.97, 4.22, and 4.39 MeV and two transitions with lesser $L=6$, $J=7$ strength leading to the states at 1.54 and 2.26 MeV. It is suggested that these states have significant components of the 2p-1h $[(\pi f_{7/2})^2(\nu f_{7/2})^{-1}]$ configuration with spins ranging from $\frac{7}{2}^-$ to $\frac{19}{2}^-$. The present results tend to confirm the conjectures for the structural nature of states at 3.3, 4.0, and 4.4 MeV which are strongly excited in the ^{48}Ca(p,π^-)^{49}Ti reaction.[4]

Microscopic DWBA calculations based on the $(1f_{7/2})^n$ shell model wave functions of Kutschera *et al.*[10] were carried out and compared to the experimental $L=6$, $J=7$ transition strengths. Although the relative strengths for some individual transitions were not satisfactorily reproduced, the summed transition strength was well accounted for compared to the $L=6$, $J=7$ transition strength in the ^{50}Ti(d,α)^{48}Sc reaction leading to the 7^+ state at 1.10 MeV. The $(1f_{7/2})^n$ model is not able to reproduce the $L=4$, $J=5$ transition strength for the ^{50}Ti(d,α)^{48}Sc reaction leading to the 5^+ state at 0.13 MeV. Here small admixtures of the pickup of the proton-neutron pair in the stretched $(1f_{7/2},2p_{3/2})_{5,0}$ configuration, which yields a differential cross section about an order of magnitude larger than the $(1f_{7/2})^2_{5,0}$ configuration, have to be taken into account.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge Professor R. Sherr for the communication of his ^{51}V(d,α)^{49}Ti data prior to publication and for many valuable discussions. This work was supported in part by the U.S. National Science Foundation.

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