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Spectroscopy of V^{50} with Direct (d, t) and (d, α) Reactions*

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About 50 levels of V^{50} below 3.2 MeV have been studied with 9- to 15-keV resolution via the $V^{51}(d,t)V^{50}$, $Cr^{52}(d,\alpha)V^{50}$, and $Ti^{48}(He^3,p)V^{50}$ reactions. Angular distributions were taken (at 16 MeV) for the $V^{51}(d,t)$ reactions and (at 17 MeV) for $Cr^{52}(d,\alpha)V^{50}$. (d,t) and (d,α) l values were extracted by comparison with distorted-wave Born-approximation calculations. For most of the levels seen, direct-reaction selection rules lead to narrow limits for the final-state spins, and in a few cases to unique J^π assignments. The spectroscopic information for the lowest levels was compared with shell-model predictions, and qualitative agreement was found. The lowest negative-parity states seen were above 2 MeV. Little $2p$ strength was found in the pickup experiments, and strong suppression of (d,α) transitions to $J^\pi=(\text{even})^+$ states suggests that the low-lying states of V^{50} are predominantly of $(f_{7/2})^n$ configuration. However, a comparison with the (d,α) spectrum for the particle-hole conjugate nucleus Sc^{46} shows that these nuclei are more dissimilar than a simple $(f_{7/2})^n$ model would suggest.

I. INTRODUCTION

The low-lying states of the odd-odd nucleus V^{50} have been described in simple shell-model terms as having the configuration $[(f_{7/2})_p^3(f_{7/2})_n^{-1}]_{J+}$ and this assumption formed the basis of a theoretical treatment by McCullen, Bayman, and Zamick (MBZ).[1] In this description the particle-hole conjugate nucleus Sc^{46} is predicted to have the same spectrum as V^{50} for positive-parity states. A previous $V^{51}(p,d)V^{50}$ study showed[2] that the $f_{7/2}$ spectroscopic strengths of the low-lying states in V^{50} have a distribution which is quite similar to the theoretical prediction. A more detailed comparison could not be made, because the V^{50} spins were not known except for the ground state. More recently, a $Ti^{50}(p,n\gamma)V^{50}$ study[3] has suggested spin assignments for the first four excited states of V^{50}, and a $V^{50}(p,p')$ study has determined the energy levels of V^{50} with 8-keV resolution up to 3.75-MeV excitation.[4]

In this paper, we report independent level-energy assignments up to about 3.2-MeV excitation, as well as detailed $V^{51}(d,t)V^{50}$ and $Cr^{52}(d,\alpha)V^{50}$ angular distributions for about 50 of these levels.[5]

II. EXPERIMENTAL PROCEDURES

A. Energy Assignments

Four high-resolution $Cr^{52}(d,\alpha)V^{50}$ spectra were taken with photographic plates in the focal plane of the Pittsburgh split-pole spectrograph. Three of these were taken at $E_d=12$ MeV with $\theta=12$, 40, and 50° while one was taken at $E_d=17$ MeV for $\theta=12°$. In addition a $Ti^{48}(He^3,p)V^{50}$ spectrum was taken at $E_{He^3}=18$ MeV, $\theta=12°$. Excitation energies were calculated using a computer code which is based on an empirical calibration of the spectrograph. As a check, a $Cr^{52}(d,\alpha)V^{50}$ spectrum and a $Cu^{63}(d,\alpha)Ni^{61}$ spectrum were taken on the same plate with identical focal-plane settings, and the well-known[6] levels of Ni^{61} were used for calibration. Good internal agreement was obtained for level energies based on these different methods. Our final level energy assignments were based on a weighted average with more weight given to the Ni^{61} comparison spectrum method than to the others. The estimated systematic (scale) uncertainty is $\lesssim 0.2\%$. One of the (d,α) plate spectra is shown in Fig. 1. Independent level energies were obtained from $V^{51}(d,t)V^{50}$. Although these measurements provided superior resolution (~9 keV), (d,t) energies are listed only for close-lying doublets, since the position-sensitive counter calibrations[7] were subject to larger errors. The V^{50} excitation energies obtained are listed and compared with other work[3,4,8-10] in Table I. The weighted energy averages fall well within the errors of our (d,α) excitation energies and are used in all other tables and figures.

B. $V^{51}(d,t)V^{50}$ Angular Distributions

The $V^{51}(d,t)V^{50}$ reaction was investigated at a

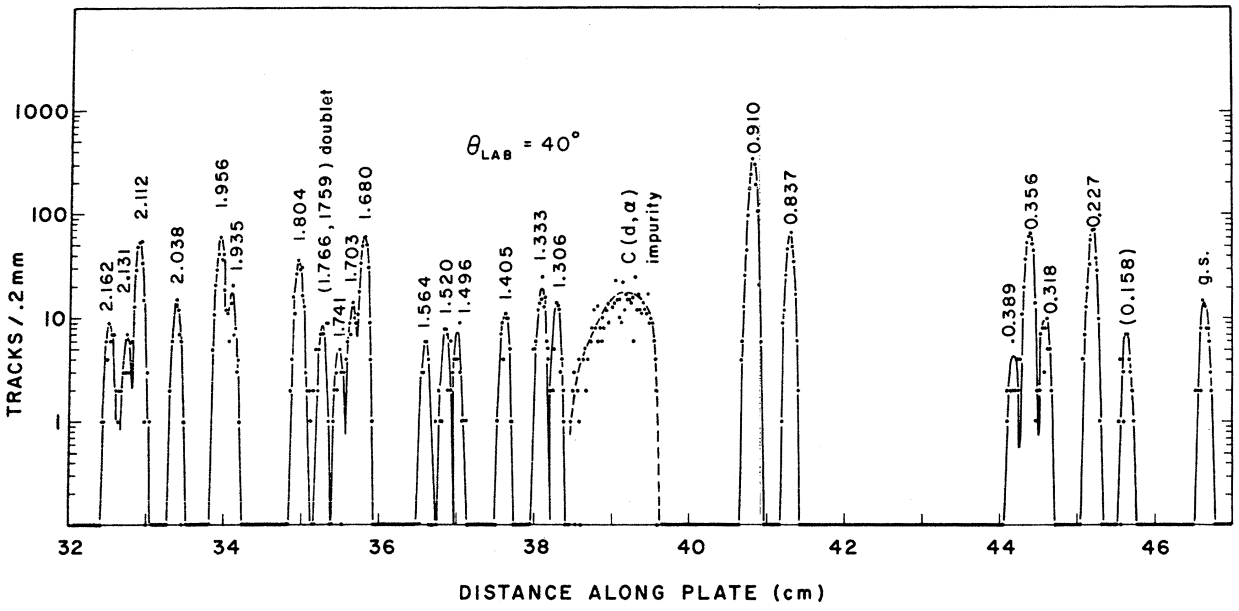


FIG. 1. A $Cr^{52}(d,\alpha)V^{50}$ photographic plate spectrum typical of those taken for excitation energy measurements. Position-counter spectra for E_d =17 MeV used for angular distributions had similar resolution, better statistics and some counter dependent energy nonlinearities. The "level" near 158 keV was barely visible for the 17-MeV data.

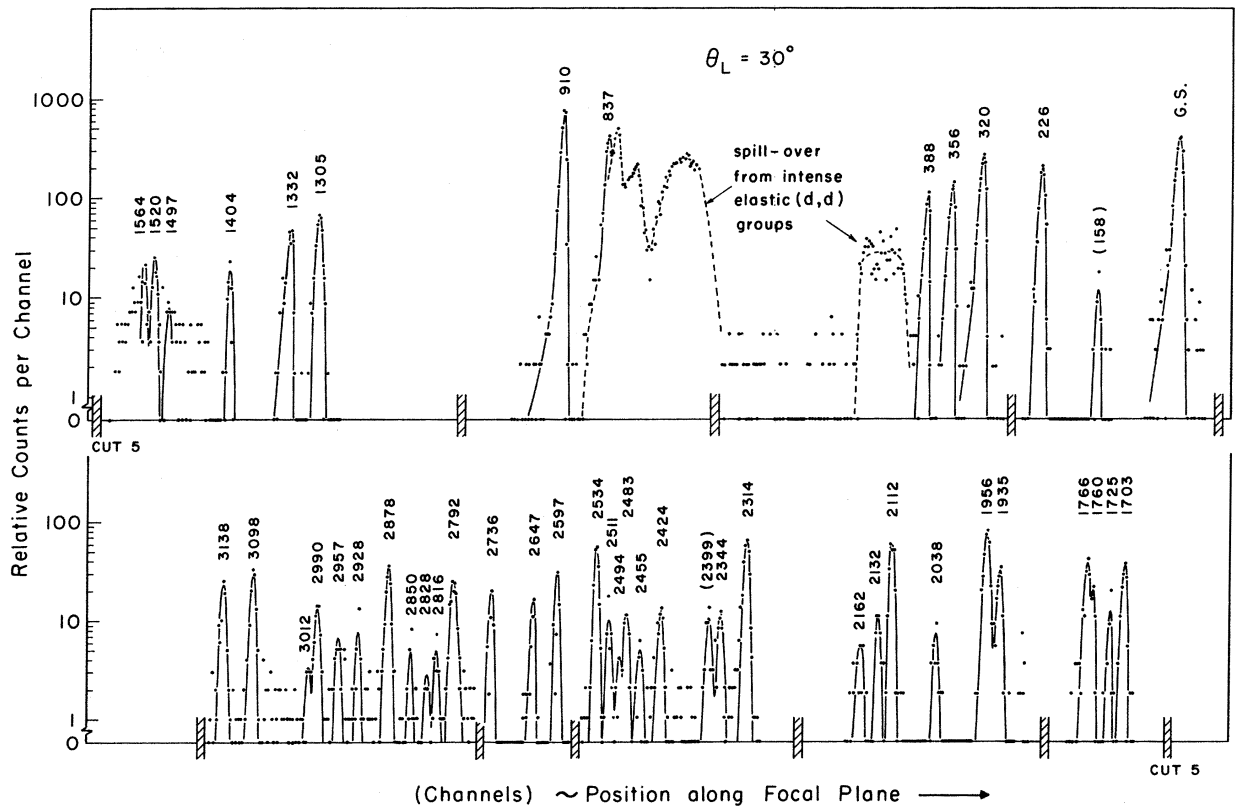


FIG. 2. $V^{51}(d,t)V^{50}$ spectrum for θ_L =30° obtained with four position-sensitive counters in four overlapping runs. Vertical bars along abscissa indicate junctions of the spectra of individual counters. The level energies (in keV) corresponds to values given in Table III. (Runs for the higher excitation regions were taken with larger beam exposures.)

TABLE I. Measured excitation energies of V^{50} in keV in comparison with previous studies.

Level No.	This work (d, α)	This work (He^3, p)	Ref. 4 (p, p')	Ref. 8 (p, p') (d, α)	Ref. 9 (d, d')	Ref. 10 [a] (He^3, d)	Ref. 3 $(p, n\gamma)$	Weighted average
0	0	(0)	0	0	0	0	0	0
	(158)	(144 ± 10)	...	...	...		(159.2)	
1	227 ± 2	(227 ± 10)	228 ± 5	228 ± 3	229 ± 3	226	226.2	226 ± 1
2	318 ± 3	weak	321 ± 5	320 ± 5	321 ± 3	318	320.1	320 ± 1
3	356 ± 2	358 ± 5	356 ± 5	359 ± 3	358 ± 10	350	355.2	356 ± 1
4	389 ± 3	389 ± 5	390 ± 5	394 ± 12	...	388	387.9	388 ± 1
	...	(449 ± 10)	...	...	...	...		
5	837 ± 2	...	838 ± 6	837 ± 12	839 ± 4	836		837 ± 2
6	910 ± 2	911 ± 5	912 ± 6	908 ± 4	912 ± 4	911		910 ± 2
7	1306 ± 3	1300 ± 10	1302 ± 5	1309 ± 5	...	1307		1305 ± 3
8	1333 ± 2	1331 ± 5	1330 ± 10	...	...	1347 (?)		1332 ± 2
9	1405 ± 3	1402 ± 5	1403 ± 6	1406 ± 12	...	...		1404 ± 2
10	1496 ± 3	1497 ± 6	...	1499 ± 12	...	...		1497 ± 3
11	1520 ± 4	1519 ± 6	1519 ± 6	...	...	...		1520 ± 4
12	1565 ± 4	1564 ± 6	1561 ± 6	1562 ± 12	...	...		1564 ± 4
13	1680 ± 3	1677 ± 10	...	...	...	...		1680 ± 3
14	1703 ± 4	1703 ± 6	1701 ± 6	...	...	...		1703 ± 4
15	(1741 ± 8)	1750 ± 10	1724 ± 6	1725 ± 4	...	...		1725 ± 4
16	1759 ± 8		1761 ± 5	...	1760 ± 4	...		1760 ± 4
17	1766 ± 8	weak	...	...	...	...		1766 ± 8
18	1804 ± 4	...	...	1808 ± 12	...	...		1805 ± 4
19	1935 ± 6	1934 ± 8	1937 ± 7		...	...		1935 ± 6
20	1956 ± 4	1950 ± 10	1957 ± 7		...	...		1956 ± 4
21	2038 ± 4	2037 ± 8	2038 ± 7		...	...		2038 ± 4
22	2112 ± 4	2103 ± 10	2112 ± 7		2112 ± 6	...		2112 ± 4
23	weak	2131 ± 8	2133 ± 7		...	...		2132 ± 7
24	2162 ± 5	2168 ± 10	2162 ± 6		...	...		2262 ± 7
25	2314 ± 4	weak	2314 ± 7		...	2300		2314 ± 4
26	2345 ± 5	2350 ± 8	2344 ± 7		2341 ± 6	2348		2344 ± 5
27	2400 ± 10	weak	2399 ± 8		...	...		2399 ± 8
28	2424 ± 4	2425 ± 8	2422 ± 7		(2419 ± 10)	2427		2424 ± 4
29	2455 ± 5	2453 ± 10	2456 ± 7		...	2467		2455 ± 5
30	2489 ± 8 [b]	...	2481 ± 7		2481 ± 6			2483 ± 6
31	2499 ± 8 [b]	...	2492 ± 7			...		2494 ± 7
32	2510 ± 5	2513 ± 10	2512 ± 6			...		2511 ± 5
33	2534 ± 5	2532 ± 10	2533 ± 7			2542		2534 ± 5
34	2596 ± 5	weak	2600 ± 7			...		2597 ± 5
35	2647 ± 8	...	...			...		2647 ± 8
36	...	...	2655 ± 9			2656		2655 ± 9
37	2735 ± 5	(2735 ± 12)	2738 ± 8			...		2736 ± 5
38	2760 ± 10	...	2763 ± 6			...		2763 ± 6
39	2792 ± 5	2782 ± 10	2792 ± 7			...		2792 ± 5
40	2818 ± 8	2816 ± 8	2815 ± 10			2814		2816 ± 7
41	...	n.r.	2828 ± 9			...		2828 ± 9
42	2850 ± 8	...	2849 ± 8			...		2850 ± 8
43	2878 ± 8	2876 ± 10	...			...		2878 ± 8
44	2923 ± 10	(2922 ± 10)	2931 ± 8			...		2928 ± 8
45	2955 ± 10	weak	2958 ± 9			...		2957 ± 9
46	...	...	2965 ± 9			2966		2965 ± 9
47	2990 ± 6	2989 ± 10	2992 ± 9 [c]			2996		2990 ± 6 [c]
48	3014 ± 10	weak	3011 ± 8			...		3012 ± 8
49	3098 ± 6	3090 ± 10	3099 ± 8			3101		3098 ± 6
50	...	...	3111 ± 8			...		3111 ± 8

TABLE I *(Continued)*

Level No.	This work (d, α)	This work (He^3, p)	Ref. 4 (p, p')	Ref. 8 (p, p') (d, α)	Ref. 9 (d, d')	Ref. 10 [a] (He^3, d)	Ref. 3 $(p, n\gamma)$	Weighted average
51	3136±6	3140±8	3142±8			3140		3138±6
52	•••	•••	3169±8			•••		3169±8
53	3200±8	weak	3202±8 [c]			•••		3201±8 [c]
54	3220±6	3216±8	•••			•••		3219±6

[a] The energy uncertainty is ±10 keV for Ref. 10.
[b] Energy values taken from our $V^{51}(d, t)$ data.
[c] Doublet.

bombarding energy of 16 MeV. The reaction products were analyzed by means of four position-sensitive detectors placed in the focal plane of the spectrograph. The beam geometry and electronic setup have been described elsewhere.[7] The multichannel analyzers were operated in the two-dimensional mode (XE vs E) in order to obtain the best possible separation between tritons and deuterons. The over-all energy resolution was 9–10 keV full width at half maximum (FWHM). Two NaI monitors were placed symmetrically at ±38° from the beam direction and were used for beam and target normalization. The target was isotopically enriched (>99.95%) in V^{51}, of about 30-μg/cm^2 thickness, and evaporated onto a carbon backing. A typical $V^{51}(d, t)V^{50}$ spectrum is shown in Fig. 2. The (d, t) angular distributions obtained are shown in Fig. 3. Error bars indicate random errors and are primarily due to counting statistics and uncertainties in background subtraction. The absolute scale error, due mainly to the elastic scattering normalization, is estimated at <±20%, and not shown in Fig. 3.

C. $Cr^{52}(d, \alpha)V^{50}$ Reaction

The $Cr^{52}(d, \alpha)V^{50}$ study was performed with a 17-MeV deuteron beam from the three stage Van de Graaff at the University of Pittsburgh. The reaction products were magnetically analyzed and detected with position sensitive detectors as described in Sec. 2, except that only one-dimensional spectra were stored. The total energy resolution was 15 keV. The Cr^{52} target was made by

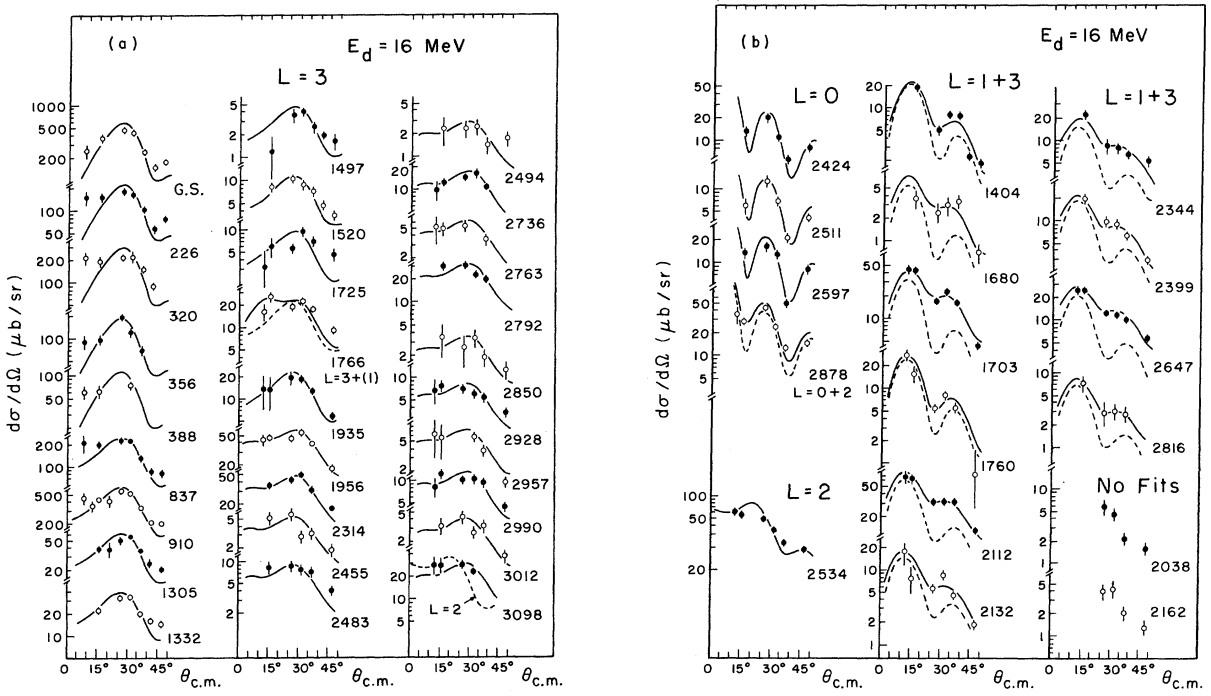


FIG. 3. (a), (b) Experimental and theoretical angular distributions for $V^{51}(d, t)V^{50}$ ordered by l value and excitation energy. The solid and dashed curves are zero-range DWBA calculations. The $l = 3$ data for levels below 1 MeV deviate at the smallest angles from the pure $l = 3$ DWBA curves shown. For the large deviations this is an indication of $l = 1$ admixture (not shown).

TABLE II. Optical-model parameters used for the (d, t) and (d, α) DWBA calculations.

Particle	V (MeV)	r_0 (fm)	a (fm)	W(vol) (MeV)	$4W_D$(surf) (MeV)	r_{i0} (fm)	a_i (fm)	r_C (fm)	Ref.
Tritons $Cr^{52}+t$	149.4	1.24	0.671	19.29	...	1.562	0.772	1.25	12
Deuterons $Cr^{52}+d$	91.76	1.147	0.705	...	48.11	1.33	0.771	1.30	This work
α	183.7	1.4	0.564	26.6	...	1.4	0.564	1.30	16
Bound nucleon		1.17	0.75	($\lambda_{so}=25$)				1.25	...

evaporation of (>99% isotopically enriched) Cr^{52} onto a carbon backing to a thickness of about 30 $\mu g/cm^2$. Additional runs for better cross section normalization were taken in our 18-in. scattering chamber at all angles but $\theta_L = 7$ and 12°, and solid-state detectors were used for the detection of reaction products and for monitoring. The 7 and 12° high resolution runs were normalized to a 30° run taken in direct succession in the spectrograph. The observed (d, α) angular distributions are shown in Fig. 4. The estimated uncertainty in the absolute cross-sections scale is less than ±10%, since $Cr^{52}+d$ elastic scattering cross sections were measured in this laboratory at 17 MeV, and could be used to calibrate the counter monitors.

III. DISTORTED-WAVE BORN APPROXIMATION ANALYSIS

A. $V^{51}(d, t)V^{50}$ Reaction

Distorted-wave Born approximation (DWBA) angular distributions for the $V^{51}(d, t)V^{50}$ reaction at 16 MeV were calculated by means of the code JULIE,[11] including a spin-orbit term. Several sets of optical parameters were tried with and without spin-orbit term for the bound state. In all cases, the shapes of the angular distributions were very similar, but variations were observed in the absolute cross sections. The sets of parameters finally used are shown in Table II. The triton parameters are based on the elastic scattering from Cr^{52} at $E_t = 20$ MeV.[12] The deuteron parameters are based on elastic scattering from Cr^{52} at $E_d = 17$ MeV, measured and analyzed in this laboratory. The experimental absolute cross section normalization was based on our deuteron elastic scattering data. As a cross check, average-fit deuteron parameters from the work of Perey[13] were used in test calculations; no significant difference was found between the elastic cross sections predicted at the monitor angle. DWBA curves were generated for several excitation energies, and the energy dependence of the cross sections was considered in extracting spectroscopic factors. The solid curves in Fig. 3 are DWBA curves calculated for an excitation energy within 0.5 MeV of the level studied.

B. $Cr^{52}(d, \alpha)V^{50}$ Reaction

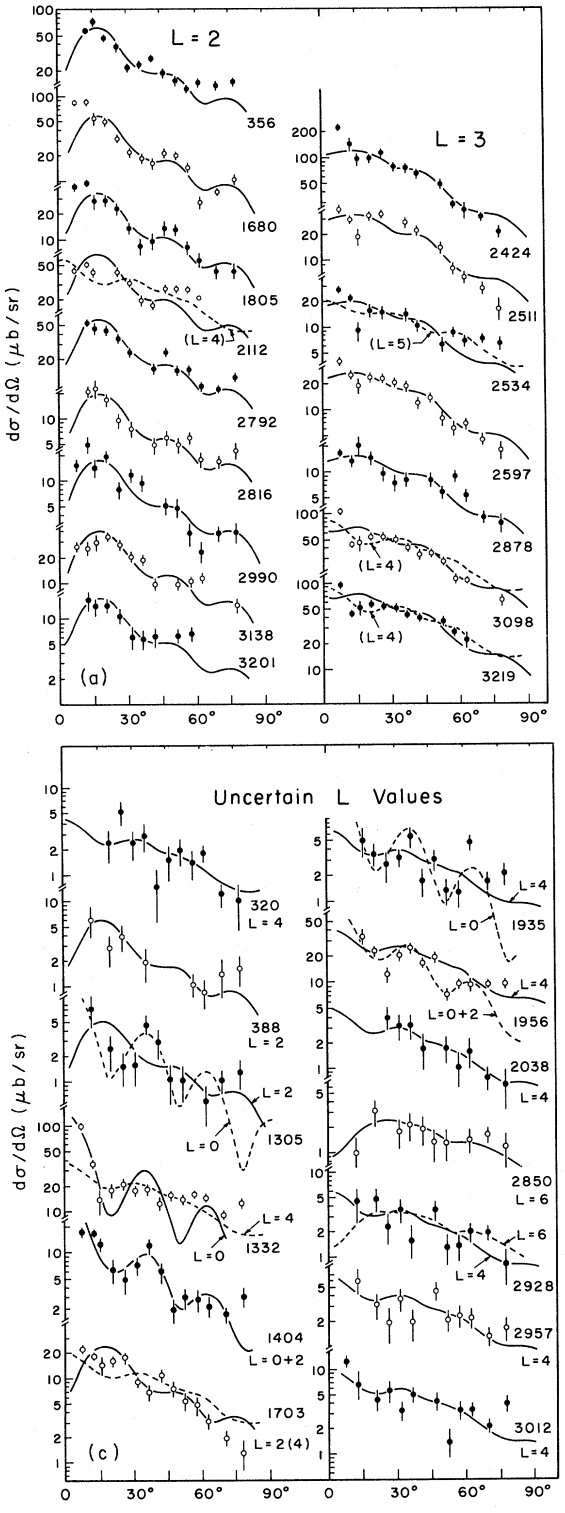
Code DWUCK[14] was used for the $Cr^{52}(d, \alpha)V^{50}$ calculations with the inclusion of finite range and nonlocality corrections. For this deuteron transfer reaction, code MIFF[15] was used to generate the two-nucleon form factor. The optical parameters used for the calculations are shown in Table II. The α parameters are taken from the work of Bock *et al.*[16] and fit a range of nuclei from $A = 48-52$ at $E_\alpha = 20$ MeV. Other deuteron and α elastic parameters were tried, and the shapes of the (d, α) angular distributions proved sensitive to the choice made. An exponential form was used for the finite-range correction, which corresponds to the assumption of a Gaussian shape for the nucleon-nucleon residual interaction and for the outgoing α particles. This first-order term was taken from the work of Chant and Mangelson[17] [Eq. 16] with the finite-range (F.R.) parameter $(4\epsilon^2)^{-1} = 0.36$ for the best fit to the data. This value is very close to the value determined[17] from the potential range and deuteron size parameter $[(4\epsilon^2)^{-1} = 0.4]$. The higher-order corrections, which are described in Ref. 17 were not included. In this approximation the Chant-Mangelson F.R. corrections resembled in size and effect those used earlier[6] although for V^{50} they gave better quantitative agreement with experiment. In contrast to the F.R. correction incorporated in code DWUCK, the exponential form has no singularities at higher values of the F.R. parameter. Nevertheless, the angular distributions were quite sensitive to the choice of this parameter. The solid curves in Fig. 4 are the DWBA calculations obtained as described above. Frequently, it was difficult on the basis of the Cr^{52}-(d, α) data alone to distinguish between $L = 3$ and $L = 4$, or $L = 4$ and $L = 5$. Hence for the fits shown in Fig. 4 the parity of the level [usually known from the (d, t) experiment] was used to choose between

TABLE III. Tabulation of experimental results, L assignments, spectroscopic factors, and max (d,α) cross sections. The J^π limits given are in agreement with the work of Ref. 10.

		$V^{51}(d,t)V^{50}$					$Cr^{52}(d,\alpha)V^{50}$		(He^3,d)		
Level No.	Energy (keV)	l_1	l_2	$C^2S_{l_1}$	$C^2S_{l_2}$	σ_{max} (μb/sr)	L dominant	$\sigma_{30°}$ (μb/sr)	Ref. 10 l_3	J^π limits	Best J^π
0	0	3	···	1.09	···	500	6	6.7	3	$5^+\,6^+\,7^+$	6^+
1	226	3	(1)	0.46	(0.02)	190	4	63.2	1 + 3	3^+–5^+	5^+
2	320	3	(1)	0.60	(0.03)	220	(0, 2, 4)	2.8	3	2^+–5^+	4^+
3	356	3	···	0.40	···	200	2	26.6	1 + 3	3^+ (2^+)	3^+
4	388	(3)[b]	···	0.24	···	(110)	(2)	3.3	3	1^+–7^+	(2^+)
5	837	3	···	0.64	···	230	4	41.9	···	3^+–5^+	(5^+)
6	910	3	···	1.72	···	580	6	206.2	3	7^+ (5^+)	7^+
7	1305	3	···	0.21	···	55	(0, 2, 4)	1.9	1 + 3	2^+–5^+	(2^+)
8	1332	3	···	0.13	···	35	0 + 2(4)	21.9	···	1^+–5^+	(1^+)
9	1404	(3)	(1)	0.01	0.005	19	0, (2)	5.3	···	1^+–3^+	
10	1497	3	···	0.02	···	4	?	≈2	···	1^+–7^+	
11	1520	3	···	0.04	···	11	?	≈2	···	1^+–7^+	
13	1680	3	(1)	0.01	0.001	4	2	26.6	···	$1^+\,2^+\,3^+$	
14	1703	3	1	0.07	0.01	45	(2, 4)	12.0	···	2^+–5^+	
15	1725	3	···	0.04	···	9	?	≈1	···	0^+–7^+	
16	1760	(3)	(1)	(0.01)	0.01	27	4	5.7	···		
17	1766	3	(1)	0.09	0.004				···	3^+–5^+	
18	1805	···	···	···	···	n.s.	2	18.6	···	1, 2, 3	
19	1935	3	···	0.10	···	20	(4 or 0)	2.7	···	1^+–5^+	
20	1956	3	···	0.27	···	54	(4 or 0)	16.0	···	1^+–5^+	
21	2038	(3, 2, 0)[b]	···	···	···	6	(4)	3	···		
22	2112	3	1	0.11	0.03	68	2(+4)	37.2	···	2^+–5^+	
23	2132	(3)	···	(0.04)	···	18	···	weak	···	···	
24	2162	(3, 2)[b]	···	···	···	4	···	≈10[b]	···	1–7	
25	2314	3	···	0.25	···	50	···	≈20[b]	1	2^+–5^+	
26	2344	(3)	1	0.03	0.01	22	···	≈3	1	2^+–5^+	
27	2399	(3)	1	0.03	0.01	20	···	weak	···	2^+–5^+	
28	2424	0	···	0.34	···	20	3	100	0	3^-4^-	
29	2455	3	···	0.03	···	6	4	15.3	1	$3^+\,4^+\,5^+$	
30	2483	3	···	0.05	···	9	(6)	22	···	1^+–7^+	
31	2494	3	(0)	0.01	···	2.5			···		
32	2511	0	···	0.30	···	13	3	26.6	···	3^-4^-	
33	2534	2	(0)	0.35	···	60	3, 5	15	0	3^-4^-	
34	2597	0	···	0.53	···	17	3	23.3	···	3^-4^-	
35	2647	3	1	0.06	0.01	25	(4, 6)	4.3	···	3^+–5^+	
36	2655	···	···	···	···	n.s.	···	n.s.	1	(2^+–5^+)	
37	2736	3	···	0.11	···	16	4, (6)	23.3	···	3^+–7^+	
38	2763	3	···	0.04	···	5	6(4)	≈6.0	···	3^+–7^+	
39	2792	3	···	0.21	···	32	2	30.0	···	$1^+\,2^+\,3^+$	
40	2816	(3)	(1)	0.01	0.005	7	2	8.6	···	$2^+\,3^+$	
42	2850	(3)	···	0.02	···	3.5	(6)	1.7	···	(5^+, 6^+, 7^+)	
43	2878	0	2	1.18	0.07	45	3	8.0	···	3^-4^-	
44	2928	3	···	0.06	···	8	(4, 6)	2.7	···	(3^+–7^+)	
45	2957	3	···	0.05	···	6	(4)	2.7	···	(3^+–5^+)	
46	2965	···	···	···	···	···	···	···	1 + 3	(2^+–5^+)	
47	2990[a]	3	···	0.09	···	11	2	9.3	···	$1^+\,2^+\,3^+$	
48	3012	3	···	0.03	···	4	(4, 6)	4.0	···	(3^+–7^+)	
49	3098	(3)	or (2)	(0.21)	(0.45)	29	3(4)	51.9	1	···	
51	3138	···					2	22.0	···	1^+, 2^+, 3^+	
53	3201[a]	···					(2)	6.7	···	($1^+\,2^+\,3^+$)	
54	3219	···					(3, 4)	57.2	···	(2–5)	

[a] Doublet.

[b] Insufficient number of data points for l determination.



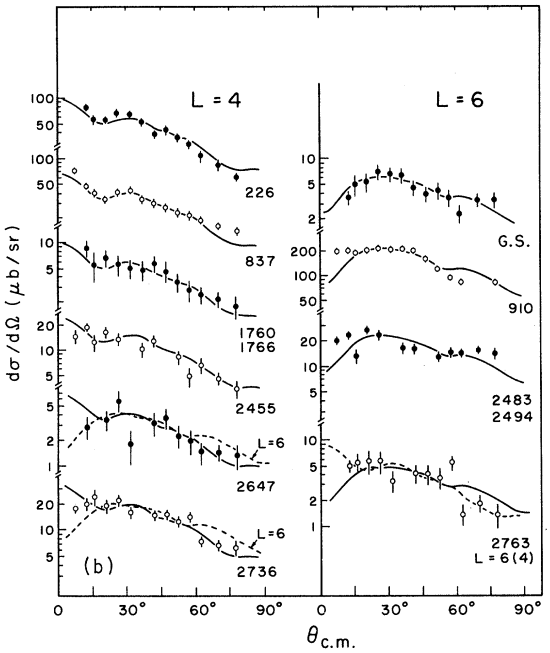


FIG. 4. (a)–(c) Angular distributions for $Cr^{52}(d,\alpha)V^{50}$ at $E_d = 17$ MeV, ordered by L value and excitation energy. Solid and dashed curves refer to DWBA calculations as described in the text. The error bars contain all known random errors.

an even or odd L calculation. It should also be noted that from the systematics of the data empirical L shapes can be found which, although they are close to the calculations, would fit the data somewhat better. Note for instance the small but persistent dip at ~15° for $L=3$ which is not reproduced by the DWBA curves. Such empirical aids were sometimes used in selecting one fit over another. Table III presents our $l(d,t)$ and $L(d,\alpha)$ assignments and lists (in brackets) such L values which, although not shown in Fig. 4 are not ruled out by the data.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

A. Energy Assignments

Our measured energy levels are given in the first two columns of Table I. Also shown are other determinations of these levels (Refs. 4, 8–10, 3), and in the last column, proposed assignments that constitute a weighted average. We see strikingly good agreement for almost all the levels given with the exception of the level which we assign as 1.741 MeV but which is independently assigned as 1.725 by two other groups. Normally, such a discrepancy is outside our errors, but as this level is extremely weak in (d,α) it is entirely possible that the (d,t) transition for which data are given goes to the 1.725-MeV state. Furthermore, four additional levels and two doublets, unresolved in our work, are found in this energy range by Ref. 4. The errors assigned to the excitation energies include the probable scale error. Generally, the difference of neighboring levels is accurate to about 2 keV.

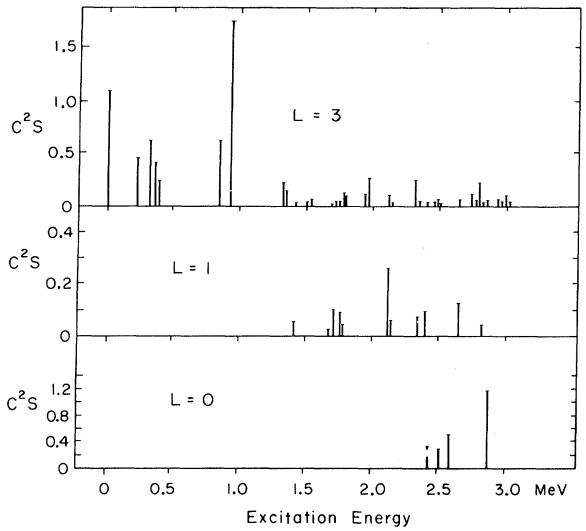


FIG. 5. Distribution of spectroscopic strengths for $V^{51}(d,t)V^{50}$.

B. $V^{51}(d, t)V^{50}$ Reactions

The spectroscopic strengths, C^2S were extracted from the data according to the formula

$$\sigma(\theta)_{\text{expt}} = \tfrac{2}{3} \times 5C^2S\sigma(\theta)_{\text{JULIE}}$$

which uses Bassel's[18] normalization. In Fig. 5, the distribution of spectroscopic strengths is plotted for various angular momentum transfers. In computing these, the value $j = l + \frac{1}{2}$ has been used so that $l=3$ refers to $f_{7/2}$, etc. The $l=2$ strength has not been plotted since only two or three levels were found with an $l=2$ component. We see that most of the $l=3$ strength is confined to levels below $E^* = 1.0$ MeV and that these are therefore presumably $(f_{7/2})^2$ states. Of special interest are the spectroscopic sums which measure the neutron-shell occupation probabilities in the ground state of V^{51}. The "valence" neutrons in V^{51} form a closed $f_{7/2}$ shell so that most of the strength is expected to be $l=3$. Table IV gives the sums and occupation probabilities. Apparently, all important $s_{1/2}$ transfers have been found. The $2s_{1/2}$ strength is exhausted by the four levels seen while the $1d_{3/2}$ levels are just beginning to emerge. The $f_{7/2}$ shell is essentially full; the next higher shell $(2p)$ is only 2–3% full.

TABLE IV. Sums of $V^{51}(d,t)V^{50}$ spectroscopic factors and measured fullness of active single-particle levels.

l transfer	Orbital	$\sum C^2S(l)$	$V_j^2(T=2)$
0	$s_{1/2}$	2.34	~(1.4)
1	$p_{3/2}$	0.094	0.02
2	$d_{3/2}$	0.97	>0.3
3	$f_{7/2}$	7.4	0.99

In Table V, a comparison is made between the larger $l=3$ spectroscopic strengths measured in this experiment with previously obtained values.[2,19] Although the agreement in absolute values is only fair, the measurements agree quite well in relative values. Also shown is a comparison with MBZ predictions[1] which is made on the basis of corresponding J^π values, not energy values. The spins given are suggested values based on this work and on Ref. 3. The MBZ spectroscopic strengths agree well with experiment, except for the 4^+ and 2^+ levels. The 2^+ strength is not found dominantly in the lowest state as predicted, but appears distributed about equally over two states, while the 4^+ levels and strengths appear to be higher and more split than expected.[1]

Figure 6 shows a more detailed comparison between this experiment and MBZ theory. Again the experimental J^π assignments include some tentative values. We see two 5^+ levels where predicted, as well as a group of 2^+, 3^+, 4^+ levels around 0.3 MeV which corresponds fairly well in energy to a similar theoretical group. The strong 7^+ level is 300 keV lower in energy than expected, as is the (1^+) level. The experimental levels which could correspond to the second 4^+ level in MBZ seem to lie much higher in energy. It is tempting to suggest that the level at 1.305 MeV is the second 2^+ state.

Bruge *et al.*[20] report significant $(f_{7/2})^2$ strength

TABLE V. Comparison of predicted and measured spectroscopic factors for $(f_{7/2})^n$ levels of V^{50}. The experimental data are grouped by energy level E^*; the calculated level sequence is changed somewhat in order to correspond to the measured order of J^π values. (Compare Fig. 6).

E^* (keV) expt.	J^π	C^2S Theory[1] MBZ	C^2S (measured) This expt.	S [a]	S [b]
0.0	6^+	1.14	1.09	0.89	1.00
226	5^+	0.53	0.46	0.36	0.42
320	4^+	0.27	0.63	0.57	0.64
356	3^+	0.39	0.40	0.36	0.36
388	2^+	0.46	0.24	0.24	0.21
837	5^+	0.64	0.64	0.64	0.65
910	7^+	1.69	1.69	1.70	1.71
1305	(2^+)	0.08	0.08	0.16	0.21
1332	(1^+)	0.14	0.14	0.16	0.15

[a] Ref. 2, renormalized by 1.07.
[b] Ref. 19, renormalized by 0.64.

near 1.27 MeV which they interpret as 1^+. Allowing for an energy scale error in Ref. 20 of about 3%, inadequate resolution (80 keV) and a considerable similarity of (He^3, t) transitions to 1^+ and 2^+ states, it appears likely that the doublet at 1305 and 1332 keV is comprised of a 2^+ and 1^+ state, in this order. The 1^+ assignment is supported by our (d, α) angular distribution, while the 1305-keV level is so weak in (d, α) that we can only give the limits $2^+ - 5^+$. However, the weak (d, α) cross section together with the strong (d, t) $l=3$ transition indicate a $(f_{7/2})^2_{J=\text{even}}$ state, hence $J^\pi = 2^+$ is a very compelling choice. We agree with Ref. 20 in the assignment of the strong 7^+ state; however, poor resolution spoiled the earlier interpretation[20] for levels 1, 2, 3, and 4 (which were analyzed as only 3 levels at incorrect energies). The Ti^{50}-$(p, n\gamma)V^{50}$ data of Ref. 3 help remove any doubts about the 5^+, 4^+, 3^+, 2^+ assignments for levels 1 through 4.

C. $Cr^{52}(d, \alpha)V^{50}$ Reaction

In addition to the familiar direct reaction spin-parity selection rules, the (d, α) reaction has a selection rule which forbids the excitation of J = even states with pure $(j^2)_J$ configurations.[21] Owing to the high $l=3$ spectroscopic strengths in (d, t) of the levels below 1 MeV, these states are expected to have dominant $(f_{7/2})^2$ configurations so that the $(j^2)_{J=\text{odd}}$ rule should apply for states strongly excited in (d, α). Theory also predicts that, where two L values contribute in the absence of extensive configuration mixing, the lower L value should dominate.

We see that the ground state, the 0.320-, 0.388-, and 1.305-MeV states are very weak in (d, α) so that $J = L =$ even is likely while for the remaining states below 1.4 MeV, $J = L + 1 =$ odd is indicated. This is the basis for the tentative J^π assignments given in Table III. The known ground-state spin-parity of 6^+ is reconfirmed while the next three level assignments are in perfect agreement with Ref. 3. The assignment of (1^+) to the 1.332 level appears unique, because $L_{d,\alpha} = 0$ means $\Delta J = 1$. The spin-parity limits given in column XI of Table III are based only on the (d, t) and (d, α) selection rules, without consideration of spectroscopic strengths.

In the MBZ theory, the particle-hole conjugate nucleus Sc^{46} should have the same spectrum as V^{50} for positive-parity states. In Fig. 7 a comparison is made between this (d, α) study and a $Ti^{48}(d, \alpha)$-Sc^{46} study at 17 MeV.[22] Only the low-lying positive-parity states are shown. The J^π assignments in brackets are tentative values. The correspondence in absolute cross sections is quite good for the lowest 1^+, 2^+, 3^+, 6^+, and 7^+ states, but agreement for the 4^+ and 5^+ excitations and their level energies is not satisfactory. The 6^+ level, which is the ground state in V^{50} is close to the ground state in Sc^{46}. While there are two 5^+ levels in V^{50}, there appears to be only one strong 5^+ level in Sc^{46}, although an additional 5^+ level appears at about the right energy in $Ti^{47}(d, He^3)Sc^{46}$.[23] The low lying 4^+ level in V^{50} should correspond to the 4^+ ground state of Sc^{46}. An additional low-lying positive-parity level has been found in Ti^{47}-

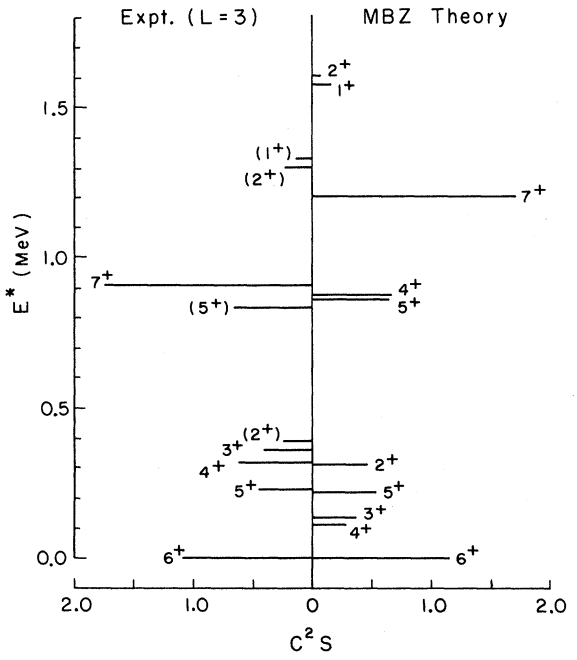


FIG. 6. Comparison of measured and predicted (MBZ) $l = 3$ spectroscopic factors for the low-lying levels of predominantly $(f_{7/2})^n$ configuration. The predicted and measured level energies are displayed along the ordinate.

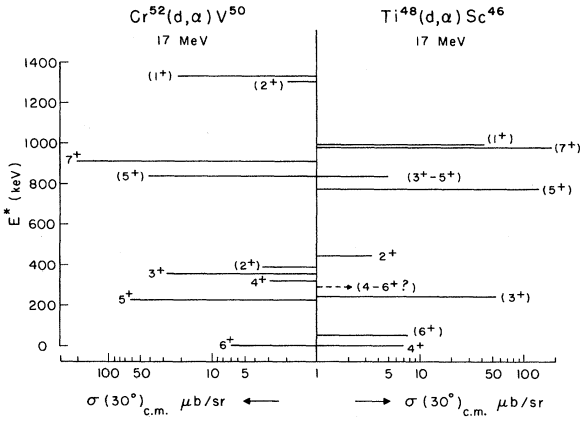


FIG. 7. Comparison of (d, α) population of the low-lying states of V^{50} and its particle-hole conjugate nucleus Sc^{46}.

$(d, He^3)Sc^{46}$ at 1.121 MeV and has been assigned $J^\pi = 2 \rightarrow 4^+$.[23] Thus, the number and kind of low-lying positive-parity levels in V^{50} and Sc^{46} seem to agree well. Although unambiguous J^π assignments have only been made for some of these levels, it is clear on the other hand that discrepancies exist in detail, particularly for the 4^+ and 5^+ states.

V. CONCLUSIONS

The angular distributions and extracted relative spectroscopic factors of the (d, t) transitions proved quite insensitive to different choices of the optical potentials and to the presence or absence of F.R. and nonlocality corrections and are in good agreement with similar data, where they exist.[2,19] Few ambiguities remain in the (d, t) results, which show good qualitative agreement with the MBZ[1] predictions.

DWBA predictions for (d, α) angular distributions are quite sensitive to F.R. corrections as well as to the optical parameters chosen. It appears that further work on F.R. effects for this two-nucleon transfer problem is needed, for the contributions from the nuclear interior have large effects on the calculated differential cross sections. These effects are not easily simulated by configuration mixing or other justifiable changes of the two-nucleon form factors. Although reasonable fits for the (d, α) data were obtained, the predictive value of DWBA was moderate. As a consequence, the results of these (d, α) calculations were used more in a qualitative than quantitative way; nevertheless, the extraction of L transfers for (d, α) was usually possible. The observed suppression (by an order of magnitude) of states believed to have $(f_{7/2})^n_{J=\text{even}}$ configurations[1] must be considered a rather sensitive indication of the relative purity of the $(f_{7/2})^2$ configuration for the low-lying states in V^{50}.

VI. ACKNOWLEDGMENTS

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