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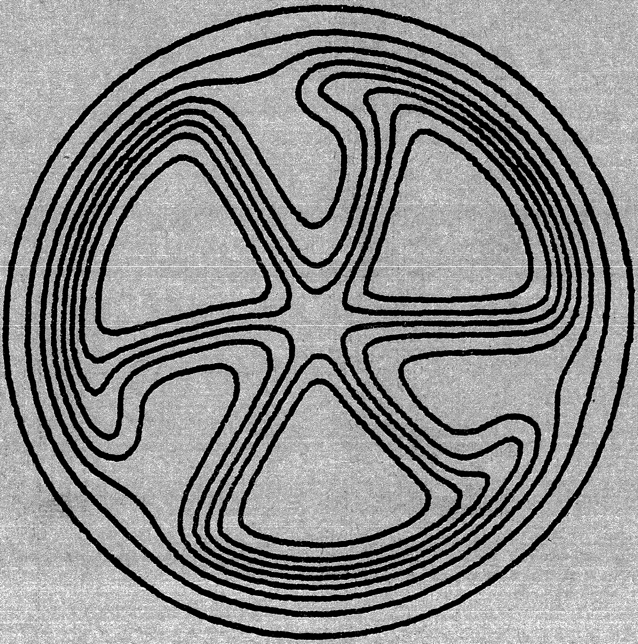

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Study of ^{48}V with the ^{50}Cr(p,^{3}He) Reaction at 44.7 MeV

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ABSTRACT

The ^{50}Cr(p,^{3}He)^{48}V reaction has been studied at 44.7 MeV for levels with an excitation energy up to 3.7 MeV. A distorted-wave Born approximation analysis permitted several L assignments. A comparison with available information on ^{48}V is made.

NUCLEAR REACTION: ^{50}Cr(p,^{3}He), E_p=44.7 MeV; measured $\sigma(E_{^3He},\theta)$; enriched target. Deduced energies, L-values of ^{48}V levels.

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I. INTRODUCTION

Studies of the ^{48}V nucleus have been quite extensively performed during the last few years by means of the single nucleon transfer reaction ^{47}Ti(^{3}He,d)[1] and the two-nucleon transfer reactions (d,α)[2,3] and (^{3}He,p)[2,4]. In the ^{47}Ti(^{3}He,d) reaction ℓ_p-values and spectroscopic factors were extracted. The ^{50}Cr(d,α) reaction was performed by Dorenbusch, *et al.*[2] at 7 MeV bombarding energy. Only excitation energies were obtained in this work, whereas several L-transfers for levels below 2.0 MeV were obtained by Bachner, *et al.* in a (d,α) experiment at 15 MeV bombarding energy. The two nucleon stripping experiment (^{3}He,p) has been performed by Dorenbusch, *et al.*[2] at 12.0 MeV and by Smith, *et al.*[4] at 17 MeV. In the latter case, the emphasis was on 1^+ states. The ^{48}V level scheme has also been investigated by means of the charge exchange reaction (^{3}He,t).[5,6] Studies involving γ-rays have been performed mainly by three groups: Huber, *et al.*,[7] Taras, *et al.*[8] and Samuelson, *et al.*[9] They have been able to give several spin parity assignments, and some high-spin states have been reported. Moreover an odd parity rotational band constructed on a low-lying 1^- level at 519 keV has been reported by Haas and Taras.[10] Recently a second rotational band built on a 4^- state at 1099 keV has been proposed by Samuelson, *et al.*[9] This latter state was identified by Taras, *et al.* as a 5^+. Since other discrepancies exist besides this one in the information available on ^{48}V, it was felt to be of interest to add information from a study of the ^{50}Cr(p,^{3}He) reaction. Moreover, due to the special features associated with this type of reaction, there is unique information to obtain. Theoretical studies[11,12] of the ^{48}V nucleus have employed the shell-model framework with only $f_{7/2}$ particles. No theoretical studies of the rotational bands have yet been made.

II. EXPERIMENTAL PROCEDURE

A 44.7 MeV proton beam of the Michigan State University Cyclotron bombarded a ^{50}Cr target enriched to 96.8%. Its thickness was 80 μg/cm^2, and it was prepared by vacuum evaporation on a carbon backing of 30 μg/cm^2. The outgoing ^{3}He were momentum analyzed in an Enge split-pole spectrograph. They were detected and identified by a wire counter and plastic scintillator combination placed in the focal plane.[13] The angular aperture of the spectrograph in the reaction plane was 2° except for angles below 16° where it was 1°. A typical energy spectrum is shown in Fig. 1. The resolution ranged from 30 to 35 keV. For some regions of the spectra, it was necessary to use the peak fitting program SAMPO[14] in order to determine the area of unresolved peaks. The angular distributions were measured between 6° and 58°; they are displayed in Fig. 2. Only statistical uncertainties are included in the error bars. The absolute cross-section determination was made by reference to the elastic scattering using an identical experimental configuration. The elastic scattering of protons on ^{50}Cr was measured between 20°-50°, and the cross-sections were then computed from the parameters of Bechetti and Greenlees[15] (with r_R=1.17). The ratio between elastic cross-sections and measured number of counts give the normalization factor needed to obtain the absolute (p,^{3}He) cross-section. The accuracy of the absolute differential cross-section

is estimated to be about 20%. The agreement with target thickness determination by means of energy loss of ^{241}Am α-particles was good.

III. DISTORTED WAVE ANALYSIS

The analysis of the experimental angular distributions has been carried out with the two-nucleon option of code DWUCK[16] in the zero-range approximation. The form factor was calculated according to the Bayman-Kallio method.[17] Optical parameters are the same as those used in Ref. 13. Several others sets have been tried without improving the quality of the fit to the data. Transitions leading to the ground state (4^+), 304 keV(2^+), 1252 keV(7^+) and 3014 keV(0^+) levels have been used for selecting the optical model parameter set. The bound state wave function of the transferred neutron and proton has been computed in, Woods-Saxon well with parameters r_o=1.20 fm a_o=0.65 fm. The shape of the angular distributions does not change with variation in r_o and a_o. The calculated angular distributions and the corresponding experimental ones are displayed on Fig. 2. It can be seen that they are in reasonable agreement. Nevertheless, one has to note that the transitions which involve a single L-transfer are not perfectly reproduced by the DW-calculations. For example, the theoretical L=4 curve does not account well for the ratio between the first maximum and first minimum of the experimental cross-section to the ground state. The same remark is also valid for the L=2 transition to the 304 keV level. The calculated L=0 curve does represent correctly the 3014 keV level below 40° but fails for the second maximum around 45°, which is predicted too low. Such an observation has also been made by Daehnick, et al.[18] in the case of a (p,t) and (p,^{3}He) experiment on ^{48}Ca. This fact has the consequence that it is difficult to obtain good fits to the unnatural parity states of mixed L values. The Q-effect on the angular distribution shape is not negligible as one can see for example by looking at the L=4 shape for the transition to the ground state and levels at 3582 and 3630 keV.

IV. RESULTS AND DISCUSSION

Our experimental results, L-value assignments and other existing information on ^{48}V are listed in Table I. Our energy scale was established by using the ground state position and two other peaks, the excitation energy of which have been accurately determined in γ-experiments: 1254.3 keV[8] and 3019 keV[4]. The uncertainty in the energy is estimated not to exceed 10 keV. One can see that the agreement with the excitation energies given for low lying levels in γ-ray work[8,9] is excellent. The excitation energies observed by various transfer reactions agree generally within 20 keV, except for a few levels.

A. $\pi f^{3}_{7/2}$ $\nu f^{-3}_{7/2}$ Levels

The low-lying positive parity states of ^{48}V are expected in the simple shell model picture, to be constructed on a $\pi f^{3}_{7/2}$ $\nu f^{-3}_{7/2}$ basis. In Fig. 3., the low-lying level scheme of the positive parity states of ^{48}V is shown as determined by the recent experiments. We also display one of the calculated energy spectra taken from Ref. 7. (Other calculated levels schemes do not differ strongly from this one except that they may have a slightly different ordering). We have attempted tentatively to find the correspondence between observed and calculated levels. It seems that most of the levels predicted have been observed except for one 3^+ state at 1110 keV (it might be the 1333 keV level observed in Ref. 6.). One can note that the ground state and first excited state are inverted in the calculation as compared to the experimental position. Nevertheless, the overall agreement is qualitatively good. Due to the fact that the $f^{-8}_{7/2}$ multiplet produces close doublets, observation of all the levels allowed by the selection rules of the (p,^{3}He) reaction has been prevented by insufficient energy resolution. But, fortunately, it seems that in general one member of the doublet is much more strongly excited than the other. For example, there exist two levels with 7 keV spacing at 417 keV which have spins of 1^+ and 5^+. Our experimental angular distribution leads us unambiguously to an L=0+2 assignment. The same is true for the 7^+-5^+ doublet at 1252 keV; our data agrees nicely with an L=6 shape therefore selecting the 7^+ state. Such a state is favored by its large structure coefficient and its spectroscopic factor (which is proportional to 2J+1). In the case of the 4^+-6^+ doublet at 614 keV the situation is less clear, but our data seems to agree better with an L=4 shape. For states belonging to an $(j)^n$ multiplet, it has been shown[13,19] that a comparison of the cross-section of (d,α) and (p,^{3}He) is of great help in J^π assignments. Unfortunately the existing (d,α) works do not permit such a comparison. The (d,α) work of Dorenbusch, et al.[2] does not give any L assignment. Moreover the incident beam energy is low (7 MeV), and it is very likely that contributions of compound nucleus processes are present. The (d,α) experiment of Bachner, et al.[3] does not give any absolute cross-section and is limited to levels below 2.0 MeV, where most of the spins are now known. It is not possible on the basis of the present experiment by itself to give any precise spin value for levels at 1680, 1729, and 1778 keV which may belong to the $f^{-8}_{7/2}$ multiplet. A comparison with the (^{3}He,t) results of Manthuruthil, et al.[6] gives a probable 5^+ for the 1729 keV level. However, discrepancies exist for the 1778 keV; the (^{3}He,t) experiment favors a 3^+ or 4^+ assignment (in agreement with $3^{(+)}$ values proposed by Samuelson, et al.[9]) but our results agree better with an L=6 angular distribution and thus with a spin value between 5 and 7. Smith et al.[4] have studied 1^+ states by means of the (^{3}He,p) reaction and have compared them with some shell model calculation, also in the $f^n_{7/2}$ scheme. In particular, they identified the experimental 1^+ states at 2280, 2397 and 3700 keV as the ones which were calculated theoretically. These levels have also been observed in our (p,^{3}He) experiment. Assuming pure $f^n_{7/2}$ configuration for target and final nuclei, one can show that the ratio, R, of experimental to theoretical cross-section should be the same for both (p,^{3}He) and (^{3}He,p) reactions. In order to avoid normalization problems, we have calculated r=R(p,^{3}He)/R(^{3}He,p), and this number should be the same for all states. In addition, we have also computed the same ratio for the analog of the ground state of ^{48}Ti, which lies at 3014 keV and which is strongly excited in both stripping and pickup reactions. The results are displayed in Table II; they have been computed at an angle of 7°, and using the (^{3}He,p) data of Smith, et al.[4] One can see that for the analog state and the 417 and 2280 keV levels this ratio is constant within a factor of two. This indicates that these levels are good candidates for the $f^n_{7/2}$ configuration. The case of the 2397 keV is rather special: the fit to the data necessitated the introduction of a large L=2 component, more than is predicted by a simple $f^2_{7/2}$ transfer. The fact that the ratio computed in Table II with only a $f^2_{7/2}$ transfer is within the range 0.5 - 1.1 is thus fortitious. The value of r (0.09) for the 3700 keV level excludes definitively a simple $f^{-8}_{7/2}$ structure. This level is very strongly excited in the (^{3}He,p) spectrum, and it is likely that some 2p transfer occurs. The only other level for which such comparisons between (^{3}He,p) and (p,^{3}He) can be done is the 2^+ state at 304 keV. The value of r reported in Table II has in this case been determined for an angle of 18.5°. It lies in the 0.5 - 1.1 range, and this level, which has been predicted in the $f^{-8}_{7/2}$ calculations, seems to display mainly this structure.

B. Negative Parity States

Low-lying levels of negative parity have been observed mainly by γ-rays experimiments.[7,8,9] However, our (p,^{3}He) experiment was able to confirm some of the γ-ray assignments.[5,6,7] A rotational band based on the 1^- state at 519 keV has been proposed by Taras, et al.[8,10] with a $\pi d^{-1}_{3/2} \pi f^4_{7/2}\ \nu f^5_{7/2}$ configuration. Some of the levels belonging to such a band can be observed in our experiment as an odd-L transfer. The 1^- state at 519 keV is not seen in our spectra as can be expected from the proposed structure. Three other members with 2^-, 3^-, and 4^- spins, respectively, at 745, 1052, and 1550 keV are well represented by the required odd-L transfer as can be seen in Fig. 2. The 519 and 1052 keV levels have been observed in the (^{3}He,d) experiment of Dorenbusch, et al.,[1] but the ℓ=3 assignment is apparently incorrect. As was pointed out by Huber, et al.,[7] an $\ell=2$ distribution is also compatible with their data. The higher spin members (5,6,7) of this band, which have been proposed by Taras, et al., have not been observed in our experiment. This is expected for the spin 6 and 7 members. The 5^- state at 2063 keV, although allowed in $(p,{}^3He)$ assuming the proposed $d^{-1}_{3/2}\ f^{9}_{7/2}$ structure, is not significantly excited in our spectra.

A second negative parity band has been proposed recently by Samuelson, et al.[9] It is based on the 1097 keV level to which they give a 4^- spin parity assignment. This level, has been previously identified by Huber, et al. as a probable positive parity state with spins ranging from 3 to 5, and a more definite 5^+ value has been given by Taras, et al. In direct reactions, this level is observed in $({}^3He,d)$ $({}^3He,p)$, (d,α) and $(p,{}^3He)$ experiments. The $\ell=3$ angular distribution in $({}^3He,d)$ may favor a positive parity assignment, but again the ambiguity between $\ell=2$ and $\ell=3$ shape made this attribution doubtful. The $({}^3He,p)$ and (d,α) experiments do not give any spectroscopic information on this level. The $({}^3He,t)$ experiment of Manthuruthil, et al.[6] does not give a definite answer inasmuch as the results are compatible with both L=5 and 6. In our experiment this level is weakly excited with a cross-section less than 600 nb. We have shown on Fig. 2 the calculated shape for L=5 and L=6 and also the L=6 experimental shape taken from the 7^+ level at 1252 keV. It seems that an L=5 may agree better with experimental points, but, due to the weakness of the cross-section, we cannot exclude an L=6 transfer. The fact that such a level is observed in the $({}^3He,p)$ experiment[2] is in favor of a positive parity assignment

because negative parity states are not observed in $({}^3He,p)$ reactions with significant strength and in fact the 2^- and 3^- states of the $K=1^-$ band are not excited. The second level (5^-) of this proposed rotational band lies at 1680 keV. We observed this level and have plotted on Fig. 2 L=5 and 6 calculated curves, as well as the experimental L=6 curve. One can see that L=5 does not represent the data well and that the fit is better with L=6. But one can observe that the L=6 experimental shape is in good agreement with the data thus favoring a positive parity assignment to this level. Taras, et al.[8] have proposed a spin of 6 without any parity indication. This level is observed in the $({}^3He,p)$ reaction[2] indicating that a positive parity is more likely. The other member of the $K=4^-$ band cannot be observed in the present experiment because their spin values are too high. To sum up, the present available information is not in good agreement with the proposed $K=4^-$ band. But a more direct experiment such as $({}^3He,d)$ at higher energies could probably give a more definite answer concerning the existence of this rotational band.

Other levels with negative parity have been observed in this experiment. The 2000 keV level is well represented by an L=3 distribution. It has also been observed with an $\ell=0$ transfer in $({}^3He,d)$[1], and Samuelson, et al.[9] give a tentative 3^- spin value. All these data are compatible, and a 3^- assignment is very likely. This level is built on a $2s_{1/2}$ hole and has the following configuration $(s^{-1}_{1/2}\ f^{9}_{7/2})$. The angular distribution of the 2325 and 2364 keV levels are fitted with L=3. Neither of these two levels was observed in the (^{3}He,d) and (^{3}He,p) experiments, which is in agreement with the presently determined L-value. In the case of the 2461 keV level, our result ($J^\pi=2^-$) is compatible with the $2^-,3^-$ values proposed by Manthuruthil, et al.[6]

C. Other Levels

There is in general a good agreement between our L determination for the levels not previously discussed and the available data. Some tentative 1^+ assignments have been made for three levels 2100, 2180 and 3379 keV, which are not observed in the (^{3}He,p) experiment or for which no assignment has been made. For example, the 2100 keV state has been observed in the (^{3}He,p) reaction by Smith, et al.[4] with a low cross section. In general 1^+ states are strongly excited in the (^{3}He,p) reaction. The fact that such a state is relatively weakly excited as compared to other 1^+ levels may indicate that the main structure is constructed on two hole states in the sd shell. The 2180 and 3379 keV are not reported in (^{3}He,p) experiments but are observed through ℓ=1 transitions in (^{3}He,d) reaction, which is compatible with the proposed 1^+ spin. The 2599 keV level appears to be strongly excited, and its angular distribution is compatible with an L=2 transfer. This level is also strongly excited in the (d,α) spectrum of Bachner, et al.[3] This large cross section in both pickup reactions is in favor of a $d^2_{3/2}$ transfer. Most of the levels observed above 3100 keV have their correspondent in the (^{3}He,d) spectrum.[1] One should note three exceptions, the levels at 3137, 3499, and

3630 keV. These levels have not been observed previously in other experiments.

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TABLE I.--^{48}V Spectroscopic Information.

	(p,^{3}He) This Work				(^{3}He,t)^a		(d,α)^b	(^{3}He,p)^b		(^{3}He,p)^c		(^{3}He,d)^d		γ work^e		γ work^f	
Level	E_x (keV)	σ_{Max} (μb/sr)	L	$J^{\pi g}$	E_x (keV)	L	E_x (keV)	E_x (keV)	L	E_x (keV)	L	E_x (keV)	ℓ	E_x (keV)	J^π	E_x (keV)	J^π
0	0	6.1	4	4^+	0	4	0			0		0	3+1	0	4^+	0	4^+
1	304	32.8	2	2^+	308	2	312	312	2	308	2	310	3+(1)	308.2	2^+	308.3	2^+
2	417	27.0	0+2	1^+	421	2		424	0	421	0+2			420.6	1^+	420.8	1^+
							427					428	3	427.9	5^+	427.9	5^+
							525					520	3	518.6	1^-	518.8	1^-
3	614	5.4	(4)	(4^+)	{ 613									613.5	4^+	613.4	$4^{(+)}$
					629	6	622	622 {		620 {		616	3 {	627.2	6^+	627.3	$6^{(+)}$
4	745	25.7	1+3	2^-	745	3	756							744.9	2^-	745.1	2^-
					767	4										765.0	3^+
							776					772	3	776.2	5^+		
5	1052	4.6	3	3^-	1057	3	1071					1064	3	1055.7	3^-	1055.9	3^-
6	1097	0.6	(5,6)		1098	5,6	1114	1124				1100	3	1099.2	5^+	1099.1	4^-
7	1252	20.7	6	7^+	1257	8	1266	1252						1254.9	7^+		
					1268											1264.6	5^+
					1333												
					1522	(2)	1533					1532	1			1521	$2^{(+)}$
8	1550	2.9	3+5	4^-	1561		1568							1557.6	4^-	1557.6	4^-
														1649.7	8^+		
9	1680	5.3	(6)	(6^+)	1685		1698	1687						1685.6	6	1685.4	5^-
10	1729	13.9	4	(5^+)	1728	6	1743	1736									
					1767		1760										
11	1778	1.7	(6)		1780	4	1793					1799	1			1781.0	$3^{(+)}$
																1882.6	(6)
12	2000	4.3	3	(3^-)			2015					1995	0			1998.6	$(3)^-$
							2077							2062.2	5^-	2062.9	(5^-)
13	2100	11.6	(0+2)	(1^+)	2098			2112		2101		2111	1				
					2120	2	2135									2119	
14	2180	16.6	(0+2)	(1^+)			2202					2178	1			2180	
					2187	3											
					2258							2247	3+1			2258	
15	2280	57.3	0+2	1^+	2287		2270	2296		2289	0+2					2289	
16	2325	11.2	3	2^--4^-	2324		2305									2322	
							2342									2333	
17	2364	21.6	3	2^--4^-												2373	
					2385		2390									2398.7	(6^-)
18	2397	51.7	0+2	1^+	2408	2	2415	2410		2408	0+2	2411	3			2408	
					2456					2456	2	2455	3+1			2458	
19	2461	14.0	1+3	2^-	2473	3	2471									2472	
							2492									2508	
												2568	(3)+1			2575	
					2580					2578						2579	
																2587	
																2605	

TABLE I.--Continued.

	(p,^{3}He) This Work				(^{3}He,t)^a		(d,α)^b	(^{3}He,p)^b		(^{3}He,p)^c		(^{3}He,d)^d		γ work^e		γ work^f	
Level	E_x (keV)	σ_{Max} (μb/sr)	L	$J^{\pi g}$	E_x (keV)	L	E_x (keV)	E_x (keV)	L	E_x (keV)	L	E_x (keV)	ℓ	E_x (keV)	J^π	E_x (keV)	J^π
20	2599	67.7	2	1^+-3^+	2610	2	2595			2611		2605	(3)+1			2607	
							2620							2627.0	$9^{(+)}$		
21	2681	10.0	(4)	(3^+-5^+)				2694									
					2715	5	2707									2716	
					2760												
					2775		2779							2779	$6^{(-)}$	2781.1	(6^-)
22	2794	29.8	(2+4)	(3^+)	2793	3	2739	2783				2786	1			2793	
					2817	(5)	2837	2828								2823	
23	2883	11.5	4	(3^+-5^+)	2893		2976										
24	2940	4.2	(4)	(3^+-5^+)			2925					2937	1+(3)			2915	
					2949		2959										
							2985									2969	
25	3014	125.7	0	$0^+T=2$	3021	0		3018	0	3019	0	3043				3022	
							3043					3031	3				
							3101	3085				3075	1				
26	3137	6.4	4	(3^+-5^+)													
																3165.8	
27	3189	16.9	(2+4)	(3^+)								3168	1				
																3175.6	(7^-)
28	3247	10.6	4	3^+-5^+								3243	1				
29	3292	5.0	(2)	(1^+-3^+)								3294	1				
												3322	1				
30	3379	34.4	(0+2)	(1^+)								3371	1+3				
																3426.6	(7^-)
31	3443	20.5	2	1^+-3^+								3440	1				
32	3499	1.5	(6)														
												3523	1				
33	3582	3.3	4	3^+-5^+								3565	1				
														3586	(7^-)		
34	3630	14.3	4	3^+-5^+													
35	3700	7.5	(0+2)	1^+				3701		3702	0+2	3593	1				

^{a}Reference 6 ^{b}Reference 2 ^{c}Reference 4 ^{d}Reference 1

^{e}Reference 8 ^{f}Reference 9 ^{g}J^π values take into account all the available information

TABLE II.--Values of ratio r calculated for different levels.

E_x keV	J^π	$r = \frac{R(p,{}^3He)^{a)}}{R({}^3He,p)}$
304	2^+	0.7
417	1^+	0.5
2280	1^+	0.6
2397	1^+	1
3014	0^+	1.1

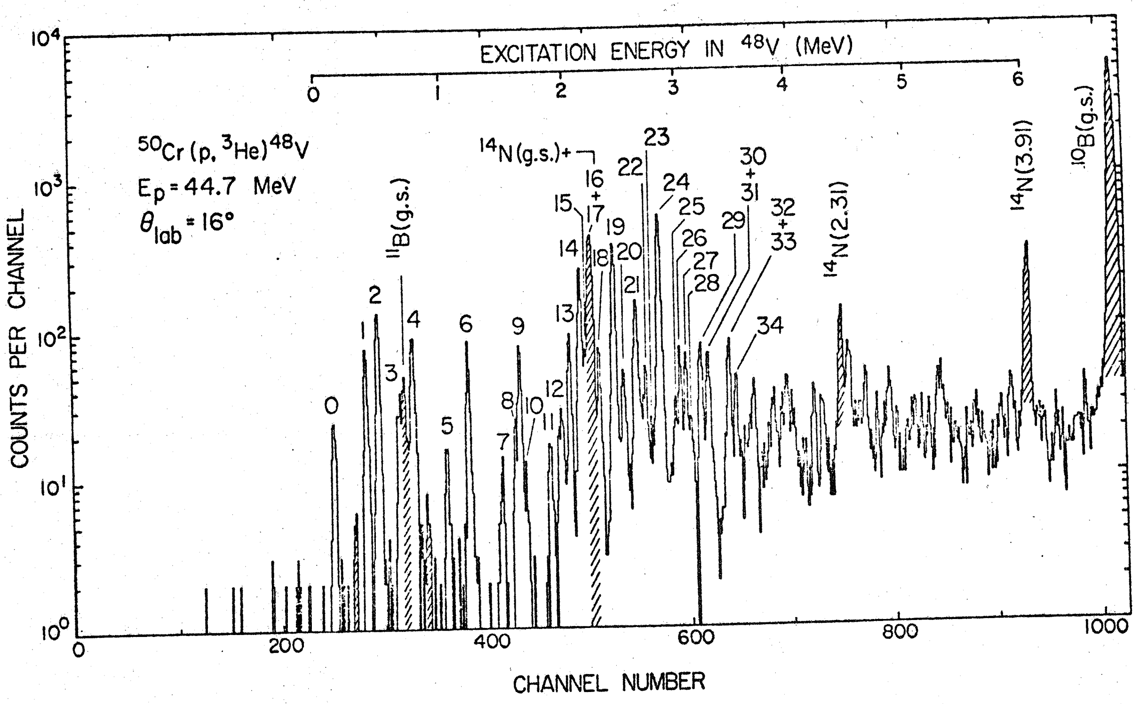
a) R is defined as the ratio between experimental and calculated cross-section.

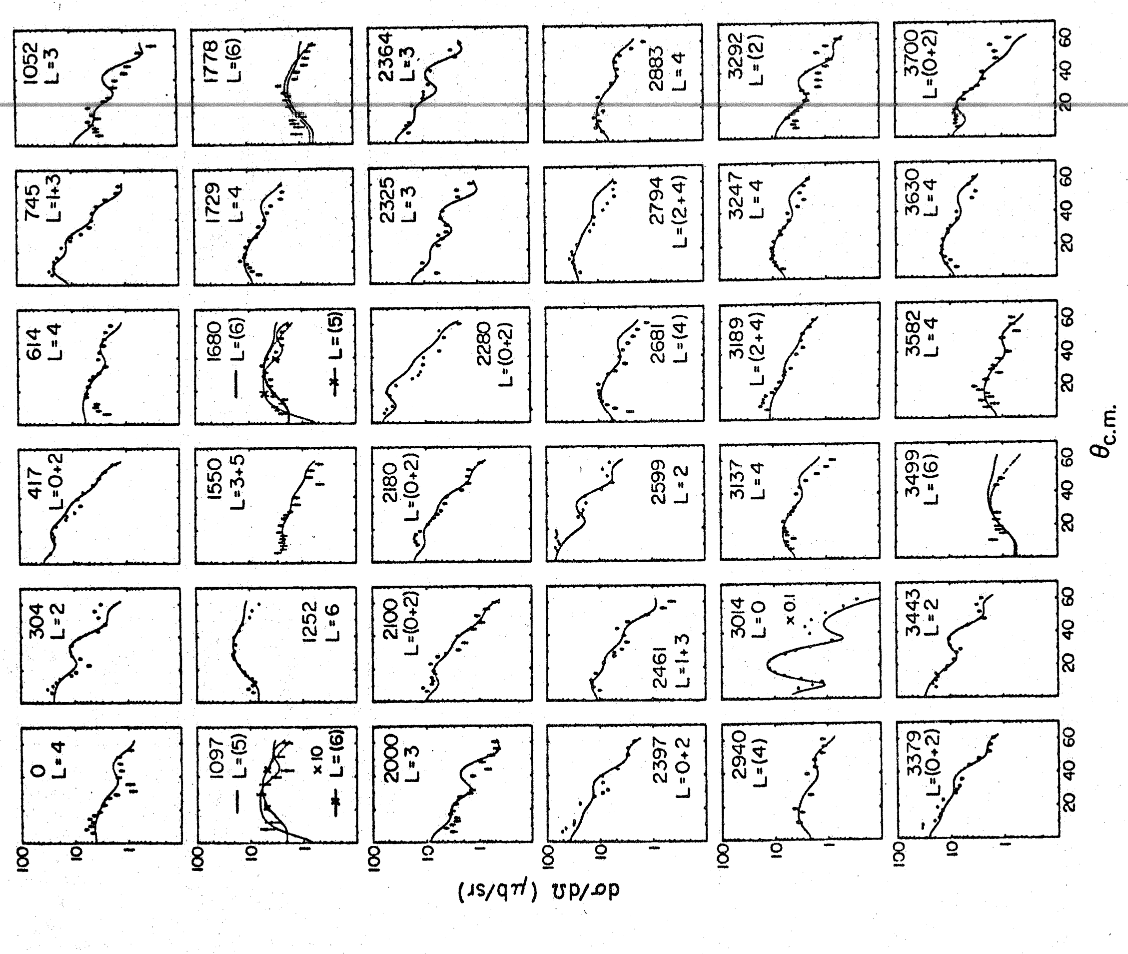
FIGURE CAPTIONS

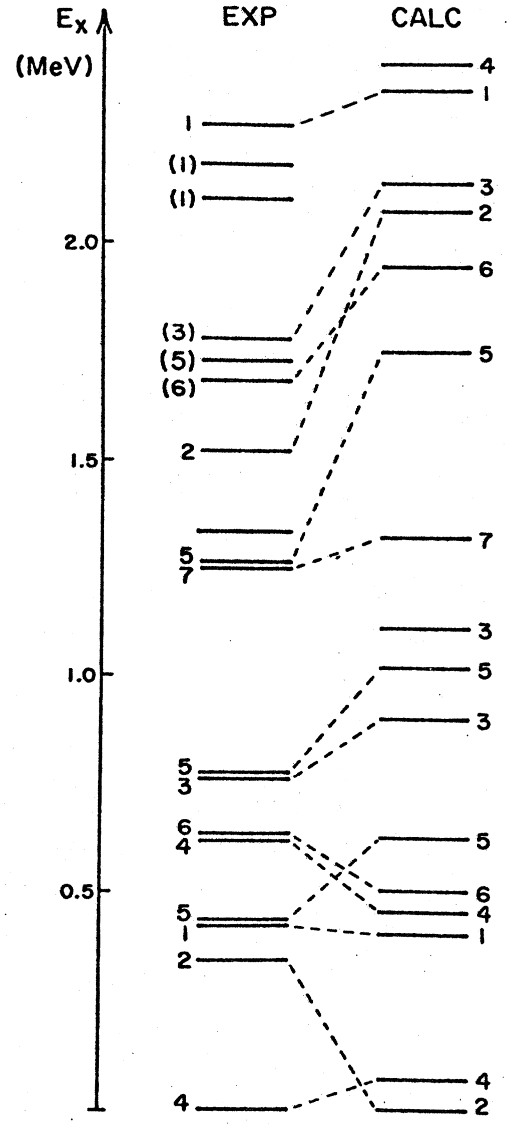
Fig. 1.--Energy spectrum of the $^{50}Cr(p,{}^3He)$ reaction at 16°.

Fig. 2.--Angular distributions of the $^{50}Cr(p,{}^3He)$ reaction. The solid curves are DWBA calculations and dashed curves represent the L=6 experimental shape deduced from the 1252 keV (7^+) level.

Fig. 3.--Experimental and calculated (Ref. 5) low lying positive parity states in ^{48}V.


EXCITATION ENERGY IN 48V (MeV)
0
1
2
3
4
5
6
50Cr (p, 3He)48V
Ep = 44.7 MeV
θlab = 16°
11B(g.s.)
14N(g.s.)+
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16+17
18
19
20
21
22
23
24
25
26
27
28
29
30+31
32+33
34
14N(2.31)
14N(3.91)
10B(g.s.)
COUNTS PER CHANNEL
10^0
10^1
10^2
10^3
10^4
0
200
400
600
800
1000
CHANNEL NUMBER


0 L=4
304 L=2
417 L=0+2
614 L=4
745 L=1+3
1052 L=3
1097 — L=(5) ×10 -*- L=(6)
1252 L=6
1550 L=3+5
1680 — L=(6) -*- L=(5)
1729 L=4
1778 L=(6)
2000 L=3
2100 L=(0+2)
2180 L=(0+2)
2280 L=(0+2)
2325 L=3
2364 L=3
2397 L=0+2
2461 L=1+3
2599 L=2
2681 L=(4)
2794 L=(2+4)
2883 L=4
2940 L=(4)
3014 L=0 ×0.1
3137 L=4
3189 L=(2+4)
3247 L=4
3292 L=(2)
3379 L=(0+2)
3443 L=2
3499 L=(6)
3582 L=4
3630 L=4
3700 L=(0+2)
dσ/dΩ (μb/sr)
100
10
1
20 40 60
θc.m.


E_x
(MeV)
EXP
CALC
2.0
1.5
1.0
0.5
1
(1)
(1)
(3)
(5)
(6)
2
5
7
5
3
6
4
5
1
2
4
4
1
3
2
6
5
7
3
5
3
5
6
4
1
4
2