MSUCL - 180

^{52}Cr(p,^{3}He)^{50}V Reaction

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ABSTRACT

The energy levels in ^{50}V have been observed up to 3.9 MeV with the ^{52}Cr(p,^{3}He) reaction at 40.2 MeV incident energy. Forty five levels have been seen, and a distorted wave analysis permitted L-assignments for most of them. These results are compared to existing information and to $f^{n}_{7/2}$ shell-model calculations.

NUCLEAR REACTION: ^{52}Cr(p,^{3}He), E_p=40.2 MeV; measured $\sigma(E_{^3He},\theta)$; enriched target. Deduced energies, L-values of ^{50}V levels.

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I. INTRODUCTION

The present work on ^{50}V is part of an investigation of the nuclear structure of some fp shell nuclei via the (p,^{3}He) reaction. The nucleus ^{50}V has been quite thoroughly investigated during the last few years. A great amount of data has been collected through inelastic scattering (p,p')[1] and (d,d')[2] as well as by one- and two-nucleon transfer and charge exchange reactions. Among recent one-nucleon experiments, the (d,t) work of Delvecchio, et al.[3] which was performed with 9 keV resolution, permitted the observation of levels below 3.2 MeV and assigning of ℓ-values for most of them. In addition, these authors also reported results on a (d,α) experiment which yielded some spin assignments. The (^{3}He,α) pick-up reaction has been investigated by Smith, et al.,[4] and Majumder, et al.[5] These latter authors have explored the ^{50}V spectrum up to 9.3 MeV and have observed five analog states of ^{50}Ti. The one nucleon stripping reaction (^{3}He,d) has been reported by Smith. et al.,[4] Sourkes, et al.,[6] and Bishop, et al.[7] In addition, Smith, et al.[4] have also performed the (^{3}He,p) and (^{3}He,pγ) experiments, mainly for the determination of 0^{+} and 1^{+} levels. A more detailed investigation of the (^{3}He,p) reaction has been made by Caldwell, et al.[8] In this experiment a resolution of 24 keV permitted the observation of ninety seven states up to 7.5 MeV. Preliminary results on the ^{50}Cr(^{3}He,t) experiment have been given by Manthuruthil, et al.[9] Studies of the γ-ray de-excitation of ^{50}V by Blasi, et al.[10] and more recently by Tomita and Tanaka[11] have permitted spin assignments for some of the low-lying levels. These experiments reveal that the ^{50}V spectrum is quite complicated and that additional information is needed. The ^{50}Cr(p,^{3}He) reaction has never been investiaged and, due to the selection rules associated with two nucleon transfer reactions, should be an interesting way of adding to the present information on ^{50}V.

II. EXPERIMENTAL PROCEDURE

The ^{52}Cr(p,^{3}He)^{50}V reaction was investigated with a 40.2 MeV proton beam from the Michigan State University Cyclotron. The ^{52}Cr target (isotopically enriched to 99.87%) had a thickness of 115 $\mu g/cm^2$ and was obtained by evaporation on a carbon backing ($\sim$30 $\mu g/cm^2$). Reaction products were anlayzed by a proportional counter and plastic scintillator combination placed in the focal plane of an Enge split-pole spectrograph. The proportional counter, designed in this laboratory,[12] was of a new slanted cathode construction with delay line readout and permitted good spatial resolution ($\sim$0.5 mm). An energy spectrum obtained at 30° is shown in Fig. 1. The overall energy resolution is 20 keV and is mainly due to energy loss in the target. The spectra have been analyzed with the peak fitting program AUTOFIT,[13] which was necessary for the determination of areas of overlapping peaks. The angular distributions, which were taken between 6° and 54° with 4° steps in general, are displayed on Fig. 2 and 3. Error bars indicate statistical uncertainties only. The uncertainty in the absolute cross section is estimated to be about 20%.

III. DISTORTED WAVE ANALYSIS

Angular distributions were analyzed, as in our previous experiments,[14] by the zero range distorted wave code DWUCK72,[15] in which the two particle form factor is evaluated according to the Bayman and Kallio[16] method. Optical model parameters are the same as those used in Ref. 14. As can be seen in Fig. 2, and 3 the agreement between calculated and experimental angular distribution is in general good. However, the following comments can be made: firstly, the fit to pure L=2 and L=4 is excellent (e.g., levels at 326 and 394 keV), but this is not the case for L=6 (e.g., g.s. transition). These facts are in agreement with our results[14] on ^{52}Mn and ^{48}V. Secondly, unnatural parity levels observed through mixed L-values display angular distributions which are quite difficult to reproduce by distorted wave calculations. This for example is the case for the 1^+ state at 1332, for which the slope of the experimental angular distribution is greater than the computed one. One can also notice that in the case of the 5^+ transitions (at 229 and 842 keV) the experimental angular distribution is shifted to back angles as compared to the theoretical L=4 curve. No attempt to reproduce the experimental 5^+ shape was made since the calculated L=6 curve did not give a good fit to the data. For the range of excitation energy covered in the present experiment (<4 MeV), the Q value affects the computed angular distribution curves slightly. This can be seen for example for the L=4 transition at 326 and 3802 keV.

IV. RESULTS AND DISCUSSION

Table I shows the results of the present work and a comparison to some of the existing data. The first column contains the excitation energy levels as listed by Caldwell, et al.[8] unless otherwise indicated. Our excitation energies are in good agreement, generally within 10 keV. They have been obtained by using a least square fit to several calibration lines including impurities such as ^{13}C, ^{16}O, ^{32}S, and the ground state and 916 keV transitions in ^{50}V. In view of the uncertainty in the position of the levels in the different experiments, it might happen that some of the proposed correspondences are not correct. A striking feature is the weakness of the cross-sections, which are typically lower than 10 μb/sr.

A. Low lying levels ($E_x < 2$ MeV).

In the shell model, ^{50}V is represented as three protons and a neutron hole in $f_{7/2}$ shell: $\pi f^3_{7/2} \nu f^{-1}_{7/2}$. McCullen, Bayman and Zamick (MBZ)[17] assumed this basis and have calculated the level scheme of ^{50}V. Figure 4 represents the level scheme computed by McCullen, et al.[17] as well as the one given by Sourkes et al.[6] (also in the $f_{7/2}$ configuration) and the observed experimental energy levels. One can see that there is a good correspondence between the theoretical and experimental level schemes up to the 3^+ level at 1397 keV. The MBZ calculation does not predict an extra pair of 4^+ and 5^+ states as was claimed by Smith, et al.[4] The 5^+ state should be identified with the experimental level at 842 keV. As for the 4^+ state, a recent $^{50}Ti(p,n\gamma)$ experiment by Tomita and Tanaka[11] has shown the presence of a 4^+ state at 916

keV, the same excitation energy which transfer reactions normally assign 7^+. Our $(p,{}^3He)$ data give an indirect confirmation of the presence of a close lying doublet at 916 keV. The angular distribution of the 916 keV is reasonably well fitted by an L=6 transition, but one can see a filling in of the minimum at 20° (which is not the case for the L=6 transition to the ground state). Only the L=4 curve presents a maximum around 20° so it is very likely that the angular distribution of the 916 keV level is in fact the summation of the 4^+ and 7^+ states; the 7^+ state is the strongest member of the doublet, due to the fact that the spectroscopic amplitude is proportional to $\sqrt{2J+1}$. For the other levels connected with the MBZ prediction, our angular momentum assignments are in agreement.

In view of the sensitivity of two nucleon transfer reaction cross-sections to small admixtures in the wave functions, it is interesting to see how good the $f^n_{7/2}$ scheme is for the levels with excitation energy less than 1.4 MeV. In this model, the ratio r of the experimental to the computed cross-section should be the same for all the states. Due to the fact that the spin-isospin strength D(S,T) of the interacting potential is not well known, we will compare separately the odd spin levels (reached only through an S=1, T=0 transition) and the even spin levels (reached only through an S=0, T=1 transition). The results are shown in Table II. One can observe that for the even parity level the ratio r is almost constant within 60%. In the case of the odd parity level the value of r displays more fluctuations but is still within a factor of two. In view of the uncertainties in obtaining r, particularly for the odd parity levels, one can say that the $f_{7/2}$ model gives a good representation of the low-lying levels. Of course, the fact that the transition to the odd parity levels require a mixing of angular momenta different than that predicted by the $f_{7/2}$ model shows that a more detailed agreement probably requires a certain amount of $p_{3/2}$ configuration mixing. This is supported by the fact that some of the levels need a small $\ell=1$ component to represent correctly the (^{3}He,d) and (d,t) angular distributions. But, our results show clearly that these levels display mainly a $f^n_{7/2}$ configuration component. This statement permits a determination of the ratio $R=\left|\frac{D(1,0)}{D(0,1)}\right|^2$ of the spin-isospin strength for the S=0 and S=1 transtions. Instead of using only the 6^+ and 7^+ states as we have done in a study[14] of ^{52}Mn (because the 7^+ state is mixed with a 4^+ state), we will take the average value of r for the S=0 (r=9.3) and S=1 (r=10.4) transtions. In this way, r(S=0)/r(S=1) is directly related to R. The average value gives R=0.33, but the error may be large: values of R between 0.1 and 0.5 are possible. However, this determination is in agreement with the usual values of R (0.3 to 0.4)[18] and particularly with the mean value of 0.28 given by Fleming, et al.[19] But, it differs quite strongly from the value 0.7 obtained in the ^{54}Fe(p,^{3}He) experiment,[14] in which case the large value was related to mixing of configurations involving the $f_{5/2}$ shell. The determination of $|D(0,1)|^2$ and $|D(1,0)|^2$ requires a knowledge of the normalization constant, D_o^2, associated with the zero range assumption of the interaction. Determinations have been made for (t,p)[20] and (p,t)[21] experiments which give a D_o^2 value of 20 to 30 x 10^4 MeV fm^3. Taking $D_o^2=25\text{x}10^4$ leads to $|D(0,1)|^2=0.62$ and $|D(1,0)|^2=0.20$. None of the presently available calculations gives such values;

however, uncertainties in the overall normalization D_o^2 together with the choice of the optical potential makes these values only tentative.

Above 1.4 MeV, the experimental level density is far greater than that predicted by MBZ calculations, and an extension of the shell model basis has to be considered. For example, in the case of the 2^+ state at 1515 keV, the ratio r of experimental to theoretical cross-section computed with an $f^2_{7/2}$ form factor is only 2.8, which is far from the 9.3 average value, and thus requires consideration of mixing of other configuration even though it is observed in one nucleon pick-up reaction through pure $\ell=3$ transition.

B. Negative parity levels

The situation with respect to negative parity levels is far from clear since the information from different sources is often contradictory. There are no ambiguities in the case of the 2421, and 2510 keV levels, for which all the data are in agreement. This is not the case, for example, for the 1957 keV level for which the (^{3}He,d) experiment of Sourkes, et al.[6] assign an $\ell_p=0$ transition, whereas (^{3}He,α) and (d,t) data favor $\ell_n=3$. Our (p,^{3}He) results give an L=0+2 angular distribution and (d,α) also favors the positive parity assignment. So either there is a close lying doublet or the $\ell_p=0$ assignment by Sourkes, et al. is not correct.

For the 2163 keV level, our data are in agreement with an L=3 or an L=0+2 distribution (although the fit is better with L=0+2). An $\ell=0$ transition is observed in one nucleon transfer reaction.[5,6] Furthermore, this level is not significantly excited in (^{3}He,p) experiment.[8] So a 3^-, 4^- spin assignment is more likely.

Discrepancies exist for the 2537 keV level for which with the exception of Smith, et al.,[4] one nucleon transfer leads to $\ell=0$ or 2 assignments; however, Smith et al. in their (^{3}He,p) experiment report an L=2 transtion for this level, which suggests a positive parity assignment. We also favor a positive parity state with an L=0+2 transition. However the (d,α) results of DelVecchio, et al.[3] give L=3 or 5. It seems necessary to suppose the existence of a close doublet in order to explain all these results.

The $\ell=0$ value for the 2791 keV by Smith, et al.[4] contradicts the other positive parity assignments found by other ways. For the 2879 keV state, our data may be fitted by L=3+5 or even better by L=2+4. The one nucleon data selects unambigously the negative parity value.

Other disagrements in the existing information also occur for the 2925, 3224, 3546, 3608 and 3755 levels. More detailed work with one and two nucleon transfer reactions is thus needed in order to remove these discrepancies.

C. Other levels

The strongest level excited in this experiment lies at 3718 keV and exhibits an L=0+2 angular distribution, in agreement with $\ell=3$ observed in one nucleon transfer reactions. The $f^2_{7/2}$ component is certainly insufficient to explain such a large strength. It is thus likely that a $d^2_{3/2}$ transfer is the main component in the form factor. This view is also supported by the fact that this level is not observed in (^{3}He,p) reactions, which populate mainly two particle states. We have represented in Fig. 5 the 1^+ states as observed in this experiment compared to those reported by Caldwell, et al.[8] One sees, for example, by a comparison

of the relative intensity that the first 1^+ state predicted by MBZ type calculations should be identified with the 1332 keV level and that the 1495 keV level certainly contains a large 2p component. The levels at 1957 and 2537 are weakly excited in the (^{3}He,p) experiment and thus must contain hole components if their 1^+ assignment is correct. On the other hand, levels at 2430, 2816 and 3566 appear only in the (^{3}He,p) results and thus are constructed essentially on $(2p,f_{5/2})^2$ components. The levels at 3755 keV, not observed in the (^{3}He,p) experiment, may also contain an $(sd)^{-2}$ hole component.

It is difficult to comment on the remaining levels in view of discrepancies in the existing information and of the lack of more complete wave functions for these levels.

IV. CONCLUSION

The present work permitted the observation of 45 levels in ^{50}V below 3.9 MeV excitation energy. Of these, 40 levels have been assigned definite or tentative L values by means of a distorted wave analysis. The cross-section of most of the levels is quite low. Comparison of our results has been made to other available data obtained with comparable or better energy resolution. Important discrepancies still remain in the present information on ^{50}V, which appears to be a very complicated nucleus. However the low-lying part of the spectrum $E_x<1.5$ MeV is reasonably represented by shell model calcualtions involving $f^n_{7/2}$ configurations only. This fact enabled the extraction of the spin-isospin strength ratio the value of which (R=0.33) is in agreement with other determinations. However a better understanding of the other levels requires further experimental and theoretical work.

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Table I. ^{50}V spectroscopic information.

E_x (keV)	$(p,^3He)$ This work E_x (keV)	$(p,^3He)$ This work $(\frac{d\sigma}{d\Omega})_{max}$ (μb/sr)	$(p,^3He)$ This work L	(d,α) L^a	(d,t) ℓ_n^a	(d,t) ℓ_n^b	$(^3He,\alpha)$ ℓ_n^c	$(^3He,\alpha)$ ℓ_n^d	$(^3He,d)$ ℓ_p^b	$(^3He,d)$ ℓ_p^d	$(^3He,d)$ ℓ_p^e	$(^3He,p)$ L^c	$(^3He,p)$ L^f	$J^{\pi g}$
0	0	2.7	6	6	3	3	3	3	3	3	3			6^+
226	229	5.4	4	4	3+(1)	1+3	3	3	1+3	1+3	1+3			5^+
320	326	4.4	4	(0,2,4)	3+(1)	1+3	3		3	3	3			4^+
356	362	6.4	2+4	2	3	3	3	3	3	3	1+3			3^+
388	394	9.5	2	(2)	(3)	3	3	3	1+3	1+3	3			2^+
837	842	2.7	4	4	3	1+3	3	3	1+3	1+3				5^+
910	916	8.1	6	6	3	3	3	3	3	3	3			$7^+(+4^+)$
1305	1303	7.6	2	(0,2,4)	3	3		3	1+3	1+3	1+3			2^+
1332	1332	12.3	0+2	0+2(4)	3	3	3	3	3	3	1+3	0+2	0+2	1^+
1404	1397	1.5	(2)	0,(2)	(3)+(1)	1						2	2	3^+
1497	1495	1.3	0+2	?	3			3				0+2	0+2	1^+
1520	1515	2.5	2	?	3		3						2	2^+
1564	1560	weak					0						(2)	(2)
1680	1675	11	2+4	2	3+(1)									3^+
1703	1675			(2,4)	3+1								4	$(4,5)^+$
1715 ^{c}							3							0^+-7^+
1725				?	3									0^+-7^+
1760				] 4	(3)+(1)			3	1			4		$(4,5)^+$
1766					3+(1)		3							
1805	1804	9.6	2	2			3		3					(1^+-3^+)
1935	1933	weak		(4 or 0)	3		3							1^+-5^+
1956	1957	5.6	0+2	(4 or 0)	3		3	3	0					$(1)^{+h}$

Table I. spectroscopic information.

E_x (keV)	(p,^{3}He) E_x (keV)	This work $(\frac{d\sigma}{d\Omega})_{max}$ (μb/sr)	L	(d,α) L^a	(d,t) ℓ_n^a	ℓ_n^b	(^{3}He,α) ℓ_n^c	ℓ_n^d	(^{3}He,d) ℓ_p^b	ℓ_p^d	ℓ_p^e	(^{3}He,p) L^d	L^f	$J^{\pi g}$
1984[c]							3							0^+-7^+
2038	2035	0.9	4	(4)	(3,2,0)				0					(3^+-5^+)
2112	2113	2.5	4	2(+4)	3+1			3	1					(3^+)
2132	2133				(3)		1		1			4	4	3^+-5^+
2162	2163	2.2	(0+2),(3)		(3,2)		0		0					$(3^-,4^-)$
2314	2319	0.9	(4),(6)		3		3	3						(3^+-7^+)
2344					(3)+1				1	1	1	4	(2)	(3^+)
2399					(3)+1		0							
2424	2421	10.4	3	3	0									$3^-,4^-$
2430												0+2	0+2	1^+
2455				4	3		0		1	1	1			h
2483				(6)	3		3		3					
2494					3									
2511	2510	3.2	3+5	3	0		0							4^-
2534	2537	11	0+2	3,5	2+(0)		2	3	0	0	0	2		h
2597	2598	2.9	(3+5),(4)	3	0		0							(4^-)
2647				(4,6)	3+1		1							3^+-5^+
2655									1	1	1			2^+-5^+
2736	2732			4,(6)	3		2	0						h

Table I. ^{50}V spectroscopic information.

E_x (keV)	(p,^{3}He) E_x (keV)	This work $(\frac{d\sigma}{d\Omega})_{max}$ (μb/sr)	L	(d,α) L^a	(d,t) ℓ_n^a	ℓ_n^b	(^{3}He,α) ℓ_n^c	ℓ_n^d	(^{3}He,d) ℓ_p^b	ℓ_p^d	ℓ_p^e	(^{3}He,p) L^d	L^f	$J^{\pi g}$
2763				6(4)	3		0							h
2792	2791	13.2	2	2	3		3	0						h
2816				2	(3)+(1)				1	1		0+2	0+2	1^+
2828														
2850				(6)	(3)									(5^+-7^+)
2878	2879	1.3	(3+5),(2+4)	3	0+2		0	0						(4^-)
2893[c]							2							2^--5^+
2928	2925	0.9	(1+3)	(4,6)	3			0	3					
2957				(4)	3		2							
2965									1	1	1+3			2^+-5^+
2990	2996	2.1	0+2	2	3				1			2		1^+
3012	3019	1.9	(2,3)	(4,6)	3		3							(3^+)
3098	3101	6	(0+2),(3)	3(4)	(3,2)		2	2						
3111														
3138				2					1	1		2	2+4	3^+
3169							0						2	h
3201	3200			(2)			0							
3219	3224	8.3	0+2	(3,4)				2				0	0+2	h
3274									1			4		3^+-5^+
3297	3296	1	4				3	3	1	1	1		(4)	3^+-5^+

E_x (keV)	(p, ^{3}He) E_x (keV)	This work $(\frac{d\sigma}{d\Omega})_{max}$ (μb/sr)	L	(d,α) L^a	(d,t) ℓ_n^a	ℓ_n^b	(^{3}He,α) ℓ_n^c	ℓ_n^d	(^{3}He,d) ℓ_p^b	ℓ_p^d	ℓ_p^e	(^{3}He,p) L^d	L^f	$J^{\pi g}$
3312							3	3						0^+-7^+
3402														
3433									1					2^+-5^+
3482	3478	6.1	0+2					3				0+2	0+2	1^+
3520^c							2							2^--5^-
3537	3546	1.4	(2)				2		1	1	1			h
3566							2					0,0+2	0+(2)	$(0^+,1^+)^h$
3606	3608	1.5	(2+4)	(1+3)			3	3	2					
3671	3684	3.3	2+4						1			2	2	3^+
3700							3	3	1	1			2	$2^+,3^+$
3722	3718	38.7	0+2				3		3					1^+
3749	3755	8.2	0+2				0							h
3789	3779	15.9	0+2											1^+
3792	3802	1.9	4									2		3^+
3820^c							3	3	1	1	1			2^+-5^+
3856	3853	4.4	2									2		1^+-3^+

a) Reference 3 b) Reference 6 c) Reference 5 d) Reference 4 e) Reference 7 f) Reference 8

g) J^π values take into account all the available information

h) discrepancies exist

Table II. Ratio r of experimental and theoretical cross-sections for the low lying levels of ^{50}V.

E_x	J^π	$r^a=\frac{\sigma_{exp}}{\sigma_{theor}}$	E_x	J^π	$r^a=\frac{\sigma_{exp}}{\sigma_{theor}}$
226	2^+	10.7	0	6^+	7
362	3^+	13.9	326	4^+	9.6
842	5^+	6.1	394	2^+	11
916	7^+	8.3	1303	2^+	9.7
1332	1^+	12.8			

a) arbitrary units.

FIGURE CAPTIONS

Fig. 1--Energy spectrum of the ^{52}Cr(p, ^{3}He)^{50}V reaction at 30°.

Fig. 2--Angular distributions for the ^{3}He groups observed in the ^{52}Cr(p, ^{3}He)^{50}V reaction. The solid and dashed curves are results of DWBA calculations for the indicated L-transfer values.

Fig. 3--See caption for Fig. 2.

Fig. 4--Experimental and calculated levels in ^{50}V below 2.5 MeV. The calculated levels (of positive parity only) comes from Ref. 6(A) and Ref. 17(B).

Fig. 5--Comparison of the population of 1^+ states in ^{50}V as observed in the ^{48}Ti(^{3}He,p) reaction (Ref. 8). and in our ^{52}Cr(p, ^{3}He) experiment.

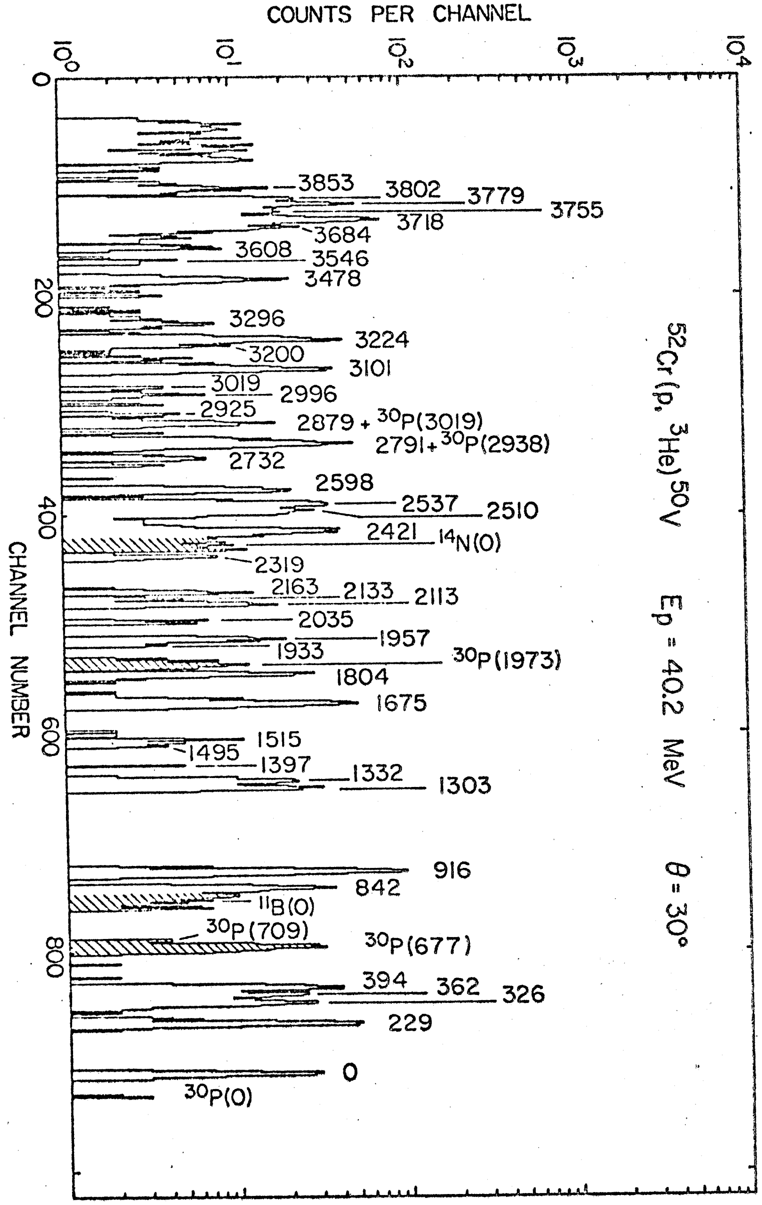

Fig. 1

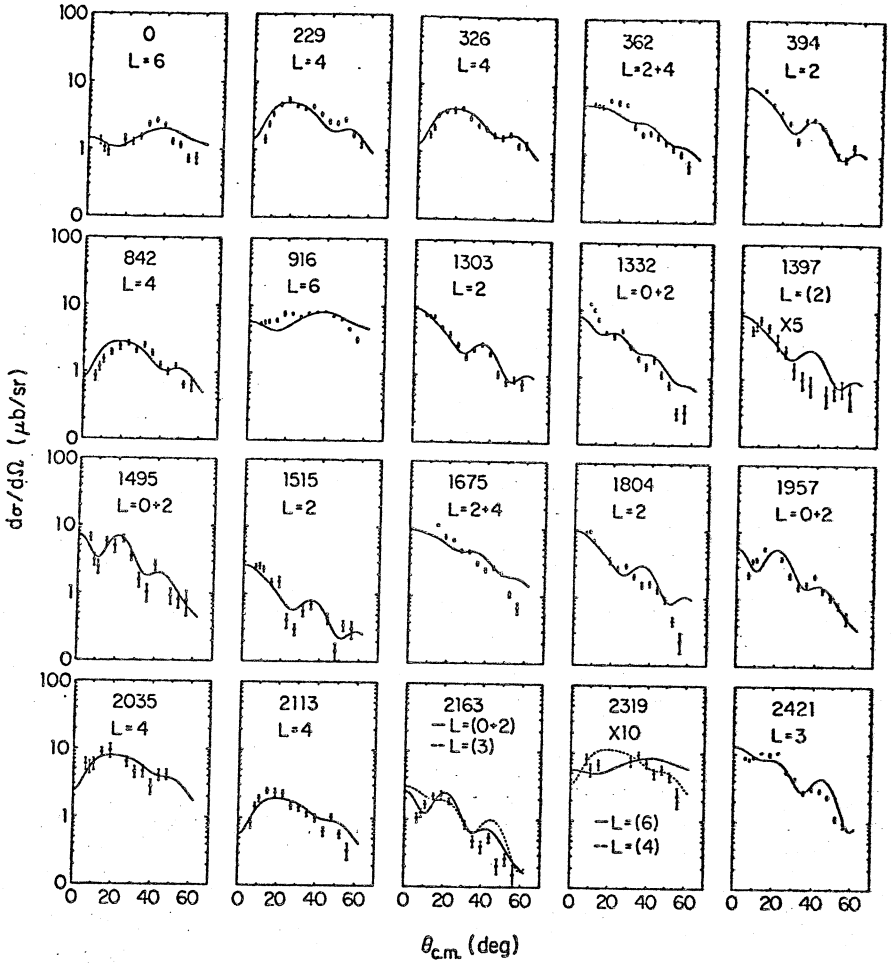
0
L=6
229
L=4
326
L=4
362
L=2+4
394
L=2
842
L=4
916
L=6
1303
L=2
1332
L=0+2
1397
L=(2)
X5
1495
L=0+2
1515
L=2
1675
L=2+4
1804
L=2
1957
L=0+2
2035
L=4
2113
L=4
2163
—L=(0+2)
--L=(3)
2319
X10
—L=(6)
--L=(4)
2421
L=3
100
10
1
0
0 20 40 60
dσ/dΩ (μb/sr)
θc.m. (deg)

Fig. 2

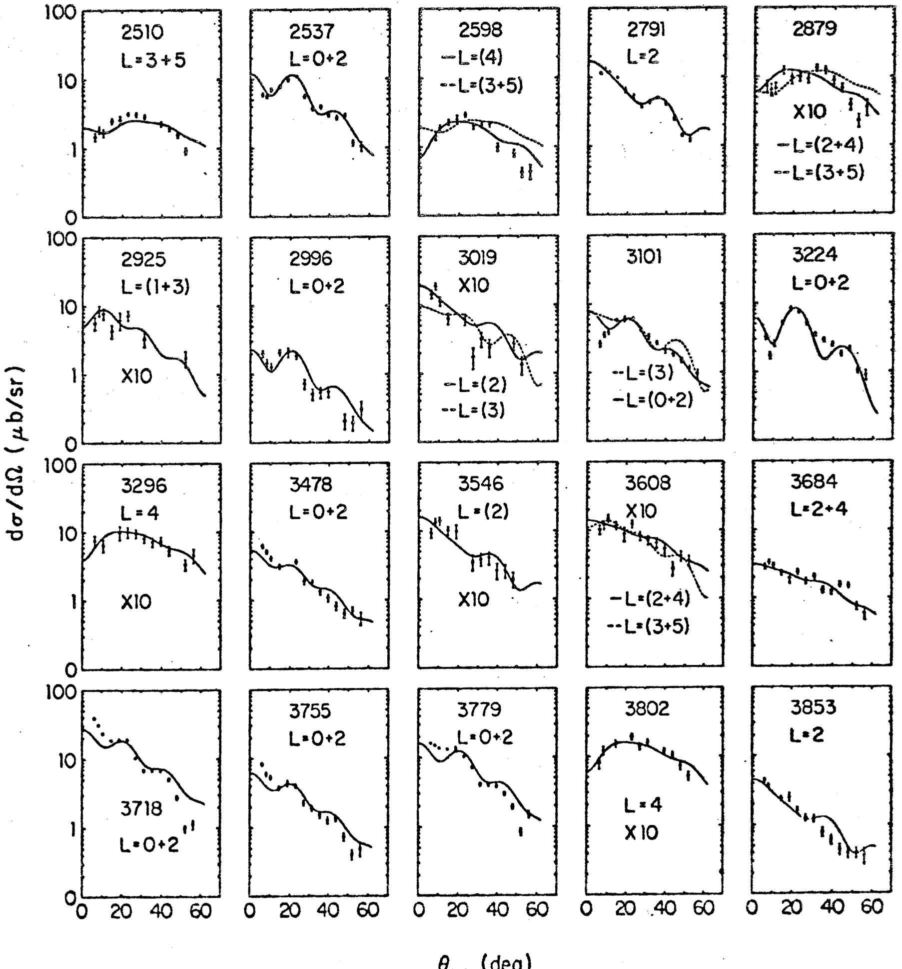
2510
L=3+5
2537
L=0+2
2598
—L=(4)
--L=(3+5)
2791
L=2
2879
X10
—L=(2+4)
--L=(3+5)
2925
L=(1+3)
X10
2996
L=0+2
3019
X10
—L=(2)
--L=(3)
3101
--L=(3)
—L=(0+2)
3224
L=0+2
3296
L=4
X10
3478
L=0+2
3546
L=(2)
X10
3608
X10
—L=(2+4)
--L=(3+5)
3684
L=2+4
3718
L=0+2
3755
L=0+2
3779
L=0+2
3802
L=4
X10
3853
L=2
100
10
1
0
0 20 40 60
dσ/dΩ (μb/sr)
θc.m. (deg)

Fig. 3

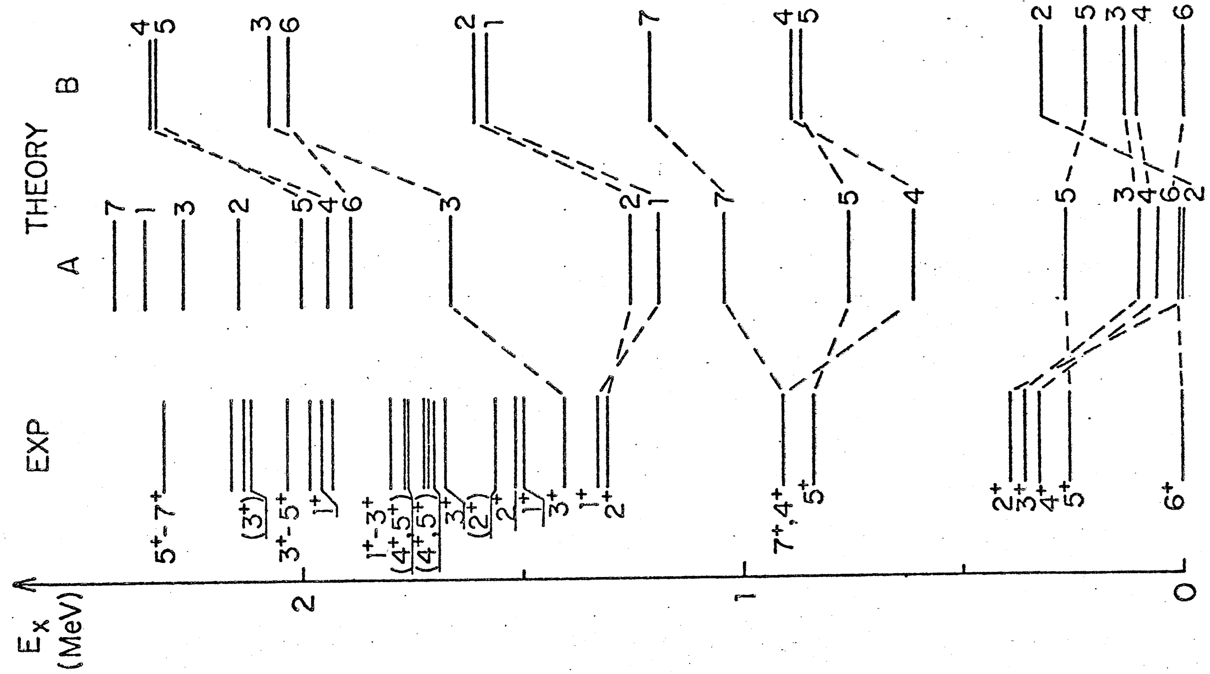
Ex (MeV)
2
1
0
EXP
THEORY
A
B
5+ - 7+
(3+)
3+ - 5+
1+
1+ - 3+
(4+,5+)
(4+,5+)
3+
(2+)
2+
1+
3+
1+
2+
7+, 4+
5+
2+
3+
4+
5+
6+
7
1
3
2
5
4
6
3
2
1
7
5
4
5
3
4
6
2
4
5
3
6
2
1
7
4
5
2
5
3
4
6

Fig. 4

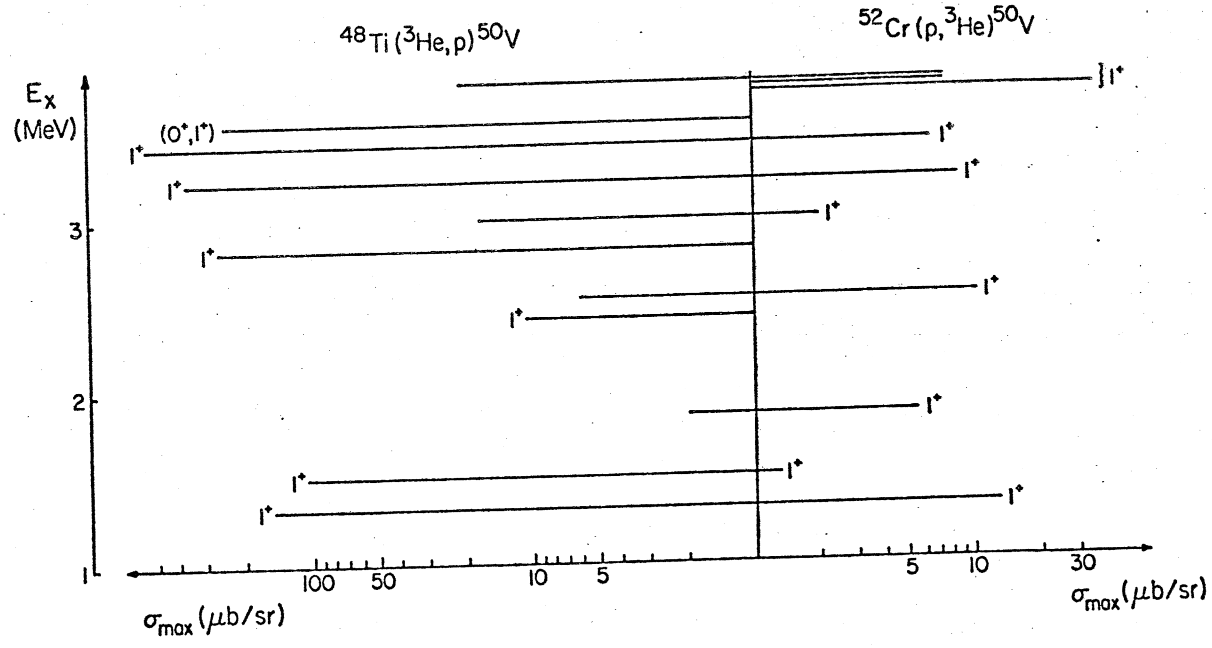
^{48}Ti (^{3}He,p)^{50}V
^{52}Cr (p,^{3}He)^{50}V
Ex (MeV)
3
2
1
1+
(0+,1+)
1+
1+
1+
1+
1+
1+
1+
1+
1+
1+
1+
1+
1+
100
50
10
5
5
10
30
σmax (μb/sr)
σmax (μb/sr)

Fig. 5