MICHIGAN STATE UNIVERSITY

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$^{48}Ti(p, ^{3}He)^{46}Sc$ Reaction

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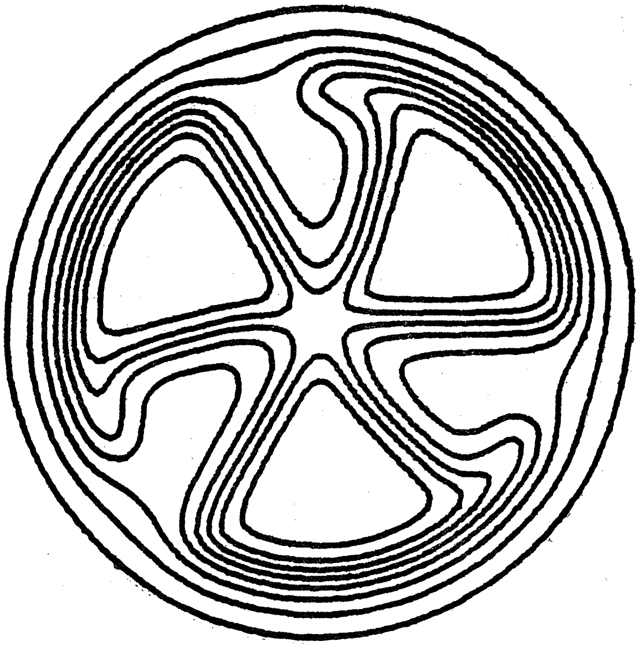

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^{48}Ti(p,^{3}He)^{46}Sc Reaction*

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ABSTRACT

The reaction ^{48}Ti(p,^{3}He)^{46}Sc has been studied at an incident energy of 40.2 MeV with an energy resolution of 17 keV. Sixty levels have been observed below 3.7 MeV. A distorted-wave Born approximation analysis permitted L assignments for most of them. A comparison with the other information on ^{46}Sc is made.

NUCLEAR REACTION: ^{48}Ti(p,^{3}He), Ep=40.2 MeV; measured $\sigma(E_{^{3}He},\theta)$; enriched target. Deduced energies L-values of ^{46}Sc levels.

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I. INTRODUCTION

The nucleus ^{46}Sc has been the subject of detailed studies during the few past years by means of particle transfer reactions and γ-ray experiments. Rapaport, Sperduto and Buechner[1] have performed a ^{45}Sc(d,p) experiment at 7 MeV incident energy with a 12 keV energy resolution and have assigned orbital angular momenta ℓ_n for most of the levels observed. The low lying levels of ^{46}Sc (up to 1.7 MeV) have been investigated with a ^{47}Ti(d,^{3}He) reaction by Lewis[2], and ℓ_p values were deduced. The (^{3}He,p) reaction has been studied by Schlegel et al.[3] at only a few angles, and only L=0 orbital angular momenta were extracted. A ^{48}Ti(d,α) experiment has been conducted by Lewis[4] at E_d=17 MeV with an energy resolution of 15 keV and by Guichard et al.[5] at E_d=26.7 MeV with a energy resolution of 90 keV. In both studies, angular momenta were extracted. The (^{3}He,t) experiment of Yntema[6] has given spin limits for some of the observed levels. Accurate excitation energies together with spin assignments have been made through (n,γ)[7,8] or (n,γγ)[9] experiments. Lifetimes of low-lying levels have been measured by Fossan et al.[10] and Dracoulis et al.[11]

These studies have thus permitted a quite complete investigation of the low lying part of the ^{46}Sc spectrum and have revealed a quite complicated level scheme. However information on levels above 1 MeV is not sufficient to give a good characterization of most of the levels. Therefore, we have undertaken the ^{48}Ti(p,^{3}He)^{46}Sc experiment in order to augment the present experimental information on ^{46}Sc. Comparison of the angular distributions with distorted wave theory allows in most cases the extraction of the transferred orbital angular momentum L and, together with other results, may lead to spin or limits on spin values for the observed levels.

This study is part of a systematic investigation of some fp shell nuclei through (p,^{3}He) reactions.[12]

II. EXPERIMENTAL PROCEDURE

The experiment was carried out at the Michigan State University Cyclotron with a 40.2 MeV proton beam. The ^{48}Ti target was isotopically enriched (99.1%) and its thickness was $\tilde{\sim}$50 μg/cm^{2}. An Enge split pole spectrograph momentum analysed the reaction products, which were detected in the focal plane by a proportional counter using delay line readout backed by a plastic scintillator. The proportional counter was designed in this laboratory[13] and has a good spatial resolution. A spectrum obtained at 30° is shown in Fig. 1. The energy resolution is 17 keV and is limited by target thickness, uncompensated beam energy spread, spectrograph abberations and detector resolution ($\tilde{\sim}$0.3 mm or $\tilde{\sim}$9 keV). The data were analyzed with the peak fitting program AUTOFIT.[14] Angular distributions have been measured from 6° to 54° with a 4° step. They are displayed in Fig. 2 and 3. The error bars represent only statistical uncertainties. The absolute cross section has been determined by reference to the proton

elastic cross-sections. The proton elastic yield has been measured under the same experimental condition, and the cross sections were computed from the parameters of Becchetti and Greenlees[15] (with r_R=1.17 fm). Such a procedure is estimated to be accurate to 20%.

III. DISTORTED WAVE ANALYSIS

The zero range distorted wave code DWUCK72[16] was used to compute the theoretical angular distributions. The two-nucleon form factor was evaluated according to the method of Bayman and Kallio.[17] The optical potential parameters are the same as those used in Ref. 12. In order to extract L-transfer values, simple configurations for the transferred neutron and proton were assumed: $f^{2}_{7/2}$ configurations in the case of even L values and $d_{3/2}\ f_{7/2}$ configuration for odd L values. There was no dependence of the calculated shape of the angular distributions on the choice of the single particle configurations. The calculated curves give reasonable fit to the data, as can be seen on Fig. 2 and 3, with the exception of L=6. The shapes of the angular distributions for the various L values are sufficiently different to permit reliable L assignments in the case of one dominant L value. However, when two L values contribute about equally, the resulting angular distribution is less structured, and finding the right combination of L values becomes difficult. The shape of the calculated angular distribution shows a slight dependence on Q values.

IV RESULTS AND DISCUSSION

The levels observed in the present experiment are listed in Table I with the angular momenta L deduced from the DWBA analysis. The first column reproduces the level scheme as given in the Nuclear Data Sheets[18] up to 2982 keV and at higher excitation energies the ones observed in the ^{45}Sc(d,p) experiment by Rapaport, *et al.*[1] We have also reported in this table some of the other existing information. Our energy scale has been established by a quadratic fit to some reference lines, involving the low-lying levels of ^{46}Sc and some of the low-lying states of ^{22}Na. Due to differential non-linearities in the system, the estimated errors for excitation energies are quite large for a high resolution experiment ($\stackrel{\sim}{<}$15 keV). In view of the uncertainties in the excitation energies in the present work and in other works, it could be that some of the proposed correspondences are not correct.

A. $\pi f_{7/2}\ \nu f^2_{7/2}$ levels. (E_x<1 MeV)

The simple shell model represents ^{46}Sc as one proton and five neutrons in the $f_{7/2}$ shell. Using such a configuration basis, McCullen, Bayman and Zamick[19] have computed the level scheme of ^{46}Sc. It has been shown[20] that for the low lying positive parity levels a correspondence can be found between experimental and calculated levels. Moreover a reasonable correspondence appears also with the cross-conjugate nucleus ^{50}V, which should display the same level sequence in the frame work of the $f^n_{7/2}$ scheme. Most of the levels predicted below 1.5 MeV by McCullen, *et al.* have been observed in this work with

the expected angular momentum transfer. An exception has to be noted for the 5^+ level at 281 keV for which our energy resolution does not permit the separation from the nearby 2^- level (290 keV). Although the presence of a doublet at 999 keV is apparent by a broadening of the corresponding peak in the spectra at some angles, we have not been able to extract separately the angular distributions of the two members of this doublet, the 1^+ and 7^+ states. In our experiment the 1^+ state is more strongly excited than the 7^+ state, the contrary of what is observed in (d,α) experiments.[4,5]

In a preceding work[12] on ^{50}V, it was found that the low-lying states display a rather pure $f^n_{7/2}$ configuration. It is interesting to see if the same statement is true for the cross-conjugate partner ^{46}Sc. In Table II, we have reported the ratio between experimental and calculated cross-section for even and odd spin states separately (as the spin-isospin strength of the interaction potential is not well known). One would expect a constant value for this ratio, and one can see from Table II that a great dispersion exists in these values. This indicates a mixing from other shells even though single particle transfer data indicate rather pure ℓ=3 transitions to these levels, and even though spectroscopic factors are in qualitative agreement with MBZ[19] predictions. However tentative ℓ_p=1 admixtures are proposed by Lewis[2] in his ^{47}Ti(d,^{3}He) experiment. Our data show clearly the presence of other configurations, the mixing being greater for low spin states (1^+, 2^+, 3^+), to which 2p shell particles are likely to contribute. Presence of 2p shell particles might be expected in view of the ^{48}Ti(p,d) results from Plauger and Kashy[21] which show large $\ell_n=1$ transitions. Indications of configuration mixing may also be found in the (d,α) work of Lewis[4] in which even spin states, forbidden by selection rules, are observed (although by an order of magnitude weaker than odd spin states). It is thus concluded that the ^{46}Sc low lying levels display more complexity than those of the cross-conjugate nucleus ^{50}V.

B. Negative parity levels

Several negative parity states have been observed at low excitation energies. Our angular momentum assignments are in agreement with those of Lewis[4] for levels at 143, 290, 590, 635 and 1140 keV. These levels are produced by pick-up of a $d_{3/2}\ f_{7/2}$ pair, this being proved by their observation with an $\ell_p=2$ transition in the $(d,{}^3\text{He})$ experiment[2] and the presence of an L=5 component in two-nucleon transfer. Raju and Spicer[8] have suggested that the 143, 290, 590 and 1140 keV levels form a rotational band based upon the $\pi d^{-1}_{3/2}\ f^7_{7/2}$ configuration. Dracoulis, et al.[11] have confirmed that these levels are the members of the $K^\pi=1^-$ rotational band and have proposed that the 635 keV (4^-) level is a member of the $K^\pi=4^-$ band. The 1^- level of the $K^\pi=1^-$ band is observed in our experiment with a low cross section although the selection rules of $(p,{}^3\text{He})$ forbid its excitation if it has a pure $d_{3/2}\ f_{7/2}$ configuration. This excitation might indicate the presence of $d_{3/2}\ p_{3/2}$ transfer or of some multistep mechanism.

The 1275 keV level is observed with an L=1+3 ($J^\pi=2^-$) transfer in our experiment instead of the L=5+(3) of the (d,α)

experiment of Lewis.[4] However, an $\ell_p=0+2$ transition is observed in the $(d,{}^3\text{He})$ experiment[2] limiting the spin values to 2^-, 3^- in agreement with our proposed 2^- assignment. Thus, it seems that the (d,α) L values are not correct, unless there exists a close doublet.

The 1648 keV level is strongly excited in the present experiment. An L=3 or 4 may be compatible with the data. However, (d,p)[1] and (d,α)[4,5] experiments indicate a negative parity state with a probable 4^- spin, which will be compatible with the L=3 assignment.

Agreement with the (d,α) results[4] is obtained for levels at 1434 (2^-), 1710 (2^-), 1803 (2^-). For the latter level however the observation of $\ell_n=1$ in (d,p) reaction may be evidence of a close doublet at this excitation energy.

Our L=4 assignment for the 2770 keV angular distribution disagrees with the (d,p)[1] ($\ell_n=0$) and (d,α)[4] (L=3) results. Unfortunately, the $({}^3\text{He},t)$[6] or $({}^3\text{He},p)$[3] data do not give any information on this level. Other odd L transitions, not reported in the (d,α) work,[4] have been observed in this experiment. A tentative L=3+5 is proposed for the 2200 keV level. L=3 transitions are observed for the 2847 and 2933 keV. These latter levels are observed with $\ell_n=0$ in the (d,p) reaction. Thus, the structure of these levels might be $s^{-1}_{1/2}\ f^7_{7/2}$.

B. 1^+ states

Several 1^+ (or possible 1^+) states have been observed in this experiment. The strongest peak of the spectrum lies at

1846 keV and displays an L=0+2 angular distribution. This assignment is in agreement with (d,α)[4], (^{3}He,t)[6] and (^{3}He,p)[3] results. Lewis[4] has proposed a dominant $(d_{3/2})^{-2}$ hole structure in view of the large cross-section. However, this level is also observed in the (^{3}He,p) reaction,[3] which is likely to populate mainly two-particle states. It thus appears that this state has a complex structure with particle and hole components.

Some of the present 1^{+} assignments are in disagreement with (d,p) results. This is the case for 2114, 2376, 2813, 3544, 3672 keV levels which are reached by an $\ell_{n}=1$ transition. This would, if the reaction mechanism is direct, indicate a lower spin limit of 2^{+} for these states. It might be possible, however, that different levels are excited in these experiments, in view of the high level density observed in ^{46}Sc.

We give in Fig. 4 the maximum cross-section of 1^{+} (or possible 1^{+}) states observed in our experiment with the cross-section at forward angles of the (^{3}He,p) works.[3,22] One can see that in addition to levels seen in (^{3}He,p) experiments, other 1^{+} states are excited in this (p,^{3}He) work. This is the case for the 2813, 3116, 3544, 3604, 3630 and 3672 keV levels; their main structure might be based on two holes in the sd shell. For the remaining 1^{+} states, it is difficult to infer their structure, but their observation in both (^{3}He,p) and (p,^{3}He) experiments points to rather complicated wave functions.

The 2965 keV level obtained with L=2 is not observed in the (d,p) experiment. A level at 2.97 MeV is reported with a

1^{+} assignment by Hansen and Nathan.[22] It is thus likely that these two levels are the same.

C. Other levels

Several likely L=2 transitions have been observed in our work which are connected in some cases with an $\ell_{n}=1$ transition in (d,p) work,[1] limiting the possible spin to 2^{+} or 3^{+}. This is the case for the 1923, 3290, 3448 keV levels. A few L=4 or L=2+4 transitions have been assigned (either definitely or tentatively) in this work; they are in general compatible with the existing information, for example levels at 2077, 2405, 2440, 2522, 2545, 3187 keV. For the remaining levels, lack of structure in the angular distributions prevent any reliable extraction of L values.

CONCLUSION

The present (p,^{3}He) experiment permitted the observation of sixty levels below 3.7 MeV. A distorted wave analysis enable the extraction of the angular momenta for most of the levels. Comparison of our results with existing information leads to some spin or spin limits assignments and to an understanding of the main structure of some of the levels. We have shown that the even parity low lying levels, unlike those of the cross-conjugate nucleus ^{50}V, do not display a simple $f^{6}_{7/2}$ structure and that other components have to be considered. A great number of 1^{+} states has been observed in our experiment, and some of these seem to have a rather complex structure. Negative parity states of the $K^{\pi}=1^{-}$ and possible $K^{\pi}=4^{-}$ band have also been excited in this experiment. However, some discrepancies exist between our results and other data. Part of this might be related to the high level density of ^{46}Sc. Lack of detailed wave functions prevented a full quantitative analysis of the present results. It is concluded that more experimental and theoretical work are necessary for a better understanding of ^{46}Sc.

ACKNOWLEDGEMENTS

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TABLE I.--^{46}Sc spectroscopic information

E_x^{a} (keV)	$J^{\pi b}$	$(p,{}^3He)$ this work E_x (keV)	level	σ_{max} (μb/sr)	L	$(d,p)^c$ ℓ_n	$(d,{}^3He,)^d$ ℓ_p	$({}^3He,t)^e$ J^π	$(d,\alpha)^f$ L	$({}^3He,p)^g$ L
0	4^+	0	0	4.2	4	3	3+(1)	4^+	4	X
52	6^+	47	1	2.5	6	3	3	$5^+,6^+$	6	X
142	1^-	143	2	1.8	1	X	2		1	
228	3^+	227	3	21.9	2+4	3	3+(1)	$3^+,4^+$	2	≥2
281	5^+					(1)	(3)	$5^+,6^+$		X
290	2^-	290	4	24.3	1+3		(2)		1+(3)	
444	2^+	450	5	23.4	2	3	(3)+(1)	$1^+,2^+$	2	≥2
585	3^-	590	6	4.0	3	X	0		3	
627	4^-	635	7	1.0	5	X	2		(3+5)	
774	5^+	780	8	10.6	4	3	3	$5^+,6^+$	4+(6)	X
835	(4^+)	840	9	0.9	4	3	3	$3^+,4^+$	4	
977	7^+					3		$6^+,7^+$	6	
991	1^+	999	10	23.4	0+2		3	$1^+,2^+$	2+(0)	0
1088	4^+	1095	11	1.7	4	1		$3^+,4^+$		
1124	$4^+,5^+$						3			
1132	4^-	1140	12	5.5	5	(0)			5+3	
1141						(3)				
1268		1275	13	2.2	1+3	X	0+2		5+(3)	
(1298)							(2)			
1321		1330	14	0.4		(1)		X	1	
1391	$3^-4^-5^-$							X	(3)	X
1398	$2^+,3^+$	1400	15	2.4	(2)	(1)				
1428	(2^-)	1434	16	5.0	3		0+2		(1)	
1435						(1)				
1526						X			(3,4)	
1648	(4^-)	1648	17	21.7	(3,4)	0			5+(3)	
1677						1				X
1700	3^-					0	0			
1712	2^-	1710	18	10.4	1+3				(1+3)	
1758						(3)				
1765						(1)				
1803	(2^-)	1803	19	1.7	(3)	1		X	1+(3)	

E_x [a] keV)	J^{π} [b]	$(p,{}^3He)$ E_x (keV)	$(p,{}^3He)$ level	this work σ_{max} (μb/sr)	this work L	(d,p) [c] ℓ_n	$(d,{}^3He,)$ [d] ℓ_p	$({}^3He,t)$ [e] J^{π}	(d,α) [f] L	$({}^3He,p)$ [g] L
824						X				
850	1^+	1846	20	128.0	0+2	X		$1^+,2^+$	0+2	0
887	$2^+,3^+$					1			2+(0)	
925	$2^+,3^+$	1923	21	1.9	2	1			X	
058		2050	22	3.2	(3,4)	(0)		$4^-,5^+$	X	
073	(3^+)	2077	23	3.7	(4)	1			(2)	
118	(1^+)	2114	24	19.4	(0+2)	1		$1^+,2^+$	X	≥2
174						X				
208	(4^-)	2200	25	1.6	(3+5)	X			X	
225	2^+	2224	26	2.0		1		$1^+,2^+$	X	
		2255	27	1.4	4					
296	2^-	2287	28	6.8	1+3	X		X	X	
307						1				X
335						1			X	
366		2376	29	12.6	(0+2)	1				X
413	3^+4^+	2405	30	3.5	4	1		$3^+,4^+$	4	X
453	3^+	2440	31	4.4	2+4	1		$3^+,4^+$	(4)	
532	(3^+)	2522	32	1.5	(2+4)	1			X	
552	$3^+4^+5^+$	2545	33	1.1	4			X	X	
566						1				
590						(0)				X
648		2651	34	4.8		(0)		X	X	
668	1^+	2677	35	2.3	0+2	X			X	X
714	3^+	2719	36	∿1.0		1		$3^+,4^+$	2	
733						1				
780		2770	37	11.0	4	0		x	3	
813		2813	38	6.4	0+2	1				
837	$3^-,4^-$	2847	39	5.0	3	0				
862						1		X		
	1^+	2876	40	12.8	2					0
897						1				
939	$3^-,4^-$	2933	41	4.2	3	(0)				
		2965	42	12.1	2					
982	$3^+,4^+$					1		$3^+,4^+$		X
005						X				

E_x [a] (keV)	J^{π} [b]	$(p,{}^3He)$ E_x (keV)	$(p,{}^3He)$ level	this work σ_{max} (μb/sr)	this work L	(d,p) [c] ℓ_n	$(d,{}^3He,)$ [d] ℓ_p	$({}^3He,t)$ [e] J^{π}	(d,α) [f] L	$({}^3He,p)$ [g] L
3021		3021	43	∿2.0		X				
3032						X				
3061		3059	44	∿2.0		X				
3087		3080	45	∿2.0		1				
	1^+	3116	46	5.6	0+2					
3142						0				
3183	$(3^+,4^+,5^+)$	3187	47	2.8	(4)	1				
		3224	48	5.9	0+2					0
3241						1				
		3264	49	2.0	(3),(2+4)					
3287	$2^+,3^+$	3290	50	3.6	2	1				
3321						1				
		3340	51	14.8	2					
3391		3396	52	4.0	(0+2),(3)	1				
3420						1				
3449	$(2^+,3^+)$	3448	53	16.7	(2)	1				
3480		3491	54	2.2	(2+4)(3)	1				
3509						1				
3539		3544	55	3.8	0+2	1				
3586		3578	56	∿1.0		1				
	1^+	3604	57	6.3	0+2					
3618						1				
	(1^+)	3630	58	4.5	(0+2)					
3661		3672	59	11.6	0+2	1				

a) Ref. 18 b) J^{π} values take into account all the available information. c) Ref. 1

d) Ref. 2 e) Ref. 6 f) Ref. 4. g) Ref. 3

The sign X indicates levels which were observed but for which no L or J^{π} assignments have been made.

TABLE II.--Ratio r of the experimental and theoretical cross-sections for the low-lying levels of ^{46}Sc.

E_x (keV)	J^π	$r^a = \frac{\sigma_{exp}}{\sigma_{theor}}$	E_x (keV)	J^π	$r^a = \frac{\sigma_{exp}}{\sigma_{theor}}$
0	4^+	5.9	227	3^+	19.5
47	6^+	6.2	780	5^+	9
450	2^+	19.5			
840	(4^+)	1.5			

a) arbitrary units.

FIGURE CAPTIONS

Figure 1.--Energy spectrum of the ^{48}Ti(p,^{3}He)^{46}Sc reaction at 30°.

Figure 2.--Angular distributions observed in the ^{48}Ti(p,^{3}He)^{46}Sc reaction. The solid and dashed curves are results of DWBA calculations for the indicated L-transfer values.

Figure 3.--See Caption for Figure 2.

Figure 4.--Comparison of the population of 1^+ states in ^{46}Sc as observed in the ^{44}Ca(^{3}He,p) and ^{48}Ti(p,^{3}He) reactions. In the case of the (^{3}He,p) experiments, solid lines represents cross-sections observed at 3.75° (Ref. 22) and dash lines, cross-sections at 5° (Ref. 3).

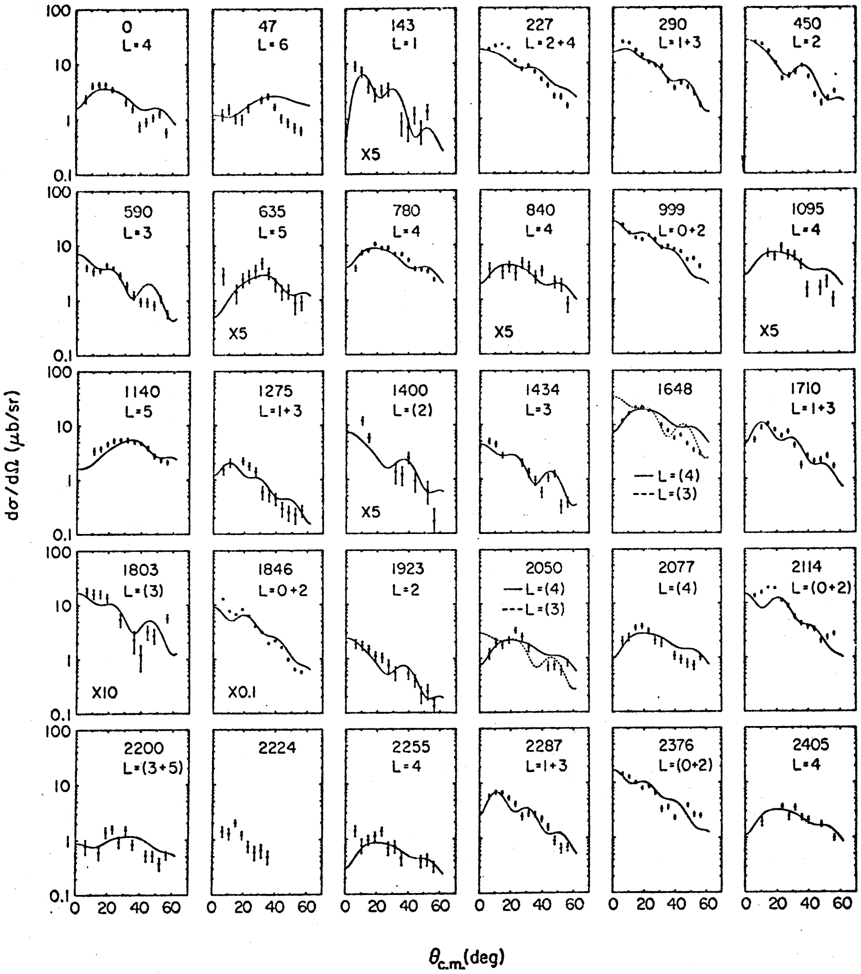

0 L=4
47 L=6
143 L=1 X5
227 L=2+4
290 L=1+3
450 L=2
590 L=3
635 L=5 X5
780 L=4
840 L=4 X5
999 L=0+2
1095 L=4 X5
1140 L=5
1275 L=1+3
1400 L=(2) X5
1434 L=3
1648 —L=(4) ---L=(3)
1710 L=1+3
1803 L=(3) X10
1846 L=0+2 X0.1
1923 L=2
2050 —L=(4) ---L=(3)
2077 L=(4)
2114 L=(0+2)
2200 L=(3+5)
2224
2255 L=4
2287 L=1+3
2376 L=(0+2)
2405 L=4
dσ/dΩ (μb/sr)
100
10
1
0.1
0 20 40 60
θc.m.(deg)

Fig. 2

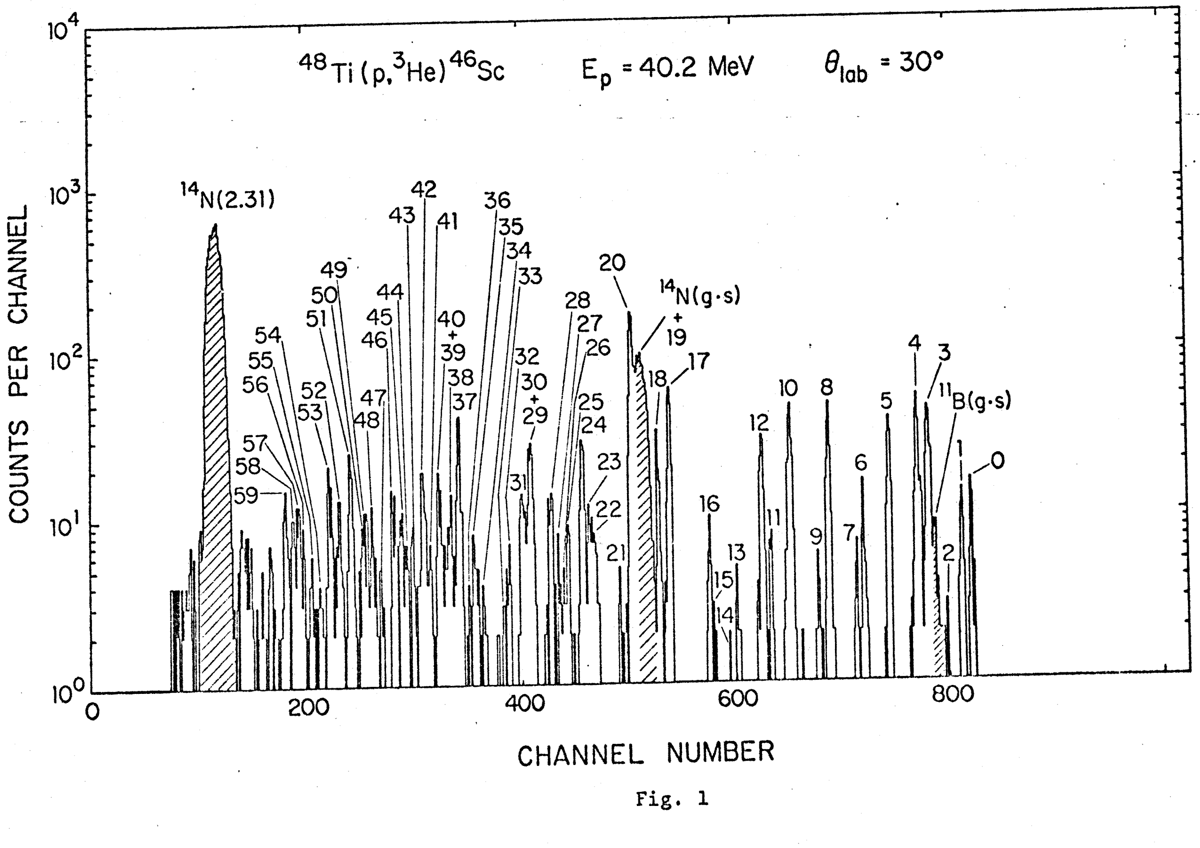
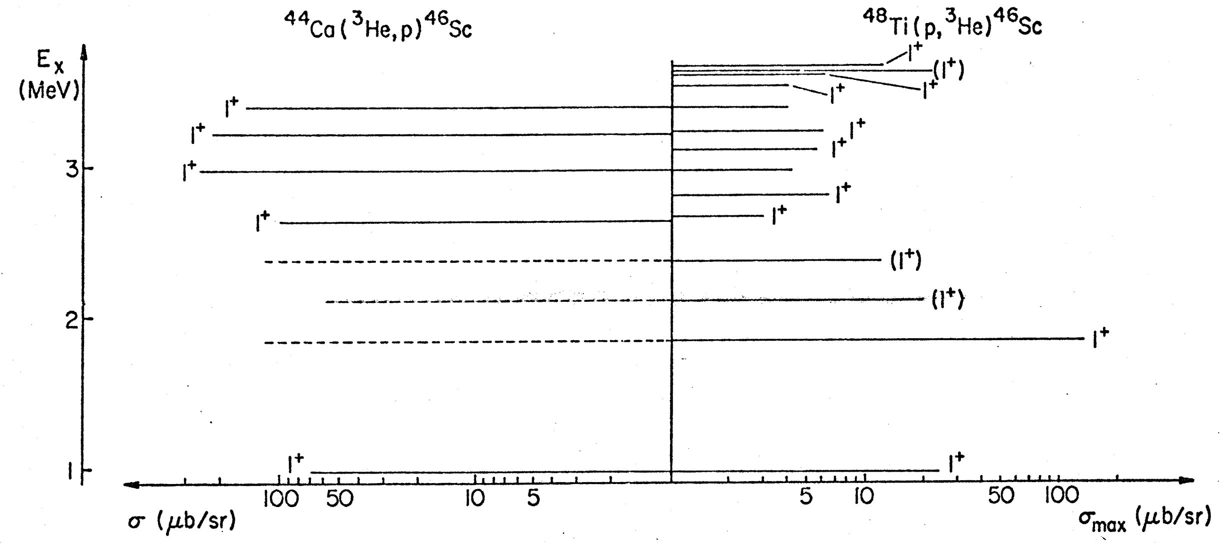
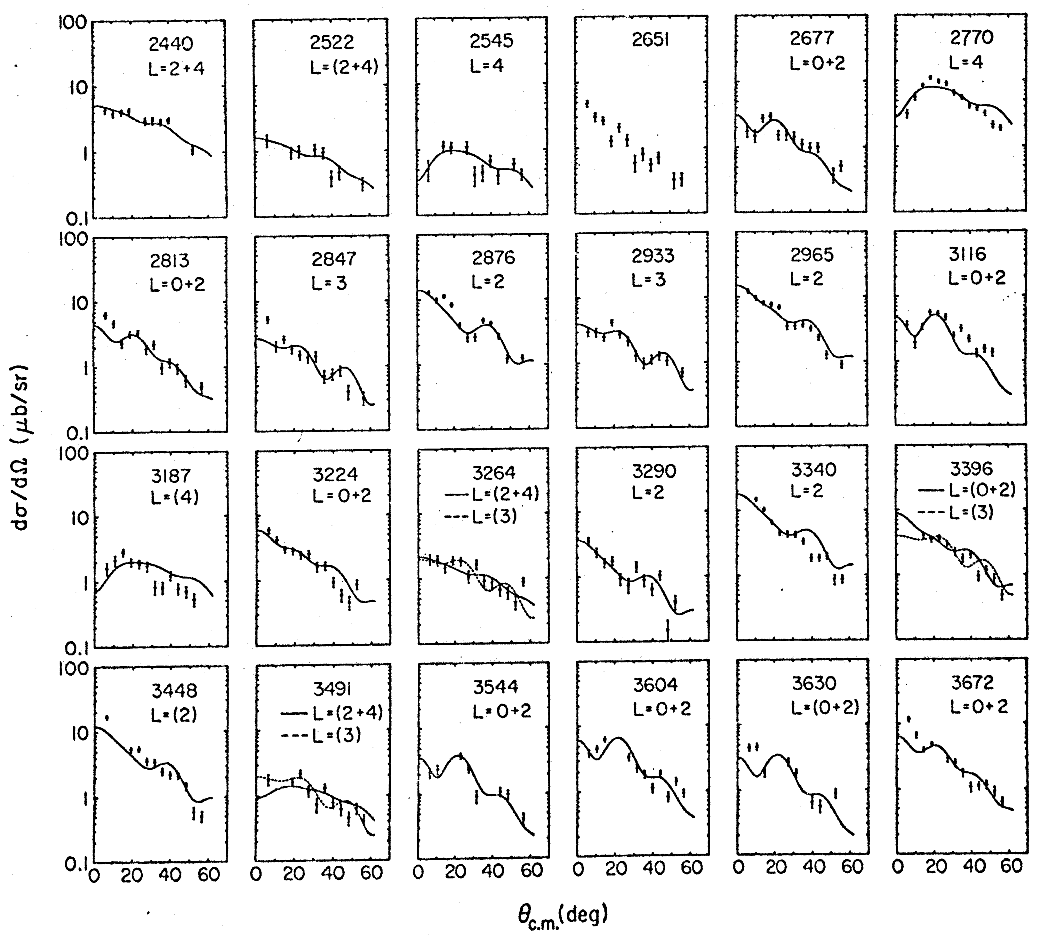

48Ti(p,3He)46Sc
Ep = 40.2 MeV
θlab = 30°
COUNTS PER CHANNEL
10^4
10^3
10^2
10^1
10^0
CHANNEL NUMBER
0
200
400
600
800
14N(2.31)
14N(g·s) + 19
11B(g·s)
59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 + 39 38 37 36 35 34 33 32 31 30 + 29 28 27 26 25 24 23 22 21 20 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0

Fig. 1



^{44}Ca(^{3}He,p)^{46}Sc
^{48}Ti(p,^{3}He)^{46}Sc
E$_x$ (MeV)
1
2
3
1$^+$
(1$^+$)
100
50
10
5
σ (μb/sr)
σ$_{max}$ (μb/sr)

Fig. 4



2440 L=2+4
2522 L=(2+4)
2545 L=4
2651
2677 L=0+2
2770 L=4
2813 L=0+2
2847 L=3
2876 L=2
2933 L=3
2965 L=2
3116 L=0+2
3187 L=(4)
3224 L=0+2
3264 —L=(2+4) ---L=(3)
3290 L=2
3340 L=2
3396 —L=(0+2) ---L=(3)
3448 L=(2)
3491 —L=(2+4) ---L=(3)
3544 L=0+2
3604 L=0+2
3630 L=(0+2)
3672 L=0+2
100
10
1
0.1
0 20 40 60
dσ/dΩ (μb/sr)
θ$_{c.m.}$(deg)

Fig. 3