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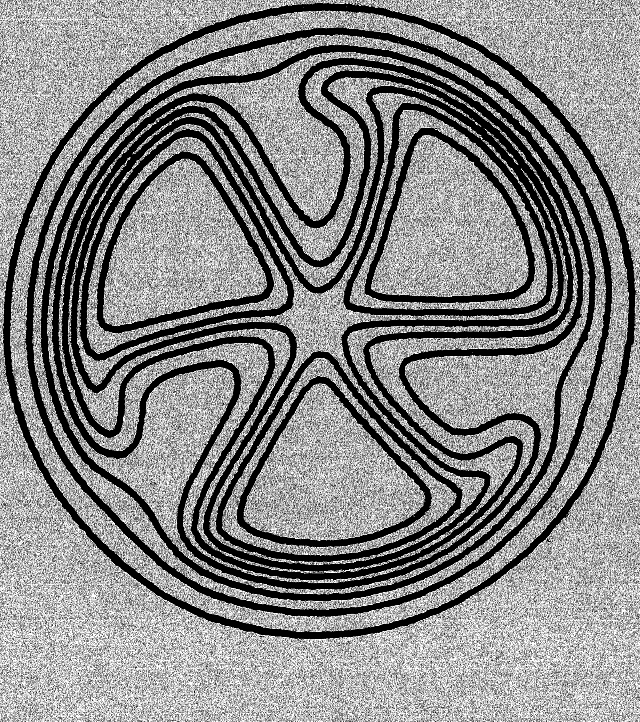

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Spectroscopy of ^{52}Mn from the ^{54}Fe(p,^{3}He) Reaction at 40.2 MeV

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ABSTRACT

The ^{54}Fe(p,^{3}He) reaction has been studied at 40.2 MeV between 4° and 60°. Assignments of L-transfers have been made with distorted wave Born approximation calculations. These results are compared with other two-nucleon transfer data and theoretical shell-model calculations.

NUCLEAR REACTION ^{54}Fe(p,^{3}He), Ep=40.2 MeV; measured $\sigma(E_{^3He},\theta)$; enriched target. Deduced energies, L-values of ^{52}Mn levels.

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I. INTRODUCTION

Spectroscopic studies with two-nucleon transfer reactions on the $f_{7/2}$ shell nuclei have been quite extensively performed during recent years. Nevertheless, information obtained on these nuclei through (p,^{3}He) reactions is rather scarce. There are several reasons for such a situation. Firstly, these nuclei have a rather high level density and need to be studied with good energy resolution. Secondly, the cross-sections of such reactions are usually low (<20 μb/sr). These two statements imply the use of thin targets and high beam intensities. The Michigan State University Cyclotron is able to deliver 1-2 μA on the target, and at the same time good overall energy resolution can be obtained using a spectrograph with live focal plane detectors. Live detectors are required because it is almost impossible to separate the low yield ^{3}He-particles from other particle types when photographic emulsion are employed. Now that live detectors with spatial resolution better than 1 mm are available it is possible to start studies on f_7 shell nuclei with (p,^{3}He) reactions. In this work we report results on the reaction ^{54}Fe(p,^{3}He)Mn^{52}. The nucleus ^{52}Mn can be reached only by a charge exchange reaction[1] or a multinucleon transfer reaction. It has been already studied by the two nucleon transfer reaction: (d,α) at 15 MeV,[2,3] 17 MeV[4] and 28 MeV,[5] (^{3}He,p) at 16 MeV[6] and 35 MeV[7] and (α,d) at 30 MeV.[8] Results obtained with these reactions are rather contradictory for some of the levels observed, and it is of interest to complete the present available data with the (p,^{3}He) reaction. This reaction is less restrictive than (d,α) since it can proceed either by S=0 or S=1 neutron-proton pair transfer. Therefore it should permit the observation and spin parity assignment for even J levels reached by $(j)^2$ transfer which are forbidden in (d,α) reactions.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 40.2 MeV proton beam from the Michigan State University Cyclotron. The target of ^{54}Fe was isotopically enriched (96.8%), and its thickness was 70 $\mu g/cm^2$. It was obtained by vacuum evaporation on an enriched carbon-12 backing of 30 $\mu g/cm^2$. The outgoing ^3He particles were detected in a single wire charge-division gas proportional counter placed in the focal plane of an Enge split-pole spectrograph. The wire counter was mounted in front of a plastic scintillator the signal of which was used to gate it, allowing good particle identification. A resolution of 25 keV was obtained as can be seen in the spectrum observed at 16° in Fig. 1. Angular distributions have been taken from 6° to 60° with 4° steps in general. The opening angle of the spectrograph in the reaction plane was 1° for angles below 12° and 2° at all other angles. The angular distributions obtained are displayed in Fig. 2. Only statistical uncertainties are included in the error bars. The accuracy of the absolute cross-section is estimated to be about 20%.

III. DISTORTED WAVE ANALYSIS

Distorted-wave Born approximation (DWBA) calculations were performed using the two-nucleon transfer option of the code DWUCK.[10] In this option the two-particle form factor is calculated by taking the individual motions of both nucleons into

account and projecting out the relative angular momentum part according to the method described by Bayman and Kallio.[11] The cross section for the $(p,{}^3He)$ reaction is given by[9]

$$\frac{d\sigma}{d\theta} = D_o^2 \sum_{LSJT} b_{ST}^2 (T_B T|T_A)^2 |(D(S,T)|^2 \sigma_{LSJT}^{DWBA}(\theta)$$

where σ_{LSJT}^{DWBA} is the calculated cross section for each set of the quantum numbers L,S,J.T of the transferred proton-neutron pair. The quantity D_o^2 is an overall normalization factor, b_{ST}^2, is a spectroscopic factor for the light particles p and ^3He and has the value 1/2. The function D(S,T) depends upon the strength of the spin-isospin-exchange terms in the interaction potential.

Optical-model parameters for the bound state, entrance and exit channels are listed in Table I. They are of the Woods-Saxon type for the real part and Woods-Saxon derivative for the imaginary part. The proton optical potential, deduced from those of Becchetti and Greenlees,[12] are taken from Ref. 13. The ^3He parameters come from the work of Nakanishi, <u>et al</u>.[14] on ^{40}Ca at 34.4 MeV. They exhibit quite large real and imaginary depths. The shape of the angular distributions depend on the choice of the optical parameters. It was found to be rather difficult to reproduce angular distributions with L=0, 2, 4 and 6 simultaneously. The experimental angular distributions chosen for selecting optical potentials were: E_x=2.923 MeV for L=0, 0.374 MeV for L=2, 0.732 MeV for L=4 and 0.867 MeV for L=6. The fits obtained for these levels can be seen in Fig. 2. One can see that the agreement is reasonable except for the L=6 transition, in which the experimental cross-section is decreasing more rapidly with the angle than the calculation predicts. Several sets of optical parameters have been tried with little success. Using the "well matching" criterion[15] does not seem to improve the fit greatly. In order to reproduce the experimental angular distributions, a large imaginary part was required for the optical potentials in both entrance and exit channel. The dependence of the shape of the calculated angular distribution on the Q-value is not very strong. Similarly changing the geometry of the well of the n-p transferred pair does not affect the shape of the angular distribution. These effects are probably related to the large imaginary term in the optical potentials which reduces contributions from the interior of the nuclei.

IV. RESULTS AND DISCUSSION

Our experimental results together with angular momentum assignments are listed in Table II. The energy level observed by Del Vecchio[4] in his (d,α) and ^{52}Cr(p,nγ) experiments are also displayed. Our energy scale has been obtained using the ground state and two reference peaks of ^{52}Mn, the excitation energy of which are known accurately from the ^{52}Cr(p,nγ) experiment (1.252 and 2.629 MeV). The agreement with previous work is excellent except for a few poorly resolved levels which differ by up to 10 keV. A new level has been observed at 3.022 MeV. In Table II are also indicated the L-values obtained in previous experiments.

A. Levels of $f_{7/2}^{-4}$ configuration.

In the simple shell model, ^{52}Mn is represented as one hole in the $f_{7/2}$ neutron shell and three holes in the proton shell:

$\pi f_{7/2}^{-3} \nu f_{7/2}^{-1}$ or in the spin isospin respresentation $f_{7/2}^{-4}$. The low-lying levels are then expected to exhibit a multiplet based on such a configuration. Shell model calculations assuming a pure $f_{7/2}^{-4}$ configuration and two-body matrix elements deduced from the experimental spectrum of ^{42}Sc have been performed by McCullen, et al.[16] and Bayman.[17] It has been found in other works[2-5] that there is reasonable correspondence between experimentally observed levels of excitation energy lower than 1.25 MeV and the theoretical ones. This will not be repeated here. The important feature of our work lies in the study of the $(f_{7/2})^{-4}$ J-even levels. In principle these are forbidden in (d,α) reactions under the assumption of the simplest configuration for ^{54}Fe, $f_{7/2}^{-2}$. Indeed, in such experiments J_{odd} states are much more strongly excited than the J_{even} states, which are seen with very low cross-section. In the spectrum of Fig. 1, one can see states of spin 6^+ (0.0 MeV), 2^+ (0.376 MeV) and 4^+ (0.728 MeV) quite strongly excited. Such states may be also reached by (^{3}He,p) reactions, but the ^{50}Cr(^{3}He,p) experiments of Hansen et al.[6] and Guichard et al.[7] show that the multiplet $f_{7/2}^{-4}$ is weakly excited. This is probably related to the structure amplitudes which favor transfers of p-shell particles by about an order of magnitude. The angular momentum L values obtained by the distorted wave analysis agree with the known J^{π} values, and fits to experimental data are in general good except for L=6 as has been already mentioned. However, one should note that it is rather difficult to obtain a good fit for the J^{+}_{odd} levels for which two values of L are allowed. The experimental angular distribution for the 1^+ and 3^+ states are structureless. A pure $f_{7/2}^2$ transfer strongly favors an L=J-1 angular momentum transfer. The observed patterns probably indicate that $2p_{3/2}$ admixtures have to be considered. Such a situation is quite likely since single-nucleon transfer reactions, like $(d,{}^3He)$[18] and $({}^3He,\alpha)$[19], have shown the presence of 2p components in the ^{54}Fe wave function.

Other levels of $f_{7/2}^{-4}$ configuration have been predicted by Bayman[17] for excitation energies around 2 MeV. We can try to identify some of them by taking into account that such levels should be weakly excited in both $({}^3He,p)$ and (α,d) experiments. An L=6 angular distribution is observed in the 1.953 MeV level in both $(p,{}^3He)$ and (d,α) experiments, and this level is not seen in $({}^3He,p)$ and (α,d) spectra. A 6^+ level has been predicted by Bayman at 2.188 MeV, and it seems likely that this state should be identified with the one observed experimentally at 1.953 MeV. Another way to confirm such an identification is to look at the ratio $\sigma(d,\alpha) / \sigma(p,{}^3He)$ for the maximum cross-section observed in (d,α) and $(p,{}^3He)$ experiments. As was emphasized by Schneider and Daehnick,[20] such a ratio should be much lower for even J states than for odd J states of positive parity. We have updated this ratio in Table III for L=4 and L=6 transitions leading to ^{52}Mn and ^{56}Co. One can see clearly that this ratio is quite small for even J states. From the value of this ratio, one can infer that the 1.953 level is most probably a 6^+. The 2.042 MeV level is observed with an L=4 angular distribution in our work and is not excited in $({}^3He,p)$ and (α,d) experiments (no L-assignments

have been made with (d,α) data). Looking again at the ratio of (d,α) and $(p,{}^3He)$ cross-sections, one finds that the spin of this level is more likely 4^+. Two levels are predicted theoretically, a 5^+ at 2.049 MeV and a 4^+ at 2.301 MeV. The 4^+ state corresponds to the experimentally observed state at 2.042 MeV. For the other levels calculated (2.209 (3^+), 2.310 (1^+) and 2.557 (2^+)) it is difficult to make any reliable correspondence with the levels observed in this experiment.

Two other L=6 angular distributions have been observed at 2.712 and 3.199 MeV. We disagree with the L=5 value found in the (d,α) reaction[2,3] for the 2.712 MeV state, but in these (d,α) experiments it was quite difficult to distinguish between L=5 and L=6 angular momentum transfers due to somewhat structureless angular distributions. The distorted waves calculations again give a poor fit to the $(p,{}^3He)$ data, but the experimental shape taken from the 0.867 MeV (7^+) state agrees nicely with the data, and so we consider the present L assignment to be quite reliable. These levels may belong to the $f_{7/2}^{-4}$ multiplet, although $f_{7/2}\ f_{5/2}$ or $f_{5/2}^2$ components cannot be ruled out. The 2.712 state is strongly excited in (d,α) experiments, and the ratio of (d,α) to $(p,{}^3He)$ (see Table III) would favor a 7^+ assignment (but 5^+ or 6^+ cannot definitively be excluded). Further state is weakly excited in the $({}^3He,p)$ reaction[6] which is in agreement with a $f_{7/2}^{-4}$ configuration. The second 7^+ level in the McCullen _et al._[16] work is calculated to lie at 3.54 MeV which is far away from the present experimental value but not totally inconsistent. The 3.199 MeV level observed with L=4 in the (d,α) reaction[4] and L=6 in our work is a 5^+ state. An L=0 transfer has been observed by Hansen et al.[6] in the (^{3}He,p) reaction for a level at 3.213 MeV. There might exist a close doublet in this energy range, each member being favored by either a pick-up or a stripping reaction.

B. Spin-isospin Strength

If the 6^+ (ground state) and 7^+ (0.867 MeV) levels were of pure $f_{7/2}^{-4}$ configuration, they would offer an interesting means of determining the ratio

$$R = \left|\frac{D\ (1,0)}{D\ (0,1)}\right|^2$$

of triplet to singlet transfer strength which is related to the spin-isospin part of the interaction potential. Indeed, the 6^+ state is reached only by an S=1, T=0 transfer and the 7^+ state only by an S=0, T=1 transfer. One can then show that the ratio of the experimental cross section is related directly to R. These high spin states, 6^+ and 7^+, have been selected in the multiplet $f_{7/2}^{-4}$ because they are expected to have the purest $f_{7/2}$ configuration. The value of R extracted in this way comes out to be 0.7 and is not very sensitive to the choice of the optical parameters. The usual values range from 0.3 to 0.4 (Ref. 22) and are much lower than our values. To explain such a discrepancy one has to look to the effect of taking into account an $f_{5/2}$ admixture in the 6^+ state, even though the single particles states of the $f_{7/2}$ and $f_{5/2}$ shells are quite far apart (at least 5.0 MeV[23]). The presence of such an admixture is supported by the observation of the 6^+ level in

(d,α) reactions. In order to see the sensitivity of R to the introduction of $f_{5/2}$ components, we have computed the 6^+ state cross section with a form factor having a 5% ($f_{7/2}f_{5/2}$) component. It was found that a destructive interference draws down the ratio R to a value of 0.12 showing the extreme sensitivity of R to small $f_{5/2}$ admixtures. So, it seems necessary to have very accurate wave functions for both ^{54}Fe and ^{52}Mn in order to extract the ratio R with some confidence. Moreover this is another indication that the low lying states of ^{52}Mn have certainly a more complicated structure than the simple $f_{7/2}^{-4}$ configuration. In fact, one can determine that the admixture of $f_{7/2}f_{5/2}$ is between 1% and 3% assuming R is between 0.3 and 0.4.

C. Negative parity levels

Negative parity levels are observed in two-nucleon pick-up reactions on even target nuclei as odd L transfers. Very few transitions with odd-L values have been observed in this work as compared to the (d,α) work[2] in which the structureless shape of angular distributions prevented unambiguous L-transfer determinations. One tentative L=1 distribution in the present experiment is proposed for the level at 2.968 MeV, but an L=6 assignment has been made in the (^{3}He,p) reaction.[7] In view of the 30 keV uncertainty given in (^{3}He,p) work for the excitation energy, it may be that two different levels have been observed in the two experiments. Distributions with L=3 are proposed for the 3.330 and 3.711 levels. In the case of the 3.330 MeV level, this assignment is in agreement with the results of

Gaillard et al.[2] but not of DelVecchio[4] who proposed an L=(2+4) value. The L=3 value for the 3.42 MeV and the L=5 value for the 2.712 and 3.097 MeV levels proposed in Ref. 2 are not confirmed by the present work. We find instead that these states are of positive parity.

D. Other levels

The most strongly excited state in the spectrum lies at a 2.923 MeV and exhibits a L=0 shape. It is the analog of the ground state of ^{52}Cr and has been identified previously by Rapaport et al.[24] The 3.42 MeV level is well represented by L=4 in our experiment and L=2 in the (^{3}He,p) reaction which leads to a 3^+ spin assignment. This level is strongly excited in (d,α) and (p,^{3}He) experiments. One may then propose a predominately $d_{3/2}^{-2}$ configuration. An argument in favor of such a configuration comes from the simple estimates made by Bruge et al.[21] in evaluating the spacing between the lowest 7^+ and the 3^+ level of $d_{3/2}^{-2}$ configuration. In the case of ^{52}Mn they found that such a 3^+ level should lie at about 3.6 MeV, which is close to the proposed level. The 1.680 MeV, 2.130 MeV and 2.337 MeV levels appear weakly excited in both (d,α) and (p,^{3}He) experiments but stronger in (α,d) experiment. This is an indication of a $(f_{7/2}p_{3/2})^{12}$ structure and of the presence of p components in the ^{54}Fe wave function. The 2.629 MeV (1^+) level is strongly excited in all two-nucleon transfer reactions. It is probably observed through p-transfers because of their large structure amplitude and inherent transfer strength. Another 1^+ state is also observed in (d,α) (p,^{3}He) and (^{3}He,p) experiments at 3.567 MeV, but it is difficult to reduce its main structure.

Some of the levels which appear in stripping and pick-up spectra are likely to be of quite complicated structure (mixing of hole and particle states) and other experiments involving γ-rays and charge exchange are needed in order to have a better understanding of the level scheme. Also more sophisticated shell-model calculations should be carried out to represent correctly the low-lyin levels of ^{52}Mn.

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Table I: Optical-model parameters used in the DWBA calculations.

	V (MeV)	r_R (fm)	a_R (fm)	W' (MeV)	r_I (fm)	a_I (fm)	r_c (fm)
P	45.5	1.20	0.70	13.0	1.25	0.70	1.25
^{3}He	242.82	1.137	0.668	18.03	1.186	0.9331	1.30
n,p transferred nucleon	variable	1.20	0.65				

Table II: ^{52}Mn spectroscopic information.

	(p,He^3) This work				(He^3,p)		(d,α)			(α,d)	
E_x $^{a)}$ (keV)	E_x (KeV)	Peak no.	σ_{max} μb/sr	L	$L^{b)}$	$L^{c)}$	$L^{a)}$	$L^{d)}$	$L^{e)}$	$L^{f)}$	J^π
0	0	0	3	6			(6)	6	(6)		6^+
378±1	374	1	31	2			(2)	2	(2)		2^+
546±1	541	2	9.5	0+2			(2)	0+2	0+2		1^+
732±1	728	3	9	4			4	4	(4)		4^+
826±1	820	4	14.5	2+4		2	2	2+4	2+4		3^+
870±1	867	5	25	6			6	6	6	(6)	7^+
884±2											
1252±1	1252	6	11.5	4		6	4+6	4	4+6	4	5^+
1646±2											
1683±1	1680	7	1.4	4		2	4	4	2+4	4	3^+
1954±2	1953	8	1.2	6			6				(6^+)
2046±4	2047	9	1.3	4							(4^+)
2130±5	2130	10	1.9	4			4	0+2		4	3^+-5^+
2252±2	2248	11	2.2	4			4	4			3^+-5^+
2285±5											
2338±2	2337	12	1.	(2)	(2)		3,2	0+2		4	(3^+)
2475±2	2476	13	29		0	0	(0+2,1)	3	1+3		
2550											
2629±3	2629	14	34	0+2	0+2	0+2	0+2	0+2	0+2	2	1^+
(2645±5)											
2667±10											
2711±3	2712	15	5.5	6				(5)	(5)		(7^+)
2785±4	2787	16	20	(4)	2	2					
2796±3							(2)	2	(2)	(0)	
2815±4											
2848±3	2850	17	33					4	2+4	2,4	(3^+)
2858±5											
2872±4											
2903±5								5	(2)	2	
2925±5	2923	18	80	0	0	0	0				0^+ T=2

able II: (cont).

2955±5										
2973±4	2968	19	36	(1)		6				
2982±3										
	3022	20	50	4						3^+-5^+
3077±4										
3106±4	3097	21	3	4			(2)	(5)		(3^+)
3199±4	3196	22	3.3	6	0		4			5^+
3226±4	3228	23	1.8	4			4+(6)			(5^+)
3245					(0+2)					(1^+)
3297±5					(2)					(1^+-3^+)
3333±3	3330	24	22	(3)			(2+4)	3		
3351±5										
3386±3	3380	25	8.8	(2+4)			(2+4)			(3^+)
3423±3	3420	26	27	4	2			3		3^+
3490±10									(4)	
3506±3	3500	27	11	4			(4)	4,5		3^+-5^+
3573±5	3567	28	10	0+2	0	0		0+2		1^+
3620±6										
3640±6	3635	29	4.7					5,6		
3655±6	3660	30	6.5							
3706±6	3711	31	3.2	(3)						(2^-,4^-)
3738±4	3742	32	3.2				4	2		3^+
3776					2	2				(1^+-3^+)

) ref. 4.
) ref. 6.
) ref. 7.
) ref. 2.
) ref. 3.
) ref. 8.

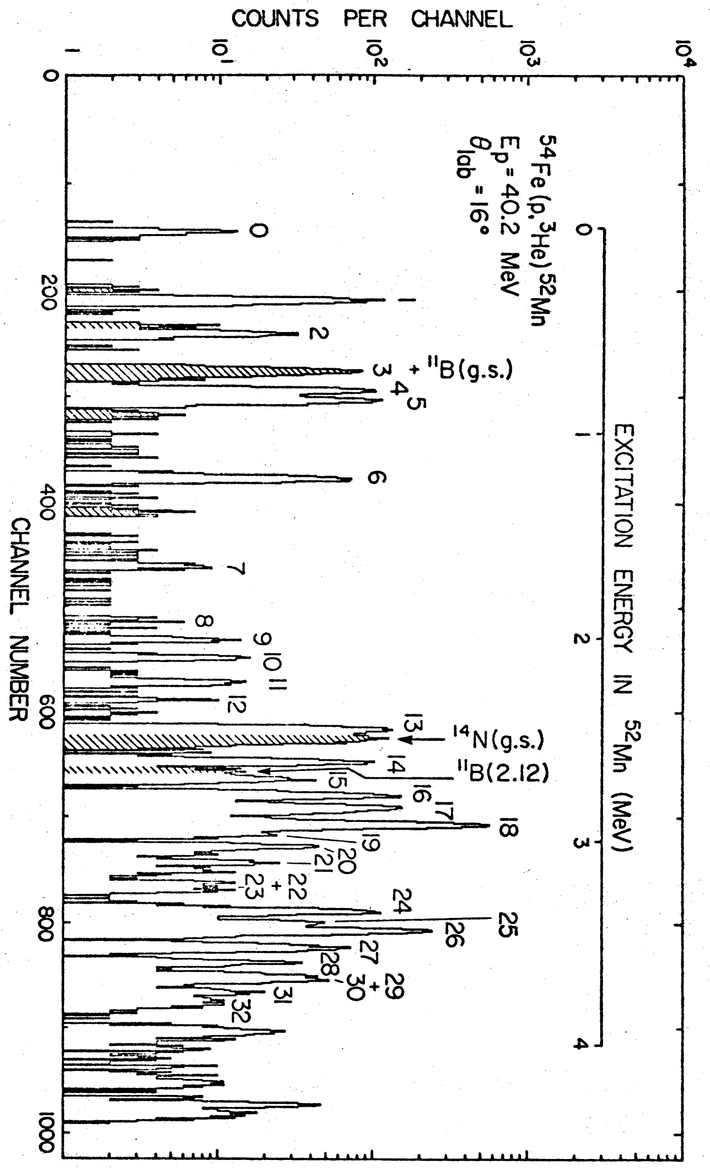
Table III: Ratio $\sigma(d,\alpha)/\sigma(p,{}^3He)$ of maximum cross section for L=4 and L=6 transitions observed in ^{52}Mn and ^{56}Co(*). (Cross-section values for ^{56}Co are from ref. 20 and 21.)

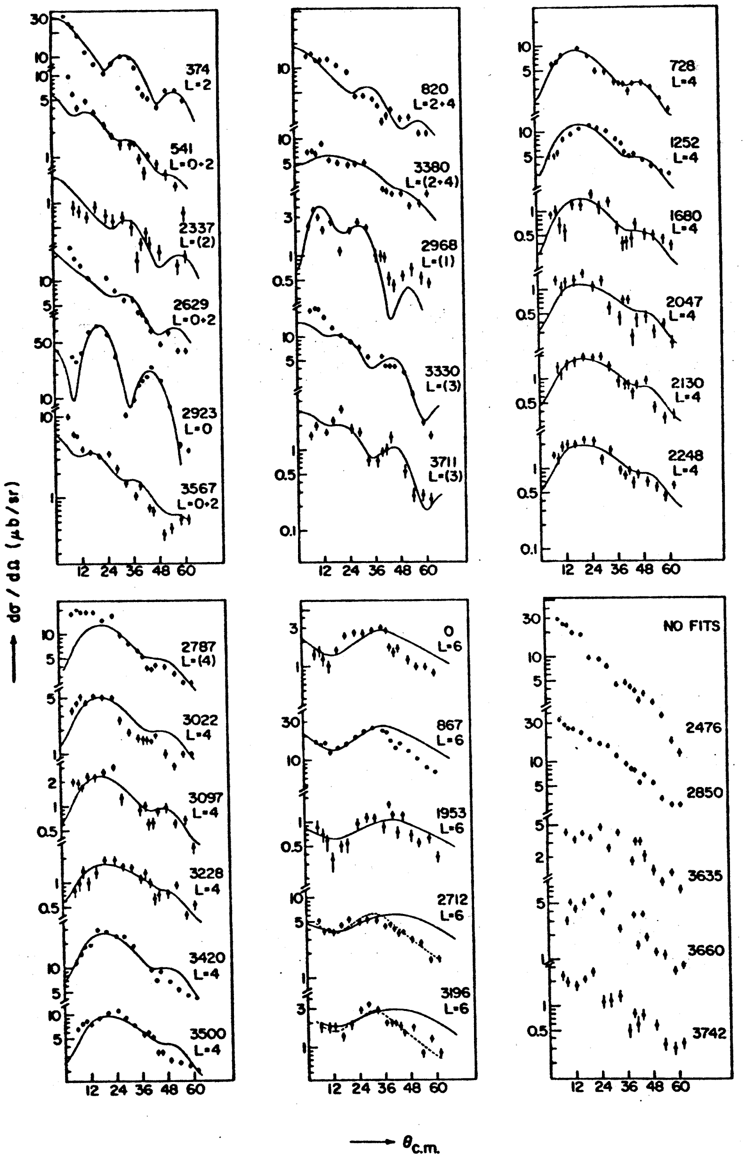
E (keV)	J^π	L=4		E (keV)	J^π	L=6	
		S=0	S=1			S=0	S=1
732	4^+	0.3		0	6^+	1	
1252	5^+		7	867	7^+		10
2046		2		1953		3	
* 0	4^+	1.5		2712			10
* 576	5^+		10	*2280	7^+		11
* 830	4^+	0.8					
*1009	5^+		10				

FIGURE CAPTIONS

Fig. 1--Energy spectrum of the ^{54}Fe(p,^{3}He) reaction at 16°.

Fig. 2--Angular distrbution of the ^{54}Fe(p,^{3}He) reaction. The solid curves are DWBA calculations and dashed curves represents the L=6 experimental shape deduced from the 0.867 MeV (7^{+}) level.




dσ / dΩ (μb/sr)
θc.m.
12 24 36 48 60
374 L=2
541 L=0+2
2337 L=(2)
2629 L=0+2
2923 L=0
3567 L=0+2
820 L=2+4
3380 L=(2+4)
2968 L=(1)
3330 L=(3)
3711 L=(3)
728 L=4
1252 L=4
1680 L=4
2047 L=4
2130 L=4
2248 L=4
2787 L=(4)
3022 L=4
3097 L=4
3228 L=4
3420 L=4
3500 L=4
0 L=6
867 L=6
1953 L=6
2712 L=6
3196 L=6
NO FITS
2476
2850
3635
3660
3742