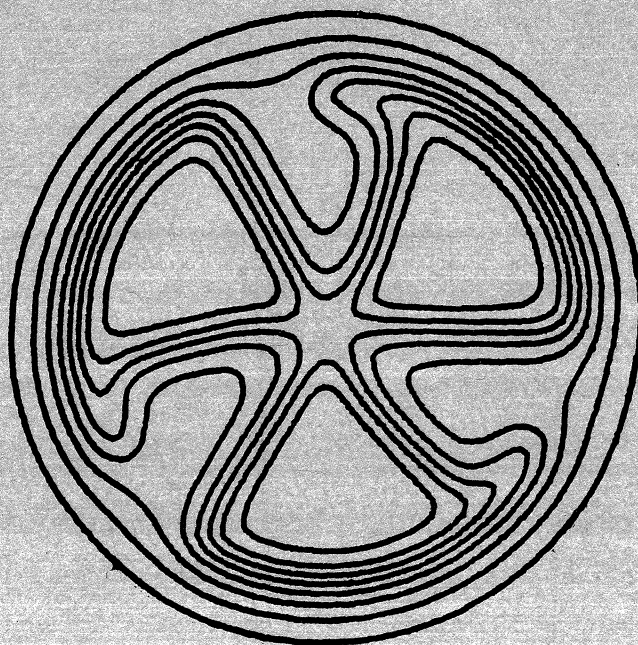


MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

LEVEL STRUCTURE OF ^{54}Mn FROM THE $^{56}\text{Fe}(p, ^3\text{He})$
REACTION AT 40.2 MeV

A. GUICHARD, W. BENENSON and H. NANN



INTRODUCTION

Nuclei with $N=29$ have been the subject of a number of theoretical studies¹⁻⁴ in the framework of the shell model. A common feature of all of these studies is that the valence neutrons are allowed to occupy $2p_{3/2}$, $2p_{1/2}$ and $1f_{5/2}$ shells whereas protons are constrained to remain in the $1f_{7/2}$ shell. The calculations differ in the manner with which they take into account n-n and n-p effective interactions. The $N=29$ nucleus, ^{54}Mn , which has been quite extensively studied during the last past years, can be reached by one- and two-nucleon transfer reactions. Among the one nucleon transfer reaction works available the ($^3\text{He}, d$) experiment of Lynn, et al.⁵ is the most complete; other information obtained through reactions such as $^{53}\text{Cr}(d, n)$ ⁶ and $^{55}\text{Mn}(p, d)$ ⁷ is quite limited. The $^{52}\text{Cr}(^3\text{He}, p)$ reaction has been performed by Lynn, et al.⁵ at 11 MeV incident energy and by Betts, et al.⁸ at 15 and 16.5 MeV. The latter were able to observe the level scheme up to 7 MeV excitation energy. (d, α) studies have been carried out by Bjerregaard, et al.⁹ (only the level scheme up to 3.2 MeV excitation energy was reported), by Hjorth¹⁰ at 15 MeV incident energy with a limited energy resolution (60 keV) and more recently by Majumder, et al.¹¹ The latter experiment was performed at 12 MeV with 25 keV energy resolution and several L assignments were obtained up to 4.3 MeV. Several γ -ray works¹²⁻¹⁵ have permitted spin and parity assignments for most of the levels of excitation energy less than 1.5 MeV. Nevertheless, the information collected up to now on this nucleus seems to be insufficient, particularly

Level Structure of ^{54}Mn from the $^{56}\text{Fe}(p, ^3\text{He})$ Reaction at 40.2 MeV *

A. Guichard **, W. Benenson and H. Nann

Cyclotron Laboratory and Physics Department
Michigan State University, East Lansing, Michigan 48824

ABSTRACT

The $^{56}\text{Fe}(p, ^3\text{He})^{54}\text{Mn}$ reaction has been studied at an incident energy of 40.2 MeV. Levels up to 6.16 MeV of excitation have been observed with an energy resolution of 25 keV. The experimental angular distributions have been analyzed with the distorted wave Born approximation. Several L assignments have been made which, when compared to other experimental data, permitted new spin assignments. A comparison with theoretical calculations is also presented.

NUCLEAR REACTION: $^{56}\text{Fe}(p, ^3\text{He})$, $E_p = 40.2$ MeV; measured $\sigma(E, \theta)$; enriched target. Deduced energies, L-values of ^{54}Mn levels.

* Supported by the National Science Foundation

** On leave of absence from Institut de Physique Nucleaire de Lyon, FRANCE.

for levels with $E_x > 1.5$ MeV. The reaction ${}^{56}\text{Fe}(p, {}^3\text{He})$ has never been utilized and should be an interesting tool to complete information on ${}^{54}\text{Mn}$, particularly in connection with other existing two-nucleon transfer reaction work.

II. EXPERIMENTAL PROCEDURE

The ${}^{56}\text{Fe}(p, {}^3\text{He})$ ${}^{54}\text{Mn}$ reaction has been studied with a 40.2 MeV proton beam energy at the Michigan State University Cyclotron. The target of 65 $\mu\text{g}/\text{cm}^2$ thickness was obtained by vacuum evaporation on a carbon backing of 30 $\mu\text{g}/\text{cm}^2$. The isotopic enrichment was 99.9% in ${}^{56}\text{Fe}$. The particles were analyzed by an Enge split-pole spectrograph. Detection and identification of particles were made by a position-sensitive single-wire counter, placed in the focal plane, in conjunction with a plastic scintillator. A typical spectrum with an overall energy resolution of 25 keV is shown in Fig. 1. The spectra were analyzed with the peak-fitting program AUTOFIT.¹⁶ Angular distributions, measured from 6° to 58° , are displayed in Fig. 2 and 3. Error bars include only statistical errors. The absolute cross-sections were obtained by normalization to the elastic scattering of protons on ${}^{56}\text{Fe}$ obtained under identical experimental conditions. The cross-section of the elastic scattering was computed with the parameters ($r_1=1.17$) of Becchetti and Greenlees.¹⁷ The accuracy of such a procedure is estimated to be 20%.

III. DISTORTED WAVES ANALYSIS

As in our previous work on ${}^{52}\text{Mn}^{18}$ and ${}^{48}\text{V}^{19}$ the experimental angular distributions were analyzed with code DWUCK,²⁰ in which the transferred pair wave function was evaluated according to the Bayman-Kallio method.²¹ The wave functions of the entrance and exit channels were computed with the same set of optical parameters which were used in Ref. 18 and 19. As can be seen in Fig. 2 the overall agreement between calculated and experimental angular distribution is in general good. Since a large excitation energy range (> 6 MeV) was covered in this study, one can see the effect of the Q-values on the shape of the calculated angular distributions. For example the $L=0$ transition at 6162 keV does not exhibit a deep first minimum like the $L=0$ transition to the 2112 keV level. In the case of $L=2$ transitions, the minimum around 25° observed for the ground state transition disappears for the 5705 and 5792 keV transitions. The choice of the orbits of the transferred nucleons has no influence on the shape of the calculated angular distribution.

IV. RESULTS AND DISCUSSION

Table I shows the results of the present analysis. We have also included the results of (d, α) ^{10,11}, $({}^3\text{He}, p)$ ⁸, $({}^3\text{He}, d)$ ⁵ reactions and also some of the γ -ray data.^{12,14,15} A total of 78 levels was observed with excitation energies up to 6162 keV. The energy excitation scale was established by means of the following reference peaks: Ground state, 1016 and 1922 keV levels. The agreement with other experiments is always within

20 keV. For some levels there are discrepancies, and it might be that some of the correspondences assumed are not valid, particularly at the higher excitation energies. A comparison of the angular momenta determined in the present work with those obtained in other experiments permitted several new J^π assignments.

A. Low Lying Levels ($E_x < 2.2$ MeV)

In the simple shell model, ^{54}Mn is represented as a $2p_{3/2}$ neutron coupled to an unpaired proton of the $f_{7/2}$ shell. Thus if the low-lying states display this structure, they will be observed in $(^3\text{He}, d)$ reaction with $\ell=3$ transitions. This is the case for levels up to 404 keV. In order to see if such a representation is correct for these levels, we have reported in Table II the ratio R between experimental and calculated cross-section for both $(p, ^3\text{He})$ and $(d, \alpha)^{11}$ works. In the case of even J transitions, only the $S=0$, $T=1$ term was used to compute the $(p, ^3\text{He})$ cross section. If the $f_{7/2}p_{3/2}$ model were correct, the ratio R would not change from state to state but could be different for the two reactions $(p, ^3\text{He})$ and (d, α) . The fact that this is clearly not the case shows that this model is too simple. Although for the ground state and 53 keV level the ratios, R , are quite similar, this is not true for the 369 keV state. There is a factor of 6 between the ratios computed for the cases of $(p, ^3\text{He})$ and (d, α) whereas this ratio is close to unity for the ground state and 53 keV state. It might be possible that the cross-section for the 369 keV state is overestimated in the (d, α) experiment due to the fact that the nearby 413 keV state is not resolved.

But our $(p, ^3\text{He})$ results show that the cross-section of this state is weaker than that of the 369 keV state. This discrepancy between the two experiments may be due to the fact that some compound nucleus effects are present in the (d, α) experiment since it was done at 12 MeV incident energy. In order to obtain a good fit to our data, it was necessary to introduce an $L=6$ component to the $L=4$ which was required by the 5^+ spin and a $1f_{7/2}2p_{3/2}$ proposed structure. It seems that either some $f_{5/2}$ or, more likely, $f_{7/2}$ components have to be present in order to explain the observed discrepancies for this state. The inconsistency of the ratio R for the first four states implies that the shell model basis has to be increased. As was pointed out in the Introduction, several calculations¹⁻⁴ have been done in which the neutrons occupy the $2p_{3/2}, 2p_{1/2}$ and $1f_{5/2}$ shells and the protons the $1f_{7/2}$ shell. We have represented in Fig. 4. the experimental level scheme ($E_x < 2.2$ MeV) as compared to the calculated one by Ohnuma.¹ One can see that up to 1.3 MeV there exists a correspondence between experimental and calculated levels. The level at 1078 keV is a 6^+ state which has no correspondent in the theoretical scheme. This level has been observed by an $\ell=3$ transition in the (d, t) experiment mentioned in the work of Kerr, et al.¹⁴ This establishes that this level is excited through pick-up in the $f_{7/2}$ shell and therefore would not be included in the existing calculations. Since there are more observed levels than predicted ones, this also casts a doubt on the validity of keeping the protons only in the $f_{7/2}$ shell. For example the 1^+ states at 1457 keV and 1649 keV cannot be

related to any calculated level. It seems that the level at 1785 keV is in fact a doublet, the pick-up experiments favoring a 5^+ assignment and the stripping experiment a spin value not greater than 3^+ . This is also the case for the 1922 keV level, for which the available data from transfer reactions favor a 1^+ value, but in an experiment by Poletti, et al.¹⁵ the observation of the γ -ray decay of ^{54}Mn after bombarding a ^{51}V target with a lithium beam shows that a level at 1925 keV is decaying towards the 6^+ state at 1078 keV. Assuming a multipolarity of 2, this means that the spin of the state is greater than 4 and that it is not the level observed in transfer reactions.

A 0^+ T=2 antianalog state is predicted to lie at 1730 keV, and Betts et al.⁸ have proposed the 2112 keV level as a candidate. We have observed this level in our experiment, and an L=0 is in agreement with the data, but an L=0+2 will clearly give a better fit to the data, making the 1^+ assignment more likely. Moreover this state has been observed in the (d, α) experiment of Majumder, et al.¹¹ which again favors the 1^+ value over the 0^+ , since 0^+ to 0^+ transitions are not allowed in such reactions. Thus, the 2112 keV state does not seem to be 0^+ and therefore is not the antianalog state. No other state below this one seems to be a candidate for a 0^+ assignment. It might be that one of the 1^+ levels observed is in fact a close doublet with a 0^+ and 1^+ , 2^+ or 3^+ member, thereby adding an L=2 component to the observed angular distribution. Experiments with much better resolution are necessary in order to solve this problem.

To sum up, the low lying level scheme of ^{54}Mn appears to be more complicated than the theoretical ones. In order to account for the observed level density, it seems necessary to introduce excitation of $f_{7/2}$ protons into higher shells and also to take into account excitation of neutrons from the $f_{7/2}$ shell.

It is interesting to note that the 1078 keV level may be viewed as the ground state of ^{52}Mn (6^+) plus a neutron pair in the $2p_{3/2}$ shell. One can wonder if such a picture is valid for other states in ^{54}Mn . It is likely that this will be the case for the high spin states, 6^+ or 7^+ , which are observed with L=6 in the (p, ^3He) experiments. Indeed, for states with spin lower than 6^+ , mixing with other shells (especially $2p_{3/2}$) is probable, and the simple model will no longer be valid. A 7^+ state is observed in ^{52}Mn at 867 keV¹⁸ the corresponding level in ^{54}Mn should lie at 1950 keV. There exists a state at 1922 MeV in ^{54}Mn , which, as mentioned previously, is a doublet. It might be that one of the members is the proposed 7^+ state. Experiments with much better resolution than obtained in this work are needed to answer this question. A probable 7^+ state at 2712 keV in ^{52}Mn is excited with reasonable intensity in the reaction $^{54}\text{Fe}(p, ^3\text{He})^{18}$ and would correspond to a level at 3790 keV in ^{54}Mn . A possible L=6 transition is observed for a level at 3760 keV. Nevertheless it should be remarked that a discrepancy exist for this level if it is a single state. The ($^3\text{He}, d$) results limit the spin to 3^+ or less. It seems likely therefore that stripping and pick-up experiments excite two different levels. There is some evidence that some levels of

^{54}Mn may be represented as ^{52}Mn plus two neutrons in the $2p_{3/2}$ shell, but more detailed work is needed to confirm such a picture.

B. Other Levels

In the absence of published wave functions for target and residual nuclei, it is difficult to discuss quantitatively the results which are collected in Table I. So only qualitative comments will be made. Some negative parity states have been observed in the present experiment and are confirmed by the (d,α) results of Majumder, et al.¹¹ This is the case for levels at 2781, 3013 (4^-), 3116 (2^-) and

3340 keV (4^-). An L=5 and L=3 angular momentum have been proposed by Majumder, et al.¹¹ for levels at 3807 and 4256 keV respectively. These levels are not observed in our experiment. The L=3 value of Majumder, et al. for the 4305 keV level is not in agreement with our L=4 value, but an L=4 assignment is also possible in the (d,α) data.

Looking at the 1^+ states, it is worthwhile to note that most of the levels observed in $(^3\text{He},p)$ experiments⁸ are present in our results. In view of the strong excitation of some of these levels (see Table I) in $(^3\text{He},p)$ these 1^+ states are constructed mainly on 2p components. The fact that these states are present in our spectrum means that the wave function of ^{56}Fe contains 2p components so that protons may occupy the $2p_{3/2}$ shell. It is also likely that some of the high lying 1^+ states are seen in our experiment through (sd) pick-up. Such a statement implies that the structure of these high lying states might be rather complicated, with a coexistence of particle and hole components.

The 3^+ state at 3711 keV is strongly excited both in (d,α) and $(p,^3\text{He})$ experiments. This may be an indication of the $(d_{3/2})_3^{-2} (f_{7/2})_0^{-2} (2p_{3/2})_0^2$ structure of this state. The 4305 keV level is observed with an L=4 angular distribution in our experiment. As mentioned above, the L=3 value given in the (d,α) experiment is doubtful, and an L=4 value is also possible. The $(^3\text{He},d)$ data lead to a probable $l=1$ value, selecting an even parity. Thus a 3^+ spin value is most likely. One should also note that this state is also strongly excited in both two-nucleon pick-up experiment and this is again in favor of $(d_{3/2})_3^{-2}$ structure.

V. CONCLUSION

The present work permitted some new spin parity assignment by comparison to other existing data. However a much better resolution is really needed for studies of odd-odd nucleus like ^{54}Mn since there exist close-lying doublets which account for most of the present discrepancies. Comparison of experimental results with available shell model calculations indicates that the structure of even the low lying levels is more complicated than assumed. Therefore, experiments with better resolution and more sophisticated shell model calculations will be necessary to understand ^{54}Mn thoroughly.

ACKNOWLEDGEMENTS

One of the authors (A.G.) wishes to thank Centre National de la Recherche Scientifique and N.A.T.O. for support while on leave of absence from Institut de Physique Nucleaire de Lyon (France).

REFERENCES

1. H. Ohnuma, Nucl. Phys. 88, 273(1966).
2. J. Vervier, Nucl. Phys. 78, 497(1966).
3. H. Horie and K. Ogawa, Prog. Theor. Phys. 46, 439(1971).
4. M. Gmitro, A. Rimini and T. Weber, N. Cim. 13A, 526(1973).
5. L.L. Lynn, W.E. Dorenbusch, T.A. Belote and J. Rapoport, Nucl. Phys. A135, 97(1969).
6. V.V. Okorokov, et al., Sov. J. Nucl. Phys. 4, 697(1967).
7. J.C. Legg and E. Rost, Phys. Rev. 134, B572(1964).
8. R.R. Betts, O. Hansen and D.J. Pullen, Nucl. Phys. A182, 69(1972).
9. J.H. Bjerregaard, P.F. Dahl, O. Hansen and G. Sidenius, Nucl. Phys. 51, 641(1964).
10. J.A. Hjorth, Ark. Fys. 33, 147(1966).
11. A.R. Majumder, H.M. Sen Gupta and A. Guichard, Nucl. Phys. A209, 615(1973).
12. M. Ogawa and H. Taketani, Nucl. Phys. A194, 259(1972).
13. J.K. Dickens, Phys. Rev. C5, 1977(1972).
14. P.G. Kerr, S.A. Wender and J.A. Cameron, Nucl. Phys. A226, 381(1974).
15. A.R. Poletti, B.A. Brown, D.B. Fossan and E.K. Warburton, Phys. Rev. C10, 2329(1974).
16. J.R. Comfort, Argonne National Laboratory (unpublished).
17. F.D. Becchetti, Jr., and G.W. Greenlees, Phys. Rev. 182, 1190(1969).
18. A. Guichard, W. Benenson and H. Nann, Phys. Rev. C11 (1975) (in press).

19. A. Guichard, W. Benenson and H. Nann, to be published.
20. P.D. Kunz, University of Colorado (unpublished).
21. B.F. Bayman and A. Kallio, Phys. Rev. 156, 1121(1967).

FIGURE CAPTIONS

Fig. 1--Energy spectrum of the $^{56}\text{Fe}(p, ^3\text{He})$ reaction at 14° .

Fig. 2--Angular distributions of the $^{56}\text{Fe}(p, ^3\text{He})$ reaction.

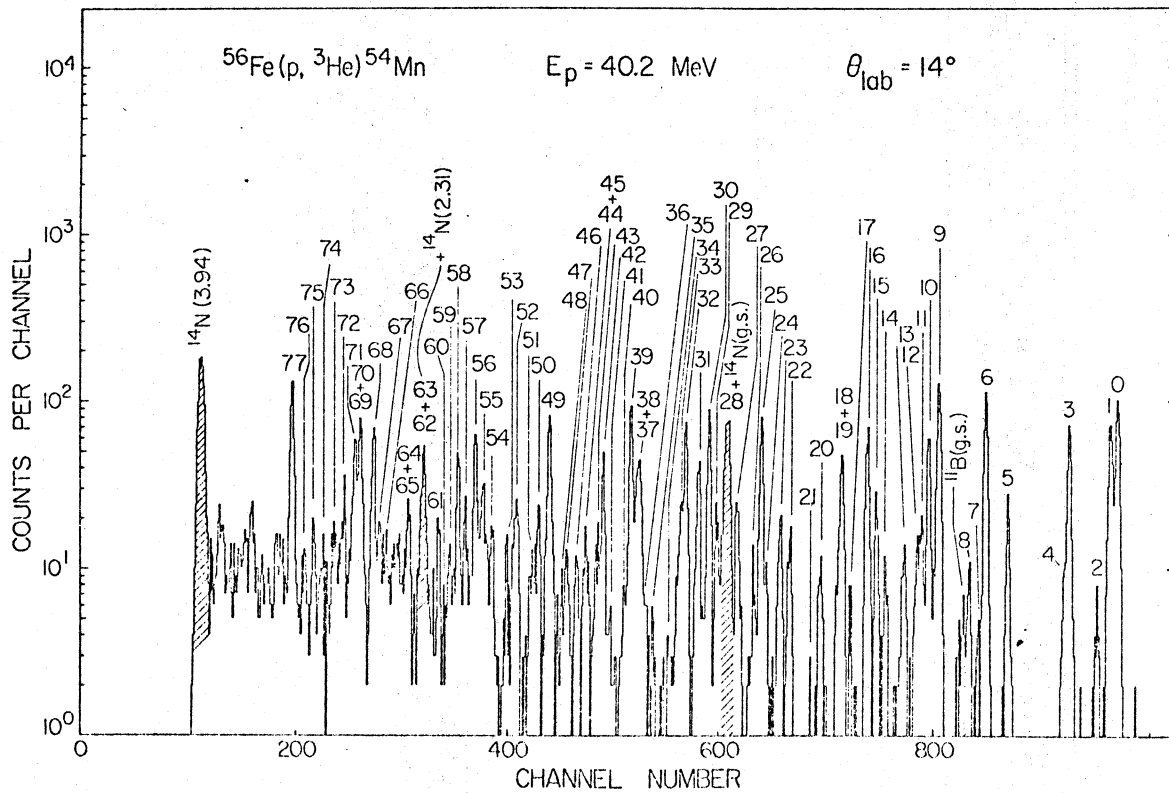
The solid and dashed curves are DWBA calculations.

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

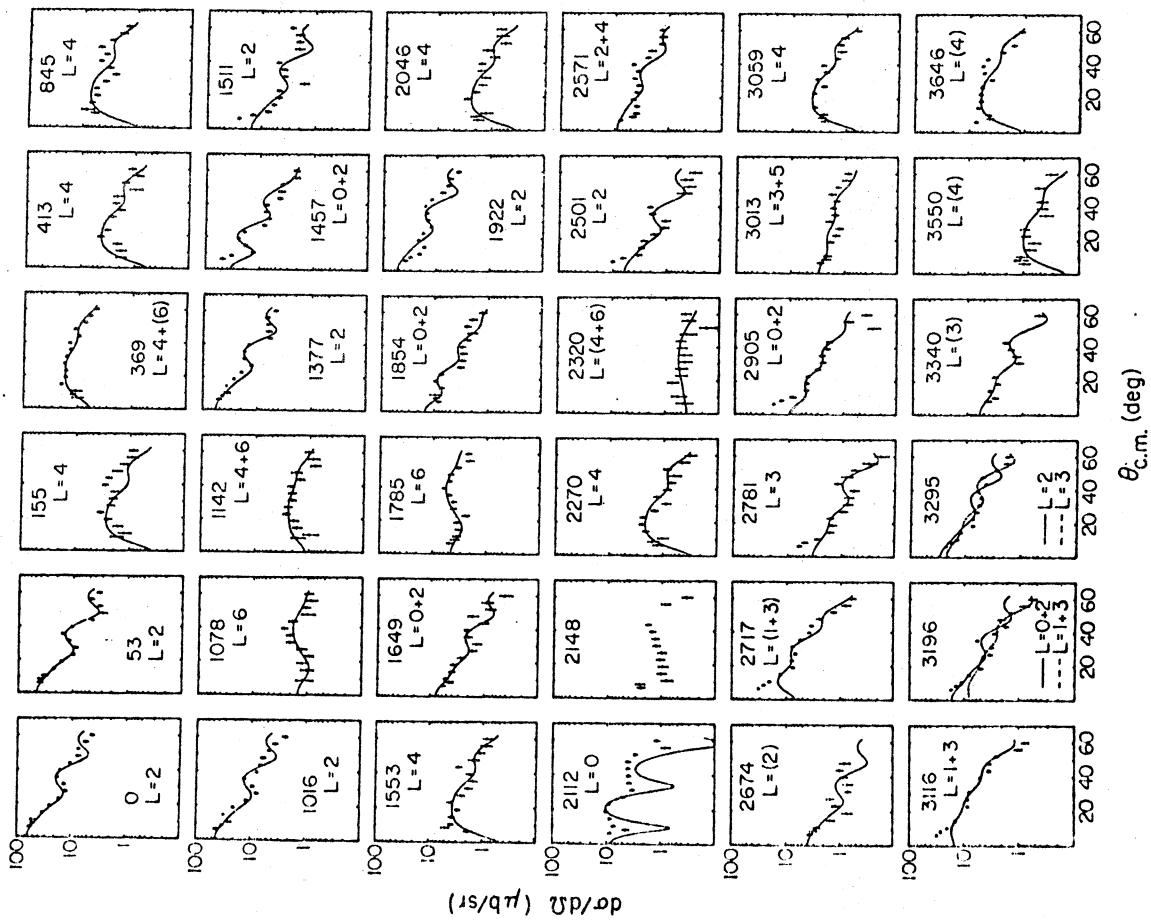
Fig. 4--Experimental and calculated (Ref. 1) low lying levels in ^{54}Mn .

TABLE II.--Ratio of experimental to calculated cross-section for $f_{7/2}p_{3/2}$ transfer in the case of (p, ^3He) and (d, α) experiments. (data for (d, α) work are from Ref. 11.)

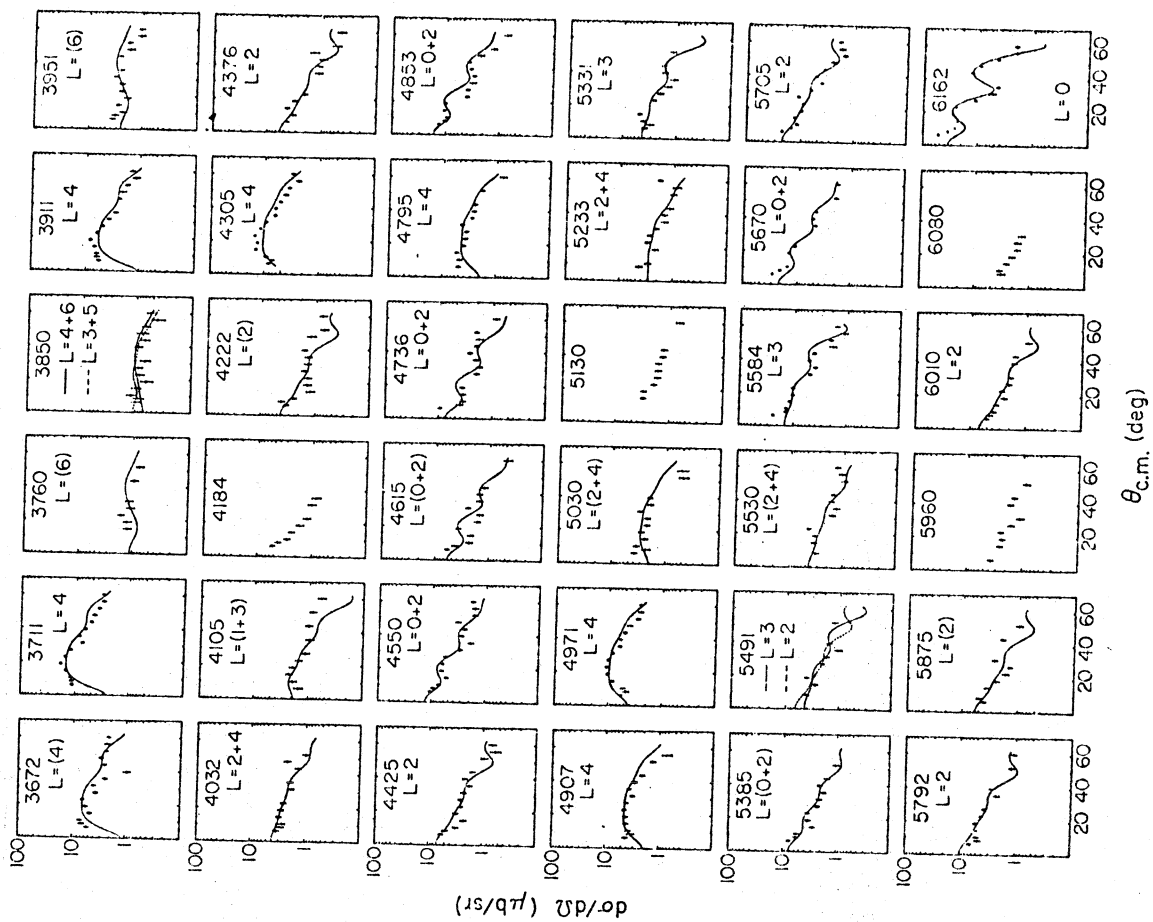
E_x (keV)	J^π	$R_1 = \frac{\sigma_{\text{exp}}(p, ^3\text{He})}{\sigma_{\text{DW}}}$	$R_2 = \frac{\sigma_{\text{exp}}(d, \alpha)}{\sigma_{\text{DW}}}$
0	3^+	35	43
53	2^+	13	16
155	4^+	2.5	
369	5^+	7	40



17



18



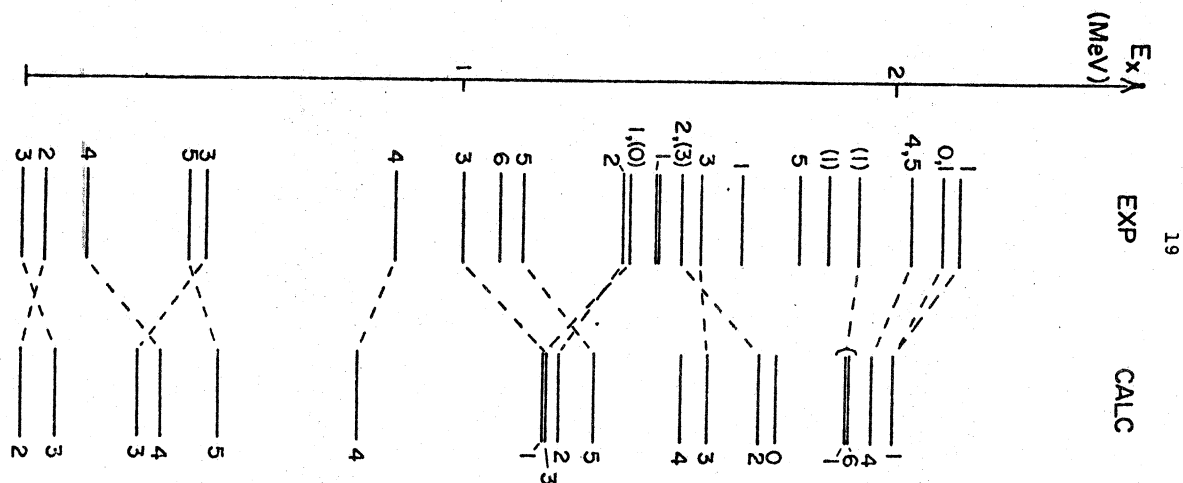


TABLE I.--⁵⁴Mn spectroscopic information.

(p, ³ He)		This work	Ref. 11 (d, α)		Ref. 10 (d, α)				Ref. 8 (³ He, p)		Ref. 5				J ^π	J ^π
level	E _x (keV)	($\frac{d\sigma}{d\Omega}$) _{max} (μb/sr)	L	E _x (keV)	($\frac{d\sigma}{d\Omega}$) _{max} (μb/sr)	L	E _x (keV)	L	E _x (keV)	($\frac{d\sigma}{d\Omega}$) _{max} ^a (μb/sr)	L	E _x (keV)	L	E _x (keV)	J ^π	J ^π
0	0	58	2	0	103	2	0	2	0	28	2	0	3	0	3 ⁺	3 ⁺
1	53	40	2	54	26	2			54	25	2	65	3	54.5 ^b	2 ⁺	2 ⁺
2	155	3	4	157	9.5		137	(2)				160	3	156.2 ^b	4 ⁺	4 ⁺
3	369	20	4+(6)				365	4	374	28	4	363	3	368.1 ^b	5 ⁺	5 ⁺
				364	262	4										
4	413	4.4	4									404	3	407.4 ^b	3 ⁺	3 ⁺
5	845	8.5	4	834	23	0+2	824	(0)						838.9 ^c	4 ⁺	4 ⁺
6	1016	4.4	2	1007	95	2	1011	2	1014	100	2	1004	1	1008.3 ^c	3 ⁺	3 ⁺
7	1078	2.5	6	1074	6.4	n.s.	1115							1072.4 ^c	6(5) ⁺	6 ⁺
8	1142	2.6	4+6	1131	24	4								1136.5 ^c	5(5) ⁺	5 ⁺
9	1377	50	2	1378	64	2	1386	4	1380	72	2	1377		1374.5 ^b	2	2
														1390.7 ^b	1(0 ⁺)	1(0 ⁺)
10	1457	48	0+2	1456	34	2			1457	286	0+2	1458	1	1454.2 ^b	1 ⁺ (0 ⁺)	1 ⁺
														1461 ^e		
														1508.7 ^b	2(3)	2 ⁺ (3) ^d
11	1511	26	2	1509	17	0+2(3)				1512				1506		
12	1553	5	4	1544	15	2	(1540)			1543			(3)	1546	3 ⁺	3 ⁺
13	1649	5.6	0+2	1634	13	(0+2)	(1610)			1649	102	0+2	1634	1	1784 ^c	1 ⁺
14	1785	4.6	6	1784	48	4	1783	(1)	1788	14	(2)	1784	1	1784 ^c	(+) ^d	1 ⁺
15	1854	9	(0+2)	1858	21	4							(1)	1857	(1) ⁺	(1) ⁺
16	1922	29	2, (0+2)	1921	91	4	1918	2	1930	739	0+2	1919	(1)	1925 ^c	4 ⁺	4 ⁺
17	2046	2.6	4						2060						4 ⁺	4 ⁺
18	2112	10	0, (0+2)	2111	16	0+2	2102	(4)	2119	561	0	2111	1		0 ⁺	0 ⁺
19	2148	2.5	2	2135	14	2	2140		2140	473	0+2	2133			1 ⁺	1 ⁺
20	2270	2.5	4	2268	16	(4)	2290	(4)	2282			2268			3 ⁺	3 ⁺
21	2320	0.7	(4+6)												5 ⁺	5 ⁺
									2366			2354				
22	2501	10	2						2504	193	0+2	2497	1		1 ⁺	1 ⁺
23	2571	8	2+4	2556	62	4	2575	2	2564	207	2	2556	1		3 ⁺	3 ⁺
24	2674	3.6	(2)	2669	15	2			2679	191	0+2	2669	1		1 ⁺	1 ⁺
25	2717	30	(1+3)	2712	54	2	2700	3(6)				2712	0	2715 ^e	(2 ⁺) ^d	(2 ⁺) ^d
26	2781	6	3	2765	15	3						2765			2 ⁺	2 ⁺
				2871			2850	(0)	2881	89	2	2871	1	2856 ^e	(1 ⁺)	(1 ⁺)
27	2905	19	0+2				(2930)		2908	183	0+2				1 ⁺	1 ⁺
28	3013	2.9	3+5	3012	27	3			3019	63	2	3012	1		d	d

TABLE 1.--Continued.

[illegible]

TABLE I.--Continued.

[illegible][illegible]

