Spectroscopy of ^{52}Mn from the ^{54}Fe(d,α) Reaction at 15 MeV

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The ^{54}Fe$(d,\alpha)^{52}$Mn reaction has been studied at 15-MeV incident energy. Angular distributions, up to an excitation energy of 4.7 MeV, have been obtained. Distorted-wave Born-approximation calculations have been carried out on the basis of the two-nucleon-transfer theory of Glendenning. The results provide information on the configuration of ^{52}Mn levels.

I. INTRODUCTION

The experimental study of ^{52}Mn is rather difficult because one cannot reach this nucleus by a single-nucleon-transfer reaction. It has been made possible to study it by the two-nucleon-transfer reactions ^{50}Cr(τ,p)[1] and ^{54}Fe(d,α)[2-4] or by the charge exchange reaction ^{52}Cr(τ,t).[5] Being an odd-odd nucleus, its study requires a good experimental resolution; the reaction ^{54}Fe$(d,\alpha)^{52}$Mn has therefore been studied with an energy resolution better than 20 keV at an incident energy of 15 MeV. While the analysis of these results was in progress, this reaction has been studied by Kelleter *et al.*[4] at the same energy. Our experimental results have, however, been obtained with a better energy resolution and in a larger excitation range (4.7 MeV).

From the theoretical point of view, there exist calculations only for $(f_{7/2})^{-4}$ configuration by McCullen, Bayman, and Zamick,[6] Bayman,[7] and Schwartz.[8] The main difference between the various calculations is in the choice of the matrix elements. There have been no calculation for other configurations.

In this work, we have tried, using the calculations of Refs. 6–8, to select the levels with $(f_{7/2})^{-4}$ configuration. We also look for levels with other configurations and compare our results with those obtained by the ^{50}Cr(τ,p) reaction.[1]

II. EXPERIMENTAL PROCEDURE AND EXPERIMENTAL RESULTS

The experiment has been performed with 15-MeV deuterons delivered by the Saclay F. N. tandem. The average current on the target was about 400 nA. The target (97.5% of ^{54}Fe) has been made by vacuum evaporation on a 20-μg/cm^2 carbon backing. Its thickness was 37 μg/cm^2. The particles were analyzed with a Buechner-type magnet and were detected by α sensitive plates. A Mylar foil of 50-μm thickness was placed in front of the plates to prevent the detection of more ionizing particles. The solid angle was a function of the position of the particles in the focal plane. On an average it was 4.5×10^{-4} sr, the opening angle in the plane of the reaction being 1/3°. A spectrum obtained at 45° is shown in Fig. 1. The position of the levels up to an excitation energy ~2 MeV is given with a precision of ±7 keV, but for higher excitation it is less precise (~±10 keV); the energy resolution is, however, less than 20 keV. Spectra have been analyzed up to an excitation energy of 4.69 MeV. For higher excitation energies, the analysis becomes too uncertain because of the higher level density. One can see (Table I) that our values giving the excitation energies are in good agreement with those obtained by Hansen, Mulligan, and Pullen[1] with a (τ,p) reaction and by Rapaport, Dorenbusch, and Belote,[2] but there is a slight shift from the values obtained by Kelleter *et al.*[4]

The measurements have been made from 10 to 70° in steps of 5°. A run has been made at 6°, but only the first few excited levels could be seen; for higher excitations, the deuteron background became too large. Figure 2 gives the angular distributions. The absolute values of the cross sections have been given with an error of ±20%.

III. METHOD OF ANALYSIS

The analysis of the experimental results has been made with the code DWUCK and a zero-range interaction. Calculation of the form factor has been performed with Glendenning's method.[9] The transferred-pair wave function is then

$$U_L(r)=\sum_N U_{NL}(r)G_{NLJ},$$

where N, L, and J are the quantum numbers of the center of mass of the transferred pair, G_{NLJ} is the structure factor tabulated by Glendenning,[10] and $U_{NL}(r)$ is the wave function calculated in an harmonic-oscillator well (whose parameter is $\nu=0.292$).

$U_L(r)$ is matched to a Hankel function at the surface of the nucleus.

The optical parameters which are needed for the calculation of the wave functions in the entrance and exit channels are given in Table II. Potentials are of the Woods-Saxon type with, in the case of the entrance channel, a Woods-Saxon derivative term for the imaginary part.

The shapes of the angular distributions depend rather strongly on the parameters chosen for the α potential.[3] The potentials used are those which give a good representation of the transitions to the 7^+ (0.88-MeV) and to the 5^+ (1.262-MeV) levels.

We have checked that the shapes of the angular distributions were not very sensitive to variations of the energy of the outgoing α particles, of the binding energy of the transferred pair, and of the configurations from which the nucleons are transferred.

Selection Rules

For a reaction $A(d, \alpha)B$, if one assumes that the incident deuteron picks a neutron-proton pair in a $T=0$, $S=1$ state, the selection rules are the following:

$$\vec{J}_A = \vec{J}_B + \vec{J} \quad \text{and} \quad \vec{J} = \vec{L} + \vec{S}$$

$$\vec{T}_A = \vec{T}_B \qquad (-1)^L = (-1)^{l_1} \times (-1)^{l_2},$$

where l_1 and l_2 are the orbital quantum numbers of the picked nucleons. In the case of ^{54}Fe $J^{\pi}_A = 0^+$, then $J_B = J$. If both nucleons are picked in the same subshell [$(lj)^2$ configuration] then J is odd.

One can see in Fig. 1 that the ground state and the 0.388- and 0.737-MeV levels of ^{52}Mn, [which are known as 6^+, 2^+, and 4^+ states having a $(f_{7/2})^{-4}$ structure] are very weakly excited. On the other hand the 7^+ state, with kinematical conditions similar to the ground state, is very strongly excited (2 orders of magnitude). This allows us to assume that, even for an energy of 15 MeV, the direct-reaction mechanism is valid.

IV. ANALYSIS AND DISCUSSION

All the experimental results and the distorted-wave Born-approximation (DWBA) calculations are shown in Fig. 2. It may be noticed here that most of the experimental angular distributions do not have pronounced structures and so there exist some ambiguities in the L assignments. The results obtained from this work as well as the data obtained from (d, α) reactions by Kelleter *et al.*,[4] Rapaport, Dorenbusch, and Belote,[2] Guichard *et al.*,[3] (τ, p) reactions by Hansen, Mulligan, and Pullen[1] and (τ, t) reactions by Bruge *et al.*[5] are listed in Table I.

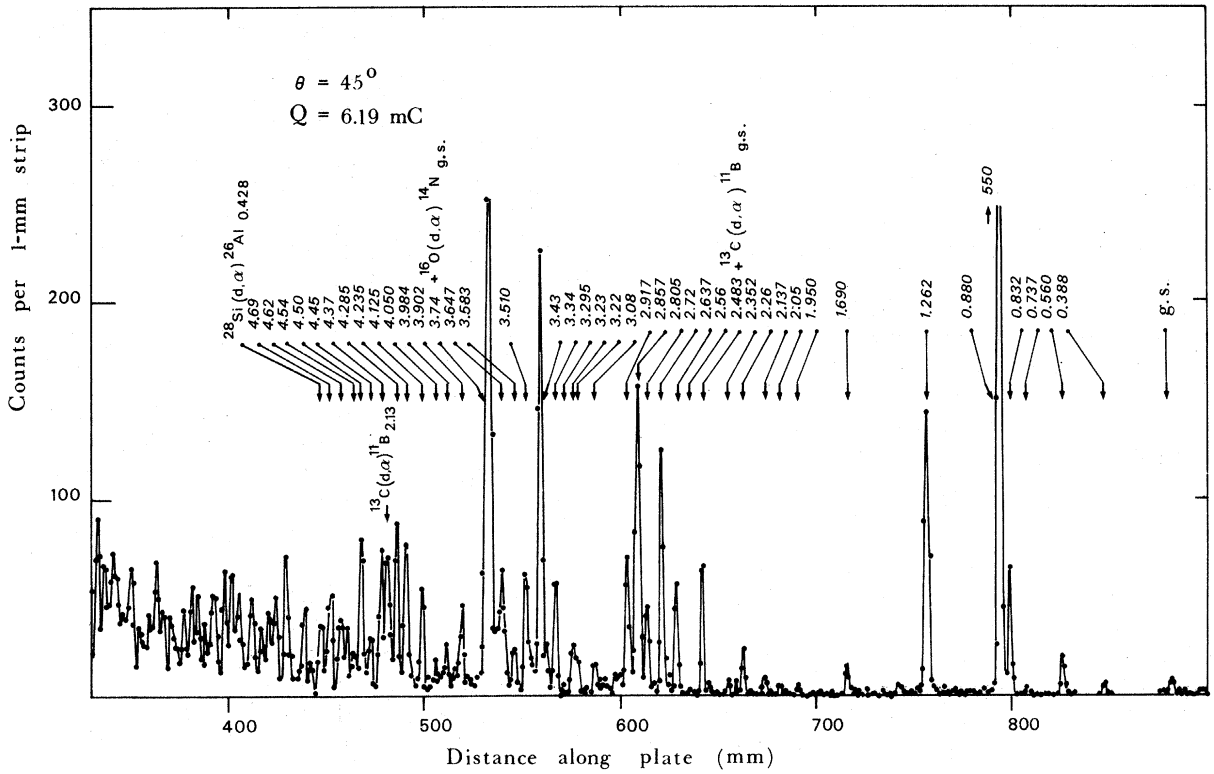

FIG. 1. α spectrum from the ^{54}Fe$(d, \alpha)^{52}$Mn reaction observed at 45° lab.

TABLE I. Excited levels of ^{52}Mn.

This work					(d, α) 15 MeV Ref. 4		(d, α) 28 MeV Ref. 3		(d, α) 7 MeV Ref. 2	^{50}Cr(τ, p) Ref. 1				^{52}Cr(τ, t) Ref. 5	
E_x	L	γ	σ_{max} (μb)	J^{π} [a]	E_x	L	E_x	L	E_x	E_x	L	J^{π}	σ_{max} (a.u.)	E_x	J^{π}
0		$f_{7/2}^{-4}$	2.4	6^+	0	(6)			0					0	6^+
0.388		$f_{7/2}^{-4}$	0.3	2^+	0.378	(2)			0.380	0.381			52	0.38	2^+
0.560		$f_{7/2}^{-4}$	18	1^+	0.546	0+2	0.55		0.546	0.554			122	0.55	1^+
0.737		$f_{7/2}^{-4}$	19	4^+	0.729	(4)			0.733					0.73	4^+
0.832	2+4	$f_{7/2}^{-4}$	32	3^+	0.828	2+4			0.828	0.828			60	0.85	
0.880	6	$f_{7/2}^{-4}$	200	7^+	0.876	6	0.85	6	0.872	0.881			95		
1.262	4	$f_{7/2}^{-4}$	80	5^+	1.271	4+6	1.26	4	1.244					1.26	5^+
					1.661				1.644						
1.690	4		12		1.701	2+4	1.67	4	1.683						
1.950					1.971				1.952						
2.050					2.06				2.04						
2.137	0+2	($f_{7/2}^{-4}$)	12	1^+	2.15		2.15	(2)	2.13						
2.26	4	($f_{7/2}^{-4}$)	10	3^+, 4^+, 5^+	2.27		2.28	4	2.26						
2.352	0+2	($f_{7/2}^{-4}$)	14	1^+	2.36				2.34	2.345	(2)		74		
										2.471	0	0^+	1149		
2.483	3	$f_{7/2}^{13}d_{3/2}^{-1}$	27		2.50	1+3	2.49	(0)(1)	2.48						
2.56					2.58				2.55						
2.637	0+2	($f_{7/2}^{10}p_{3/2}^{2}$)	65	1^+	2.66	0+2	2.64	0	2.63	2.634	0+2		3663		
					2.69				2.67	2.677			69	2.66	2^+
2.72	(5)	$f_{7/2}^{13}d_{3/2}^{-1}$	50		2.74	(5)	2.71	(3)	2.70	2.714			39		
									2.79	2.788	2		543		
2.805	2		30		2.82	(2)				2.803				2.82	1^+, 2^+
2.857	4		85		2.88	2+4	2.87	3	2.85	2.86			180		
										2.873			180		
										2.903	0	0^+,1^+	218		
2.917	5		29		2.94	(2)									
										2.93	0	0^+	1520	2.91	0^+
									2.97						
3.08	(5)	$f_{7/2}^{13}d^{-1}$	8				3.08		3.10						
3.22										3.213	0		228		
3.23									3.23						
							3.25	2		3.245	0+2		312		
3.295										3.296	2		74	3.31	
3.34	3	$f_{7/2}^{13}(sd)^{-1}$	40							3.337			70		
										3.418	2		184		
3.43	3	($f_{7/2}^{13}s_{1/2}^{-1}$)	120	(4^-)			3.46		3.42						
										3.48			2.44		
3.51	4,5		40												
3.583	0+2		20	1^+			3.58		3.58						
3.647	5,6		30						3.65						
3.74	2		30						3.75						
										3.776	2		315		
									3.87						
										3.885	(4)		85		
3.902	5	$f_{7/2}^{13}d^{-1}$													
3.984	0+2		41	1^+			3.96	(1,2)		3.975	(0+2)		169		
4.125	4		28	3^+-5^+						4.136			135		
4.235	6,5		28							4.237			258		
										4.281	2		245		
4.285	5	$f_{7/2}^{13}d^{-1}$	30												
										4.314			146		

TABLE I *(Continued)*

This work					(d,α) 15 MeV Ref. 4		(d,α) 28 MeV Ref. 3		(d,α) 7 MeV Ref. 2	$^{50}Cr(\tau,p)$ Ref. 1				$^{52}Cr(\tau,t)$ Ref. 5	
E_x	L	γ	σ_{max} (μb)	J^π [a]	E_x	L	E_x	L	E_x	E_x	L	J^π	σ_{max} (a.u.)	E_x	J^π
4.37	0+2		40	1^+			4.31			4.375	0+2	1^+	1224	4.39	(2^+)
4.45	4		21	3^+-5^+			4.42			4.44	2		204		
										4.46			51		
4.50	3	$f_{7/2}{}^{13}(sd)^{-1}$	30							4.50	0+2	1^+	418	4.50	(2^+)
4.54	3, 4		15				4.56								
4.62	3	$f_{7/2}{}^{13}(sd)^{-1}$	25							4.679			109		
4.69			30				4.7			4.704			185		

[a] The J^π values indicated here are those obtained from other previous experiments and from this work.

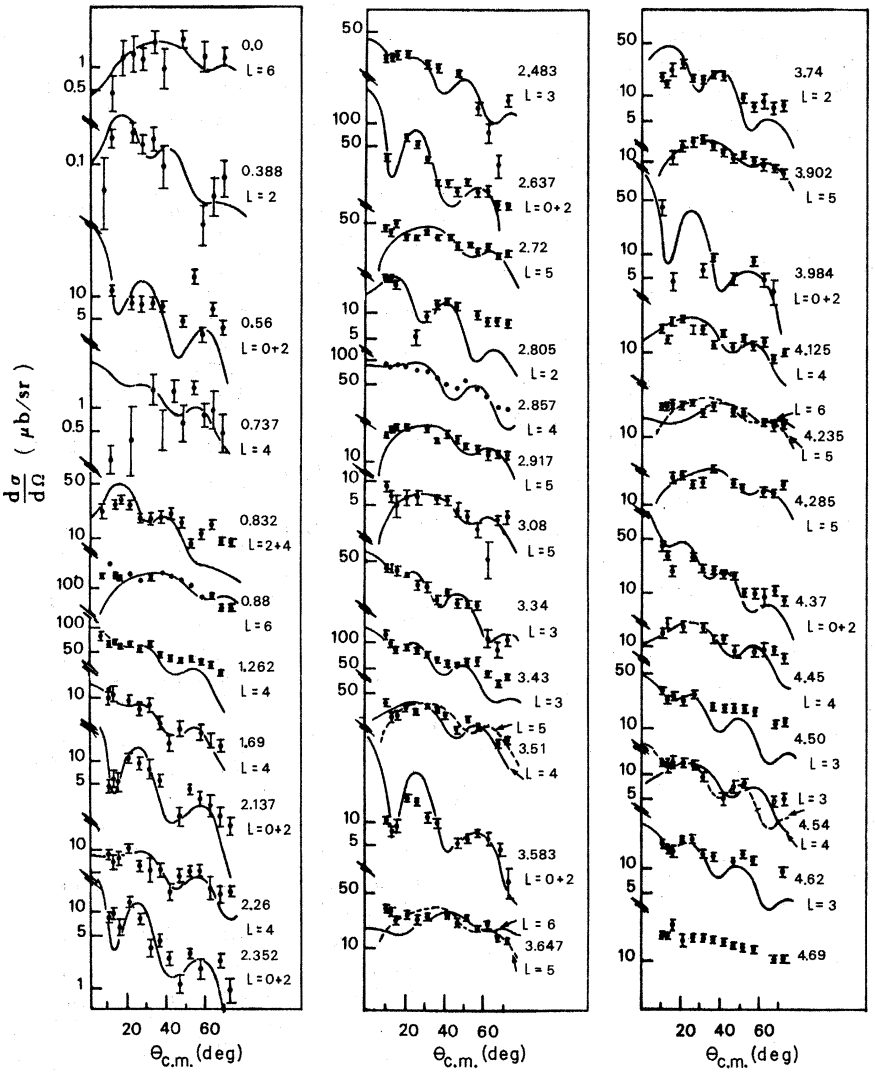

FIG. 2. Angular distributions obtained for $^{54}Fe(d,\alpha)^{52}Mn$ reaction. Solid curves are DWBA calculations made for the indicated L values.

TABLE II. Optical-potential parameters for the deuteron and α channels.

	V (MeV)	r_0 (fm)	a (fm)	W (vol) (MeV)	W_D (surf.) (MeV)	r_{0i} (fm)	a_i (fm)	r_c (fm)	Reference
d	64.8	1.448	0.689		26.6	1.412	0.461	1.3	a
α	180	1.22	0.796	31.65		1.63	0.423	1.3	b

[a] C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).
[b] R. Stock *et al.*, Nucl. Phys. A104, 136 (1967).

Spectroscopy of ^{52}Mn is not well known because it is not possible to reach this nucleus by a single-nucleon-transfer reaction. Furthermore, we have no detailed wave functions for various excited levels of ^{52}Mn. The only calculations which have been made, in a $(f_{7/2})^4$ configuration, used an effective interaction deduced from the experimental spectra of ^{42}Sc.[6-8] One should remark that, in a pure $(f_{7/2})^n$ configuration, the level schemes of cross-conjugate nuclei, ^{44}Sc, and ^{52}Mn, should be the same. For other configurations, we have no information.

$\pi(f_{7/2})^5\nu(f_{7/2})^7$ Configurations

Spins and parities of the first excited states of ^{52}Mn (up to 1.262 MeV) are known. These states have mainly a $\pi(f_{7/2})^5\nu(f_{7/2})^7$ structure. One can notice in Fig. 1 that the 6^+, 2^+, and 4^+ states are very weakly excited, which is in agreement with the assumed reaction mechanism and the selection rules. However, the fact that such levels are seen can be attributed:
(1) to a different reaction mechanism (compound nucleus, for instance). In a (d, α) reaction at 7 MeV, the 6^+ level is more strongly excited.
(2) to the existence of a weak component of the $[(f_{7/2})^{13}(f_{5/2})^1]^{J=0^+}$ configuration in ^{54}Fe. Such a component has been observed in the ground state of ^{48}Ti by Pohl, Santo, and Wagner.[11] Calculations made by Pittel[12] show that such components, with excitation of particles in the p and f shells, can be important.

One can also note that the 0.88-MeV $J=7^+$ level is strongly excited. This can be explained because the structure coefficients for the pickup of a $(f_{7/2})^2$ pair coupled to $J=7$ are large, and also the spectroscopic factor is proportional to $2J+1$.

The 0.560-, 0.832-, and 1.262-MeV states have spins 1^+, 3^+, and 5^+, respectively, and belong mainly to the $(f_{7/2})^{12}$ multiplet. In Table III we have shown the spectroscopic factor (S_{AB}) divided by $2J+1$ for these states, this ratio has been normalized to one for the 7^+ state. It should be constant if these levels had truly a pure $(f_{7/2})^{12}$ structure, and if the DWBA analysis was valid. For the 1^+ state, the discrepancy is important. This can be explained by the fact that the DWBA does not fit the experimental distribution. Our results confirm those obtained by Kelleter *et al.*[4]

Figure 3 shows the level schemes calculated in $(f_{7/2})^{-4}$ configuration by McCullen, Bayman, and Zamick[6] and by Bayman.[7] It is rather easy to obtain a good correspondence between the low-lying energy levels. However, the situation is different at higher energies because of the large level density.

Three other 7^+ levels were predicted by McCullen, Bayman, and Zamick at 3.54, 3.98, and 6.92 MeV. The last two of them should be weakly excited, but the 3.54 level should be, theoretically, 6 times less excited than the 0.880-MeV 7^+ level. Taking this into account, this 7^+ level could be identified with several levels: 3.647, 4.235, and 4.285 MeV. The angular distributions of these levels are characterized by $L=5$ or 6 (the distinction between $L=5$ or 6 is sometimes ambiguous) and furthermore, the cross sections are in the range of the expected order of magnitude.

Bayman[7] predicted a 1^+ level at 2.30 MeV. In this energy range, we observe two levels with $L=0+2$, $J^\pi=1^+$ distribution. One of these levels could be identified with the one calculated by Bayman, and could then have a $(f_{7/2})^{12}$ structure.

Bayman also obtains a 5^+ level at 2.05 MeV and a 3^+ level at 2.21 MeV. The observed level at 2.26 MeV is characterized by $L=4$. If its structure is

TABLE III. Experimental spectroscopic factors divided by $2J+1$ normalized to the 7^+ (0.880-MeV) level for the low-lying states of ^{52}Mn.

E_x	J^π	$S_{AB}/(2J+1)$ [a]	$S_{AB}/(2J+1)$ [b]
0.880	7^+	1	1
1.262	5^+	0.82	0.72
0.832	3^+	0.6	0.43
0.560	1^+	0.3	0.25

[a] This work.
[b] Reference 4.

$(f_{7/2})^{12}$, the fact that $L=4$ means $J=5^+$ because, in this case, for a given J, the minimum L is dominant in the angular distribution.

$(f_{7/2}{}^{13}d_{3/2}{}^{-1})$ or $(f_{7/2}{}^{13}s_{1/2}{}^{-1})$ Configurations

The angular distributions for levels having this structure are characterized by an odd transferred angular momentum and a negative parity. The level at 2.483 MeV, observed with $L=3$ in this work and with $L=1+3$, $J=2^-$ by Kelleter *et al.* has a $(f_{7/2}{}^{13}d_{3/2}{}^{-1})$ structure. This level is different from the level observed at 2.471 MeV in a (τ, p) reaction by Hansen, Mulligan, and Pullen[1] with $L=0$, and, probably, $J=0^+$. Such a state cannot be seen in a (d, α) reaction. The 2.72-MeV state could be represented by $L=5$ at 15 MeV and $L=3$ at 28 MeV, which would be compatible with a $J=4^-$ spin and a $(f_{7/2}{}^{13}d_{3/2}{}^{-1})$ structure. This level could then be identified with the level obtained at 2.714 MeV in the (τ, p) reaction, with a weak intensity. Kelleter *et al.* attribute to the 2.94-MeV level an orbital angular momentum $L=2$, while we attribute to this level the value $L=5$. These two values are not compatible; however, the agreement between experimental points and theoretical curve obtained by Kelleter *et al.* is not very convincing. It seems therefore that this level may not have been observed in the (τ, p) reaction[1] [the 2.93-MeV level is the isobaric analog state of ^{52}Cr, which cannot be seen in a (d, α) reaction].

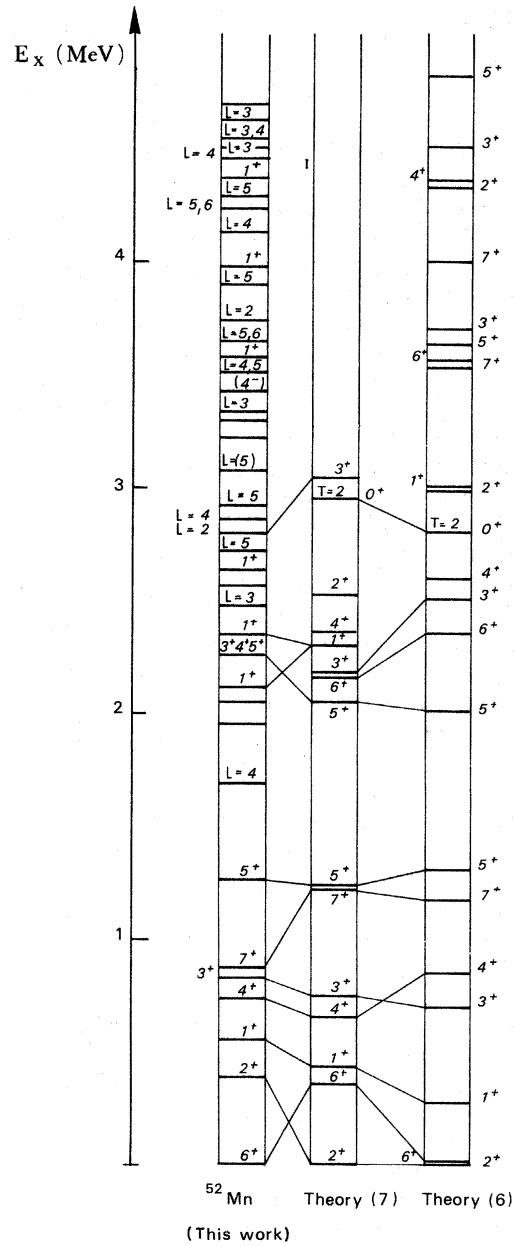

FIG. 3. Level scheme of ^{52}Mn and comparison with levels calculated by McCullen, Bayman, and Zamick (Ref. 6) and Bayman (Ref. 7) in $(f^{7/2})^4$ configuration.

The levels at 3.08, 3.902, and 4.285 MeV may be characterized by $L=5$. They may then have a $(f_{7/2}{}^{13}d^{-1})$ configuration mainly. The $L=3$ levels belong either to the $(f_{7/2}{}^{13}s_{1/2}{}^{-1})$ multiplet or to the $(f_{7/2}{}^{13}d^{-1})$ multiplet. However it may be noticed that $(f_{7/2}{}^{13}s_{1/2}{}^{-1})$ structure coefficients are very large for $L=3$ $J=4$, which leads to a high cross section. The 3.43 level, which fits to a $L=3$ distribution, is strongly excited; it could therefore be identified with such a state. For several other levels (3.34, 4.50, 4.54, and 4.62 MeV) also reproduced by $L=3$ distributions, it has not been possible to say from which shell (s or d) a nucleon has been picked. The 4.50-MeV level has been strongly excited in the (τ, p) reaction with a $0+2$ distribution. It is probably not the same level.

Other Configurations

The 2.637-MeV level is well represented by a $L=0+2$, $J^\pi=1^+$ distribution. It is very strongly excited in a (τ, p) reaction, also with a $L=0+2$, $J^\pi=1^+$ distribution. Hansen, Mulligan, and Pullen attribute to this level a $(2p)^2$ structure because the structure coefficients are then very large, and the reaction kinematic enhances the small transferred momenta. The fact that such a level is seen in the (d, α) reactions means the existence of a $2p$ component in the wave function of the ground state of ^{54}Fe. This is confirmed by the ^{54}Fe$(d, \tau)^{13}$ reaction at 34.4 MeV and the ^{54}Fe$(\tau, \alpha)^{14}$ reaction at 13 MeV, which show $l=1$ components. It seems that other levels observed in (d, α) reaction show also $(2p)$ components. It is the case of 4.37-MeV level, spin 1^+, obtained in the (τ, p) reaction with a strong in-

tensity, which indicates the probable existence of $2p$ components. It can also be the case of the 3.583-MeV level.

The 2.805-MeV level is characterized by $L=2$ in (d, α) and (τ, p) reactions: in the latter case, it is observed with a strong intensity. Its structure could also include $(2p\text{-}f)$ components.

Some other levels are also seen in both (d, α) and (τ, p) reactions, in this last case with rather weak intensities. It is then difficult to say what is the main configuration of these levels. It is the case of the 2.857- ($L=4$), 4.125- ($L=4$), and 3.984-MeV ($L=0+2$) levels. The 3.51- and 3.74-MeV states may be characterized by $L=4$ and $L=2$, respectively. They do not seem to be excited in the (τ, p) reaction. It is possible that they correspond to (d^{-2}) structures.

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