Spin-parity combinations and low-lying 2p-4h states in ^{54}Mn

A. A. Pilt, J. A. Cameron, and J. A. Kuehner
Tandem Accelerator Laboratory, McMaster University, Hamilton, Ontario, L8S 4M1 Canada
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The tensor analyzing powers T_{20} of outgoing α particles at $\theta = 4^\circ$ have been measured in the ^{56}Fe($\vec{d}$,α)^{54}Mn reaction at incident energies of 7.5, 8.0, 8.5, 9.0, and 9.5 MeV. The resulting determination of natural or unnatural parity led to the following new unambiguous J^π assignments: 839 keV, 4^+; 1073 keV, 6^+; 1137 keV, 5^+; 1391 keV, 1^+; 1454 keV, 1^+; 1.51 MeV, 2^+; and 1.87 MeV, 3^+. In addition, natural or unnatural parity assignments were made to several levels above 2 MeV excitation for which no spin information existed prior to this experiment. A measurement of the angular distribution of outgoing α particles in an unpolarized (d,α) reaction led to a tentative 0^+ assignment to a state at 1.68 MeV on the basis of decreasing cross section at forward angles. The results are compared to 1p3h + 2p4h shell model calculations and we suggest that the 1.51, 1.68, and 1.85 MeV levels are largely 2p-4h states.

[NUCLEAR REACTIONS ^{56}Fe($\vec{d}$,α), E=7.5, 8.0, 8.5, 9.0, and 9.5 MeV; measured $T_{20}(4^\circ)$; ^{54}Mn deduced levels, J, π. ^{56}Fe(d,α), E=9.0 MeV; measured $\sigma(E_\alpha, \theta)$; ^{54}Mn level deduced $J^\pi = (0^+)$. Comparison with shell-model calculations.]

I. INTRODUCTION

It has been shown in several recent papers[1-4] that measurements of the ($\vec{d}$,α) reaction, using tensor-polarized deuterons on even-even nuclei, lead to model-independent values of spin-parity combinations in the residual odd-odd nuclei. Briefly, the method is as follows. The tensor analyzing power (TAP) of α particles emitted near 0° (or 180°) in the ($\vec{d}$,α) reaction is measured. It can be shown[1] that $T_{20} = 1/\sqrt{2}$ for natural parity [$\pi = (-)^J$] states (but not $J^\pi = 0^+$ for which the 0° cross section vanishes) and $T_{20} = -\sqrt{2}$ for $J^\pi = 0^-$ states. For unnatural parity [$\pi = (-)^{J+1}$] states, T_{20} can take on any value between these two limits: $-\sqrt{2} \leq T_{20} \leq 1/\sqrt{2}$. Thus an unnatural parity assignment may readily be made if T_{20} is not near one or the other of these limits.

Possible erroneous assignments may result from two sources: (1) an accidental value of $T_{20} = 1/\sqrt{2}$ or $-\sqrt{2}$ for an unnatural parity state, resulting in a misidentification of such a state as a natural parity or 0^- one, respectively, and (2) a severe attenuation of T_{20} from either of its limiting values due to the experimental necessity of detecting the α particles at a small but nonzero angle (here, $\theta_\alpha = 4^\circ$). This would lead to a natural parity or 0^- state not being recognized as such.

Possibility (1) is usually avoided by measuring the TAP at several different incident beam energies. The assumption that the reaction proceeds via compound nucleus formation (implying that T_{20} fluctuates rapidly with energy) is usually invoked and has been shown to give good results: If T_{20} stays at one or the other of the two limits, $+1/\sqrt{2}$ or $-\sqrt{2}$, for several ($\geq$ 3) incident energies, then one can say with good confidence[4] that the state has natural parity or is 0^-, respectively. If the reaction is direct, however, there is no *a priori* reason why this argument should hold and a constant T_{20} of $1/\sqrt{2}$ (say) might occur. The present experiment was, therefore, carried out at low deuteron energies (E_d = 8–10 MeV) where CN effects are expected[5] to dominate.

Attenuation of T_{20} from its limiting values occurs if the exiting α particles are not measured at precisely 0° or 180°. This attenuation has been calculated for both compound[2] and direct[6] reaction mechanisms and has been found to be about the same for both assumptions, as shown in Fig. 1. For example, the 4° value for T_{20} for a natural parity state is ~0.65 instead of 0.71—an 8% attenuation. This is comparable with the error limits on the measured T_{20} values.

In this paper, we apply this technique to the ^{56}Fe($\vec{d}$,α)^{54}Mn reaction. Odd-odd pf shell nuclei have been extensively studied by various direct[7] and fusion-evaporation[8] reactions, but many J^π ambiguities still exist, largely because transfer reactions to odd-odd nuclei can only determine L values and not J. Such J assignments are, however, important for the determination of empirical $f_{7/2}$ matrix elements[9] and the identification of particle-hole "intruder" states.

The currently available data[10] on ^{54}Mn reflect these ambiguities. For example, the level at 839 keV has $J^\pi = (4,5)^+$ and the two levels at 1073 and 1137 keV each have $J^\pi = (5,6)^+$ assignments. It is clear that a T_{20} measurement as described above should be able to distinguish between the two possibilities for each state (natural or unnatural parity). Indeed, we show in this work

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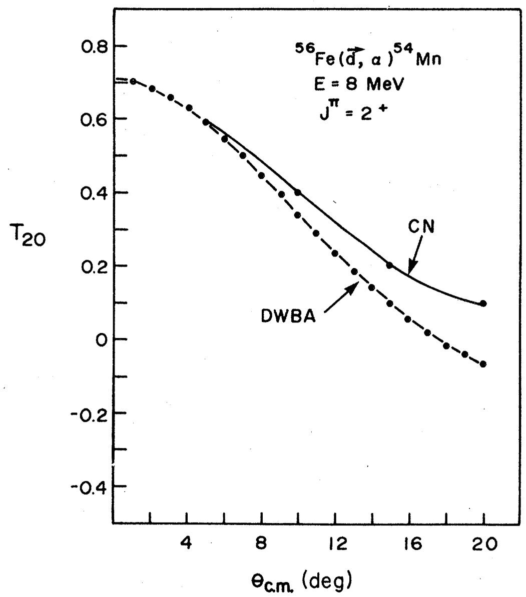

FIG. 1. Calculated values of T_{20} as a function of angle for a $J^{\pi}=2^{+}$ level. The direct-reaction calculation (dashed curve) is described in the text and Ref. 6. The CN calculation (solid curve) is from Ref. 4.

that the following new J^{π} assignments can be made to ^{54}Mn levels: 839 keV, 4^{+}; 1073 keV, 6^{+}; 1137 keV, 5^{+}; 1391 and 1454 keV, each 1^{+}. Less is known about higher states and we present several new N or U assignments to ^{54}Mn levels above 1.5 MeV excitation. In particular, we suggest 2^{+}, 0^{+}, and 3^{+} assignments to states at 1.51, 1.68, and 1.85 MeV.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

Beams of tensor-polarized deuterons from the Lamb-shift polarized ion source and FN tandem accelerator at McMaster University were used to bombard targets of enriched (98%) ^{56}Fe. The targets had a thickness of ~25 $\mu g/cm^2$ and were evaporated on 30 $\mu g/cm^2$ carbon backings. Average beam currents were 30 nA. The outgoing α particles were momentum analyzed by an Enge split-pole spectrograph and detected by a position sensitive gas proportional counter at the focal plane. An energy resolution of ~45 keV was obtained. Because of the difficulties[2] of 0° detection, α-particle spectra were taken at 4°. As discussed above, this should not affect our results appreciably.

To determine values of T_{20} at a particular bombarding energy, two α-particle spectra were collected using the same target: one with the deuterons preferentially polarized in the $m=0$ substate and the other in the $m=1$ substate, where the quantization axis is taken along the incident beam direction. The polarization of a deuteron beam is more commonly described by tensor components and for present purposes the significant component is t_{20}; for the "$m=0$" polarized beam $t_{20}=-P_0\sqrt{2}$ and for an "$m=1$" beam $t_{20}=P_1/\sqrt{2}$ where P_i ($i=0$ or 1) is the fraction of the beam which is polarized in the desired substate. The measurements of P and hence of t_{20} relied upon the so-called quench ratio method,[11] that is, by direct measurement of both the total beam current and, after appropriate alteration of the spin filter field in the ion source, the unpolarized component. (In general it is preferable also to calibrate directly the beam polarization using spectrum peaks corresponding to levels in the nucleus being studied which are known to have $J^{\pi}=0^{-}$ or natural parity. Unfortunately, no suitable levels were available in the present work.) Thus, P was determined from the quench ratio at frequent intervals during the course of the experiment and was found to be approximately constant at $P=0.70\pm0.06$ over the 3-day run. This value of P was used in the subsequent analysis and it was also assumed that $P_0=P_1$.

α-particle spectra were obtained at deuteron

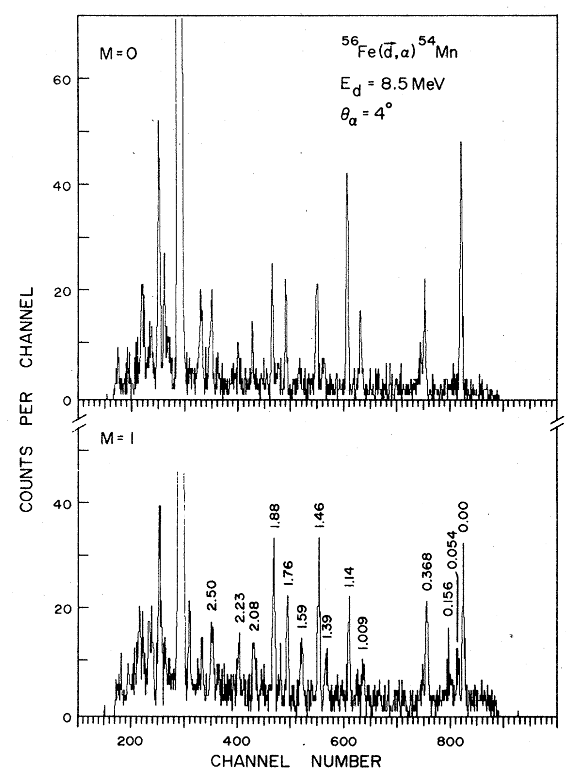

FIG. 2. Typical spectra of the $^{56}Fe(\vec{d},\alpha)^{54}Mn$ reaction at 8.5 MeV. Top: $t_{20}=-P\sqrt{2}$, bottom: $t_{20}=P/\sqrt{2}$. Peaks are labeled by excitation energy in ^{54}Mn. The 0.839 MeV level is populated very weakly at this energy.

energies of 7.50, 8.00, 8.50, 9.00, and 9.50 MeV. The range in excitation covered was ~0–3.0 MeV. Typical spectra for the two beam polarizations obtained at an incident energy of 8.5 MeV are shown in Fig. 2. Excitation energies in ^{54}Mn above 1 MeV were obtained from the lower states and the known spectrometer calibration. They are believed to be accurate to within ± 15 keV for states below 2.0 MeV excitation. For higher states, the increasing level density and detector nonlinearity makes identification of observed levels with known ones problematical. However, their energies should be accurate to ± 30 keV. Our resulting energies are compared with those from the literature in Table I. The major contaminant peaks resulted from the ^{16}O$(d,\alpha)^{14}$N and ^{12}C(d,α) ^{10}B reactions, which obscured peaks of interest in ^{54}Mn at some energies.

$J^\pi = 0^+$ levels cannot be populated at 0° in a (d,α) reaction on an even-even nucleus. To search for states in ^{54}Mn, an angular distribution measurement was carried out at 9 MeV beam energy at $\theta = 4°$, 10°, 15°, and 20°. For this measurement, an unpolarized deuteron beam was used (obtained by turning off the spin filter field in the ion source). The resulting beam currents were ~ 80 nA.

TABLE I. Excitation energies, parity determinations, and resulting spin-parity assignments to ^{54}Mn levels.

E_x (MeV) Present[a]	Previous[b]	Parity[c]	J^π Previous[d]	Present[e]
0.00	0.00	U	3^+	A
0.05	0.054	N	2^+	A
0.16	0.156	N	4^+	A
0.36	0.368	U	5^+	A
0.41	0.407	U[i]	3^+	A
0.84	0.838	N	$(4,5)^+$	4^+
1.01	1.009	U	3^+	A
1.07	1.073	N	$(5,6)^+$	6^+
1.14	1.136	U	$(5,6)^+$	5^+
1.39	1.390	U	$(0,1)^+$	1^+
1.45	1.454	U	$(0,1)^+$	1^+
1.53	1.508(1.543)[f]	N	$(2,3)^+$	2^+
1.68		(0^+)[j]		(0^+)
1.76	1.784 + 1.785	U	7^+	A
1.87	1.852	U	$(2,3)^+$[k]	3^+
2.03	2.050	(N)[i]		
2.08	g			
2.23	2.267	(N)[i]		
2.50	2.497	U		
2.56	h	U[i]		
2.65	h	U		
2.71	h	U		
2.78		(N)[i]		

[a] Average of (d,α) results of three or more energies unless noted. Errors are ±15 keV at E_x < 2 MeV and ±30 keV at E_x > 2 MeV. Wide, unusually shaped peaks and multiplets have not been included since T_{20} is unreliable.

[b] Reference 10.

[c] N means natural parity, U means unnatural parity.

[d] Reference 10.

[e] A means in agreement with previous work.

[f] Believed to correspond to 1.508 MeV level. See text for details.

[g] Multiplet (Ref. 10).

[h] Not listed as "adopted" in Ref. 10.

[i] Observed at only one or two energies. See Fig. 3.

[j] From angular distribution measurement. See text.

[k] Reference 12.

III. RESULTS AND DISCUSSION

At each incident energy the peak areas (after background subtraction) in the two spectra were normalized to the same integrated beam charge and the tensor analyzing power T_{20} was calculated for each peak from the ratio of the yields for the $m = 0$ and $m = 1$ polarization states of the deuteron beam. The results are shown in Figs. 3–5, where for each peak the T_{20} values are plotted from left to right in order of increasing bombarding energy. In some cases satisfactory data could not be obtained at all incident energies due to the corresponding level being too weakly populated or its contribution being obscured by a strong peak nearby. The principal sources of error in the results are statistical uncertainties, uncertainties in the

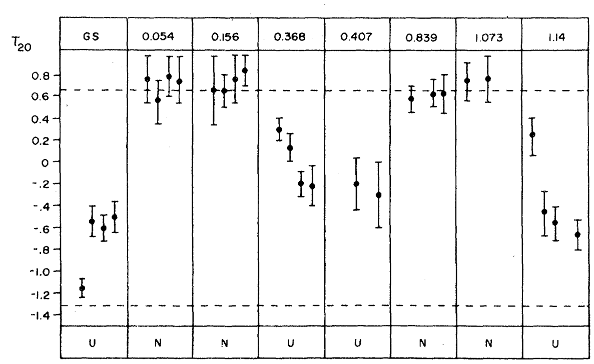

FIG. 3. Tensor analyzing powers T_{20} for the ^{56}Fe(d,α) reaction leading to levels of ^{54}Mn below 1.2 MeV excitation. The data for each level are grouped together and plotted from left to right in order of increasing bombarding energy. Note that not all states were populated at all bombarding energies (e.g., there is no 8.5 MeV point for the 0.839 MeV level). Each group is labeled at the top by the excitation energy in MeV of the corresponding level (or levels). At the bottom the spin-parity combinations deduced for the levels are given; N signifies natural parity, not including 0^+ and U signifies unnatural parity not including 0^-. The horizontal dashed lines indicate the values of T_{20} expected for natural parity and for 0^- levels when the reaction is observed at a laboratory angle of 4°, i.e., the attenuation described in Sec. I has been taken into account.

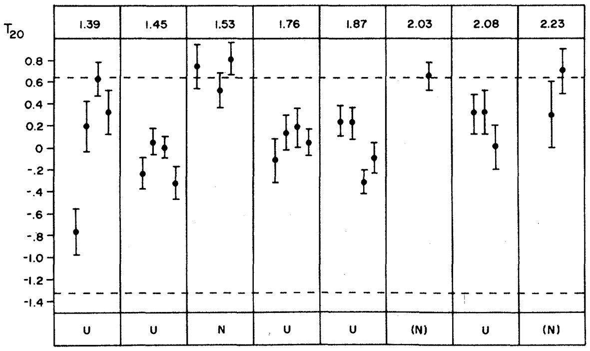

FIG. 4. Same as Fig. 3, but for levels in ^{54}Mn between 1.39 and 2.23 MeV.

degree of polarization of the incident beam, errors in determing the separate intensities of peaks where they were not completely resolved from one another, and uncertainties in background subtraction.

At the higher excitations, some peaks appeared to contain contributions from more than one level and reliable T_{20} values could again not be extracted. Accordingly, above 1.5 MeV in excitation, data are presented only for strongly excited levels which showed no evidence (e.g., shoulders or anomalously large peak widths) of doublet structure.

In Table I we also present spectroscopic information for ^{54}Mn deduced from a synthesis of the present and previous work. New information was obtained for levels at 0.839, 1.073, 1.136, 1.454, 1.53, and 1.87 MeV, and these levels are discussed in further detail below. The assignments for the other states, notably those below 0.5 MeV, are in agreement with the values presented[10] in the recent compilation.

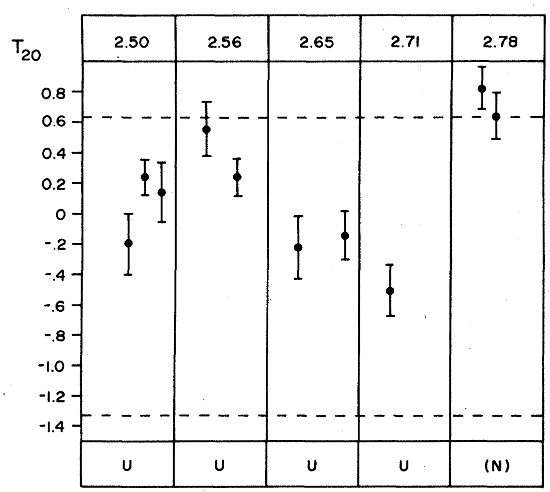

FIG. 5. Same as Fig. 3, but for levels between 2.5 and 2.8 MeV.

A. The 0.839 MeV level

This state has a $(4,5)^+$ assignment and exemplifies the usefulness of the $(\vec{d},\alpha)$ technique to resolve such ambiguities. The value of T_{20} is close to + 0.7 at each energy where this state was excited and thus a natural parity assignment can be made. Hence $J^\pi = 4^+$. γ-ray angular distribution measurements[10] apparently favor a 4^+ assignment, in agreement with the present result. A recent measurement[12] of the lifetime of this state also leads to a $J=4$ spin assignment.

B. The 1.073 MeV level

The compilation[10] gives $J^\pi = (6,5)^+$ for this state, with 6^+ apparently favored from the γ-ray work. The ^{55}Mn$(d,t)^{54}$Mn experiment of Taylor and Cameron[13] is also consistent with 6^+, but 5^+ cannot be excluded. The recent ^{52}Cr$(\alpha,pn\gamma)^{54}$Mn experiment of Toulemonde *et al.*[14] assigns 6^+ uniquely on the basis of γ-ray angular distribution, linear polarization, and angular correlation data; $J^\pi = 5^+$ could be excluded at the 99.9% confidence limit. The present experiment is in excellent agreement with this result. Although the level was rather weakly populated at the two energies where it was observed, T_{20} was near 0.7 in each case. Thus a natural parity assignment can be made with good confidence, resulting in a $J^\pi = 6^+$ assignment.

C. The 1.137 MeV level

This state also has a $J^\pi = (5,6)^+$ assignment.[10] But unlike the nearby 1.073 MeV level, there appears no reason to prefer one spin over the other from previous data. This state is strongly populated in the (d,α) reaction at several energies and it is clear from Fig. 2 that the T_{20} values are not near either $1/\sqrt{2}$ or $-\sqrt{2}$. Thus an unnatural parity assignment can be made, and consequently $J^\pi = 5^+$. This is consistent with the recent lifetime measurement[12] as well.

D. 1.391 and 1.454 MeV levels

Both of these states have $(1,0)^+$ assignments[10] from γ-ray spectroscopy. The upper of these two states was populated in the (d,t) reaction[13] with $l_n = 1+3$, limiting the allowed J^π values to $(1-4)^+$ and a resulting $J^\pi = 1^+$ assignment. Both of these states were observed in the (d,α) reaction at several energies. $J^\pi = 0^+$ states cannot be populated at 0° in the (d,α) reaction (irrespective of whether the beam is polarized or not) and hence the 0^+ possibilities can be immediately ruled out. The T_{20} measurements at several angles indicates unnatural parity as well, consistent with $J^\pi = 1^+$

assignments for both levels. These results are in agreement with the lifetime measurement.[12]

A nearby level[10] at 1.37 MeV was not observed at any of the energies studied. Careful calibration ensured that it was indeed the 1.39 MeV level which was populated in the present work.

E. Levels above 1.5 MeV with unnatural parity

A number of excited states were observed between 1.5 and 3.0 MeV, but many of them were either very weakly populated in the (d,α) reaction or appeared to be doublets or multiplets. Thus T_{20} measurements were carried out only for a few strong states in this region of excitation. Levels at 1.76, 1.87, 2.09, 2.50, 2.56, 2.65, and 2.71 MeV were all observed at two or more different energies. For some of these, it is possible to identify them with states previously observed in the (d,α) and other reactions[10] (see Table I). It appears that the groups observed at 1.76 and 2.09 MeV are close multiplets, not resolved by the present experiment, and thus T_{20} measurements are not meaningful. It is only known[14] that the 1.784 MeV level has $J^\pi = 7^+$.

The state at 1.87 MeV presumably corresponds to the known[10] state at 1.852 MeV. This state is known to have positive parity[10] and the lifetime measurement[12] restricted its spin to 2 or 3, with $J^\pi = 3^+$ the more probable one. It is seen from Fig. 4 that this state must have unnatural parity. Thus a definite $J^\pi = 3^+$ assignment can be made on this basis.

At higher energies, the correspondence between the present and previous work becomes more problematical. Furthermore, little or no spin and parity information is known for these bound states. It can be said only that the levels observed at 2.50, 2.56, 2.65, and 2.71 MeV all have T_{20} not near either $+1/\sqrt{2}$ or $-\sqrt{2}$ (see Figs. 4 and 5) and hence must have unnatural parity.

F. Levels above 1.5 MeV with natural parity

From Figs. 4 and 5, it appears that states at 1.53, 2.03, 2.23, and 2.78 MeV have natural parity, although some of them were observed at only two energies, rather than the three required for a firm spin-parity assignment. The 1.53 MeV level may correspond to either the 1.508 or 1.543 MeV levels listed[10] in the compilation. It was observed at three energies, and T_{20} was close to 0.7 at each of them. The 1.543 MeV has recently[12] been shown to have $J^\pi = 3^+$, inconsistent with the present data. Thus it is likely that we have observed the 1.508 MeV state, which has a $J^\pi = (2,3)^+$ assignment. If this is so, its spin and parity must be 2^+.

The 2.03 MeV state was observed only at 9 MeV, but had $T_{20} = 0.65 \pm 0.12$, suggestive of natural parity. This may be the 2.05 MeV level listed[10] in the compilation, but the (N) assignment must again remain very tentative in view of the absence of other data. No other information for the 2.23 and 2.78 MeV levels, aside from the present N assignments, is available.

G. Possible $J^\pi = 0^+$ levels in ^{54}Mn

Parity conservation implies[1,2] that $J^\pi = 0^+$ levels should not be populated in the (d,α) reaction at $\theta = 0°$. The angular distribution measurement at 9 MeV bombarding energy mentioned in Sec. II, carried out to search for possible 0^+ levels below ≈ 2.5 MeV excitation, gave tentative evidence for one such state, at 1.68 MeV. Figure 6 shows spectra of the region near 1.7 MeV excitation at 4°, 10°, 15°, and 20°. It is seen that one weak peak, shown by an asterisk in each spectrum, appears to be weakly excited at 4° and more strongly excited at more backward angles. Figure 7 shows an angular distribution of this peak. One can calculate the expected angular distribution to some reasonable angle (say 10°) with a simple model. One writes, following Jolivette and Richards,[15]

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{\lambda\!\!\!^{-2}}{12} \left| \sum_{l=1}^{\infty} \frac{2l+1}{[l(l+1)]^{1/2}} S_l \frac{dP_l(\cos\theta)}{d\theta} \right|^2 ,$$

where S_l is the complex amplitude of the lth partial wave and θ is measured in the c.m. system. Invoking a sharp cutoff model, we write S_l = constant for $l \leq L$ and $S_l = 0$ for $l > L$, where L is the grazing orbital angular momentum. The usual relation $kR = [l(l+1)]^{1/2}$ gives, for 9 MeV deuterons and a sharp cutoff radius of $R = 1.2(2^{1/3} + 56^{1/3}) = 6.10$ fm, a value $L \sim 6$. The resulting calculation of $d\sigma/d\Omega$ is given by the solid curve in Fig. 7. To demonstrate the insensitivity of the results to the model, a single $L = 6$ resonance calculation was also carried out and gave results indistinguishable from the first one.

It is clear that the results are consistent with a $J^\pi = 0^+$ assignment to the 1.68 MeV level, but this result must remain tentative in view of the weakness of the peak involved and the resulting large uncertainties in the measured cross sections.

The lowest 0^+ level in ^{54}Mn with a definite spin assignment, according to the compilation,[10] lies at 2.109 MeV. No evidence for this state was found in the present experiment. The significance of the (0^+) assignment to the 1.68 MeV level will be discussed below.

IV. 2p-4h STATES IN ^{54}Mn

A number of shell-model calculations[16] of the ^{54}Mn level scheme have been carried out. Most

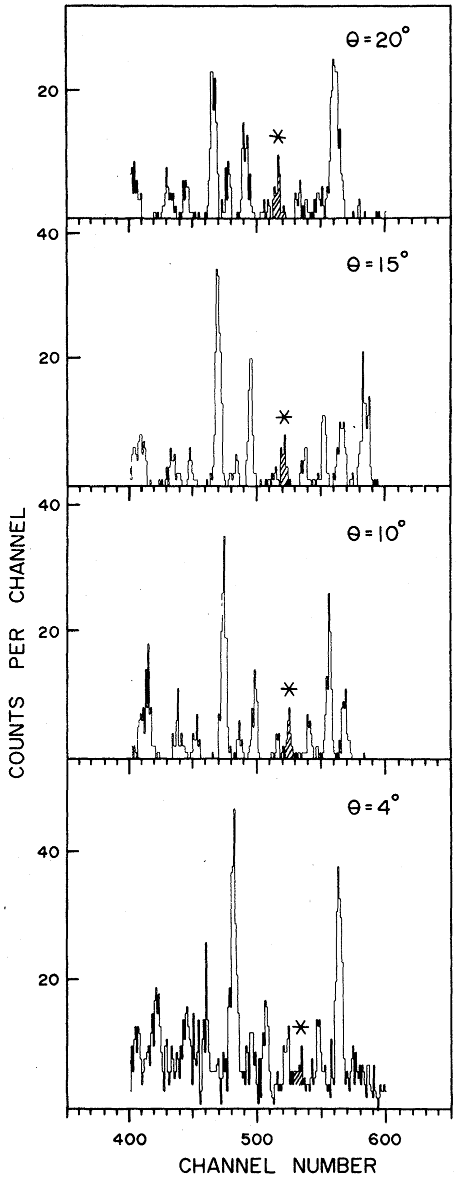

FIG. 6. Spectra of the excitation energy around 1.7 MeV taken with an unpolarized 9 MeV deuteron beam at angles of 4°, 10°, 15°, and 20°. The peak marked (*) is a proposed 0^+ state and is discussed in the text.

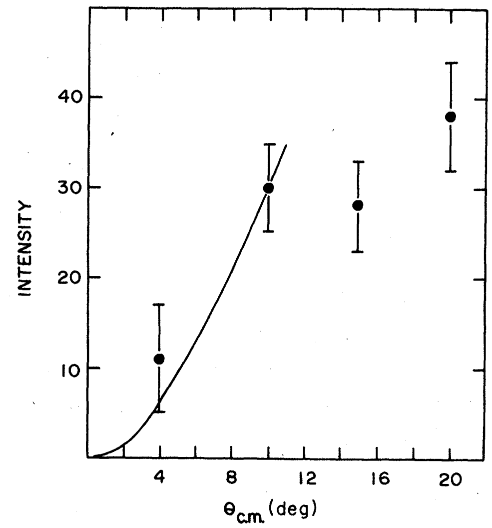

FIG. 7. Calculated and experimental angular distributions for the 0^+ level. The solid line results from a calculation assuming a sharp-cutoff model. The curve is normalized to the $\theta = 10°$ experimental point. For details, see text.

of these have used the lowest $(p_{3/2}f_{5/2}p_{1/2})^p f_{7/2}^{-h}$ configurations relative to the ^{56}Ni closed shell, and have been quite successful. Nevertheless, these calculations do not predict all the observed levels, some of which presumably[13] included core-excited configurations. More successful in this regard was a modified weak-coupling model[17] of Johnstone and Benson, who did include 2p-4h excitations in the ^{54}Mn model space. They found that this extension of the shell-model basis resulted in a much better agreement with experiment and concluded, surprisingly, that several low-lying ^{54}Mn levels could be described as relatively pure 2p-4h states, with very little mixing into 1p-3h states of the same spin and parity.

In particular, they suggested[17] that a calculated 6^+ state at 1.12 MeV of 2p-4h character, not previously considered, be identified with the high-spin[10] state at 1.073 MeV. That state had been given a $(5,6)^+$ assignment,[10] as described above, with 6^+ the more likely[12] possibility. The present experiment has confirmed the 6^+ assignment and lends credence to this argument.

An interesting feature of the calculation[17] was the prediction of two $J^\pi = 0^+$ levels at 1.65 and 1.73 MeV. These had 1p-3h and 2p-4h configurations, respectively. To date, only one 0^+ state was known, at 2.11 MeV (see above). The 2p-4h state should have a large [20 Weisskopf units (W.u.)] $E2$ strength to the 2^+ first excited state at 0.054 MeV,[17] while the $E2$ decay from the 2.11 MeV level is less than 1 W.u.[12] Perhaps the new 0^+ state at 1.68 MeV proposed by this work can be identified as the 2p-4h state. However, this does not explain the failure of Betts *et al.*[7] to observe any $L = 0$ transfers to states below 2.5 MeV in their ^{52}Cr(^{3}He,p)^{54}Mn reaction study. It is clear that a ^{56}Fe($d,\alpha\gamma$)^{54}Mn study to determine the γ-decay properties of the 1.68 MeV level should lead to more definite conclusions regarding the structure of this state.

Other 2p-4h states predicted by Johnstone and Benson[17] included 1^+, 2^+, 3^+, and 4^+ states at 1.36, 1.49, 2.00, and 2.20 MeV, respectively. In fact a second 1^+ state, nearly degenerate with the first, was also predicted, but of 1p-3h nature. It is likely that the two levels at 1.39 and 1.45 MeV, both shown to have $J^\pi = 1^+$ by the present experiment, can be identified with these model states. The strong $l = 3$ pickup strength[13] to the 1.39 MeV level observed in the ^{55}Mn$(d,t)^{54}$Mn reaction makes this state a good candidate for the 2p-4h member. The 1.51 MeV level, suggested[10,12,13] to have $J^\pi = 2^+$ or 3^+, also had a strong $l = 3$ strength in the (d,t) reaction.[13] As shown in Sec. III, this state appears to have natural parity and hence $J^\pi = 2^+$. It thus has the properties expected for a 2p-4h state. The 3^+ assignment to the 1.86 MeV level suggests that it too has 2p-4h structure. This state was not reported in the original (d,t) data,[13] but a reexamination[13] of the plates has revealed a strong state near 1.87 MeV. At $\theta_t = 20°$, it has a cross section about 75% of the $J^\pi = 2^+$ 2p-4h state, and this, together with its excitation energy, makes a 2p-4h assignment very attractive. The 4^+ state may correspond to the natural parity level observed at 2.23 MeV in the present work. This assignment, however, is hypothetical since there are many 1p-3h states predicted[17] above 2 MeV excitation as well. Figure 8 summarizes the evidence for 2p-4h states in ^{54}Mn.

No evidence was found in the present work for the high-spin states reported[14] and predicted[17] in the region above 2.5 MeV, although it cannot be ruled out that they correspond to one or another of the many very weak peaks observed.

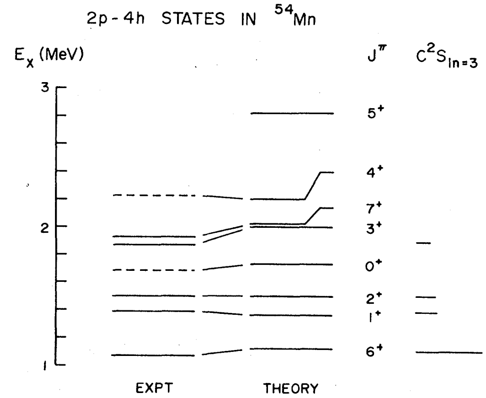

FIG. 8. Experimental and calculated (Ref. 17) 2p-4h states in ^{54}Mn. The experimental level scheme is a synthesis of the present work and Refs. 12–14. The dashed lines are tentative assignments (see text). Also shown are $C^2S_{l_n=3}$ values (spectroscopic factors) for the ^{55}Mn$(d,t)^{54}$Mn reaction (Ref. 13).

V. CONCLUSIONS

Measurements of tensor analyzing powers of the $(\vec{d},\alpha)$ reaction near 0° have been shown to be a powerful tool for making J^π assignments in odd-odd nuclei, even in the *pf* shell where the cross sections are quite small. Several previous spin-parity ambiguities have been resolved, resulting in seven new J^π assignments to ^{54}Mn bound states. A new $J^\pi = 0^+$ level is proposed at 1.68 MeV on the basis of a rapidly decreasing cross section at forward angles.

The present results are combined with the work of previous investigators to arrive at new evidence for 2p-4h states in ^{54}Mn, in good agreement with the results of a recent[17] shell-model calculation. ^{55}Mn(d,t) and $(\vec{d},t)$ measurements are now under way in order to provide further evidence of the configurational purity of these 2p-4h states.

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