PHYSICAL REVIEW C VOLUME 10, NUMBER 4 OCTOBER 1974

Weak states in $^{19}F(d,p)^{20}F$†

H. T. Fortune and R. R. Betts*
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19174
(Received 26 June 1974)

The $^{19}F(d,p)^{20}F$ reaction has been reinvestigated with special emphasis on the weak states. The structure of all states below 4.2 MeV is reviewed and compared with $(sd)^4$ and open-core shell-model calculations.

[NUCLEAR REACTIONS $^{19}F(d,p)$, $E=12.0$ MeV, measured $\sigma(\theta)$, DWBA analysis, comparison with shell model.]

I. INTRODUCTION

A previous study of the $^{19}F(d,p)^{20}F$ reaction,[1] for excitation energies below 4.3 MeV, showed good agreement between the experimental results and theoretical predictions[2] for all of the states that were strongly excited. However, in that study, many of the low-lying states of ^{20}F were excited too weakly to allow any definite conclusions to be reached concerning their structure. Since that time, there have appeared shell-model calculations[3,4] that include excitations out of the $1p$ shell, and hence should be capable of describing these additional states. We have reinvestigated this reaction with special emphasis on the weak states.

The experiment was performed with a 12-MeV deuteron beam from the University of Pennsylvania tandem accelerator. Outgoing protons were momentum analyzed in a multiangle spectrograph and detected in K5 nuclear emulsion plates. The target consisted of approximately 25 $\mu g/cm^2$ of ^7LiF on a 10-$\mu g/cm^2$ ^{12}C backing. Absolute cross sections were not measured, but were obtained by normalizing the spectroscopic strength for the 2.04-MeV state to that obtained[1] at 16 MeV. The resulting absolute cross sections agree within 20% with those calculated from the nominal target thickness. A spectrum obtained at $3\frac{3}{4}°$ is displayed in Fig. 1. In order to collect sufficient yield for the weak states, the strong $l=0$ states were too strong at forward angles to be scanned. Angular distributions for them were extracted only at larger angles. Angular distributions for the states below 4.2 MeV in excitation are displayed in Figs. 2–5. The angular distributions have been analyzed with the distorted-wave Born approximation (DWBA) code DWUCK.[5] The optical-model parameters (listed in Table I) were those used in Ref. 1, except for the energy dependence required in the original references.[6,7] For completeness, the 16-MeV data for the weak states were also analyzed for a variety of l values. The results are listed in Table II and are discussed below.

II. RESULTS

Strong transitions

States at $E_x=0.66$, 2.04, 2.19, and 2.97 MeV are populated with pure $l=2$. Their angular distributions are displayed in Fig. 2. These states now have unique J^π assignments[1,8-10] of 3^+, 2^+, 3^+, and 3^+, respectively. The 2.04-MeV state provided the normalization between this experiment and the one performed at $E_d=16$ MeV. The agreement between present and previous spectroscopic strengths for the other three states is excellent. States at 3.49 and 3.53 MeV were previously observed[1] to be populated with strong, essentially pure $l=0$ transitions. In the present experiment, these two states are over-exposed at forward angles but the present results at larger angles (see Fig. 3) are consistent with those of the previous study. The theoretical angular distributions shown in Fig. 3 for these two states are for the spectroscopic strengths of Ref. 1.

Weak transitions

Ground state. The ground state is extremely weak, as expected from the shell-model calculations. Its angular distribution (Fig. 2) is well fitted by $l=2$. The present spectroscopic strength of 0.054 is in agreement with the result of Ref. 1.

0.82 MeV. This state now has a rather firm assignment[11] of $J^\pi=4^+$. If that assignment is correct, it can be reached in stripping only via $l=4$. The spectroscopic strength extracted assuming $1g_{9/2}$ transfer (Fig. 4) is 0.49. A similar analysis of the 16-MeV data yields 0.42. This strength is only a small fraction (~4%) of the $1g_{9/2}$ single-particle strength, but is large for a state at so low an excitation. It is likely that the major con-

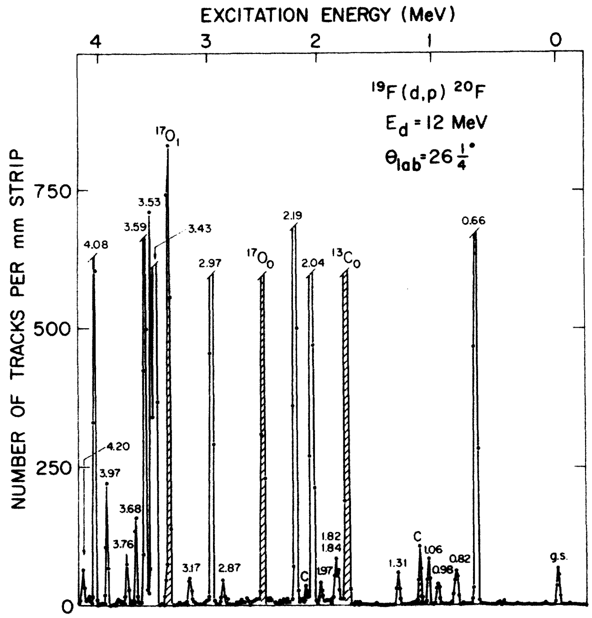

FIG. 1. Spectrum of the $^{19}F(d,p)^{20}F$ reaction obtained at a laboratory angle of 3.75°. The bombarding energy is 12.0 MeV.

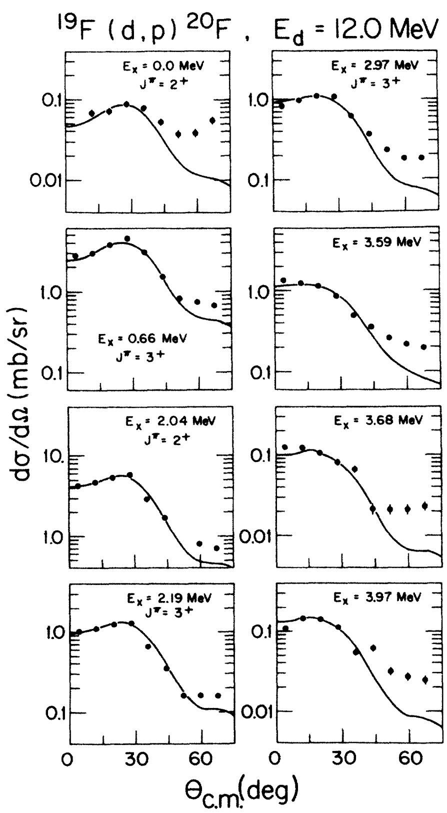

FIG. 2. Angular distributions for states populated with pure $l=2$ transition.

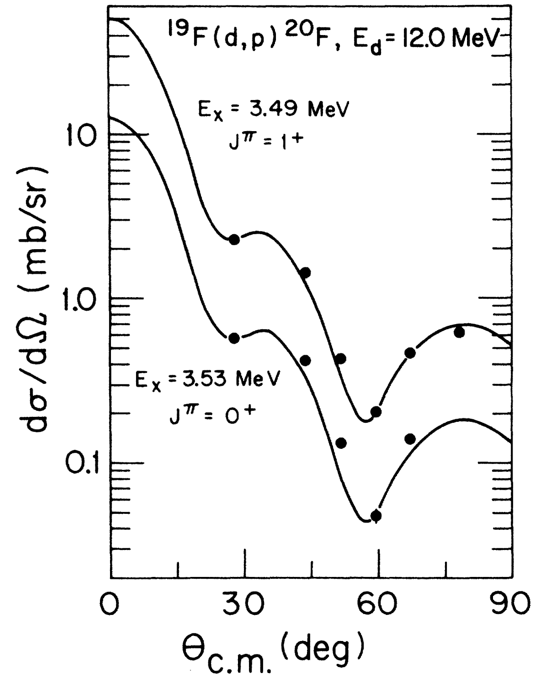

FIG. 3. Angular distributions for states populated with pure $l=0$. The curves are drawn for the spectroscopic strengths of Ref. 1.

tribution to the cross section for this state arises from a second-order process.

0.98 MeV. This state now has a firm J^π assignment[12,13] of 1^-, and hence can be reached in stripping only via $l=1$. The spectroscopic strength obtained (see Fig. 4) assuming p-wave stripping is quite small, for both the 12- and 16-MeV data. This small spectroscopic factor is consistent with the expectation[3,4] that this state is predominantly a hole state—a $p_{1/2}$ hole coupled to the ^{21}Ne ground state.

1.06 MeV. This state is known[8,14] to have $J^\pi = 1^+$. Its angular distribution (Fig. 5) contains both $l=0$ and $l=2$. The extracted spectroscopic strengths agree with those of Ref. 1.

1.31 MeV. This state has been assigned[12,13] $J^\pi = 2^-$, and is presumably dominantly $(p_{1/2})^{-1} \otimes {}^{21}$Ne (g.s.). The spectroscopic strength extracted at both 12 and 16 MeV is quite small—essentially equal to that for the 0.98-MeV state. There is some indication for a small $l=3$ contribution to this angular distribution (Fig. 4).

1.82- 1.84-MeV doublet. These two states now appear[13,15,16] to be 5^+ and 2^-. The 5^+ member can be reached in stripping only via $l=4$. An assumption of $1g_{9/2}$ transfer yields a spectroscopic strength comparable to that extracted for the 4^+ state at 0.82 MeV. Again, this state is probably populated by some second-order process. The 2^-

TABLE I. Optical-model parameters used in the DWBA analysis of the reaction $^{19}F(d,p)^{20}F$ at $E_d = 12.0$ MeV.

Channel	V_0 (MeV)	$r_0 = r_{so}$ (fm)	$a = a_{so}$ (fm)	$W' = 4W_D$ (MeV)	r_0' (fm)	a' (fm)	V_{so} (MeV)	r_c (fm)
$^{19}F + d$ [a]	105	1.02	0.86	61.7	1.42	0.65	6.0	1.30
$^{20}F + p$ [b]	56.9	1.135	0.57	34.7	1.135	0.50	5.5	1.4
Bound State	Varied	1.26	0.60	...	...	...	$\lambda = 25$	...

[a] See Ref. 6.
[b] See Ref. 7. Parameters given are for the ground state. The energy dependence of Ref. 7 was used.

state can be reached via either $l=1$ or 3, or both. The p-wave strength obtained for this state from the 12-MeV data (Fig. 4) is comparable to that extracted for the two lower-lying negative parity states. However, the decomposition into $l=1$ and $l=4$ at 16 MeV does not agree with the 12-MeV result. The 16-MeV data appear to require more $l=1$. However, such a decomposition is only qualitative, at best. This state is also most likely a hole state—a $p_{1/2}$ hole coupled to the $\frac{5}{2}^+$ first excited state of ^{21}Ne.

1.97 MeV. This state is a good candidate[16] for the 3^- hole state with dominant configuration $(p_{1/2})^{-1} \otimes {}^{21}Ne$ (1st exc.). Its angular distribution is shown in Fig. 4. If it is 3^-, it cannot be reached via $l=1$, but rather requires $l=3$. An analysis of both the 12- and 16-MeV data yields a consistent $1f_{7/2}$ spectroscopic strength of 0.05. An assumption of $l=1$ transfer, however, yields results at the two energies that differ by a factor of 3. A 3^- assignment is therefore reasonable.

2.87 MeV. This state also appears to have negative parity.[17] In the 16-MeV data, it was too weak to allow an angular distribution to be extracted. The 12-MeV angular distribution (Fig. 4) is consistent with pure $l=3$, with a spectroscopic strength of 0.046. An $l=3$ transfer requires $J^\pi = 2^-$, 3^-, or 4^-. The absence of an $l=1$ component makes a 2^- assignment unlikely. Coupled with the results of the $^{14}N(^7Li,p)^{20}F$ reaction,[16] the most likely assignment is $J^\pi = 3^-$. This state is then a good candidate for the 3^- hole state obtained by coupling a $1p_{1/2}$ hole to the $\frac{7}{2}^+$ second excited state of ^{21}Ne.

3.18 MeV. Very little is known about this state. The $^{14}N(^7Li,p)^{20}F$ results[16] favor low spin. Its only

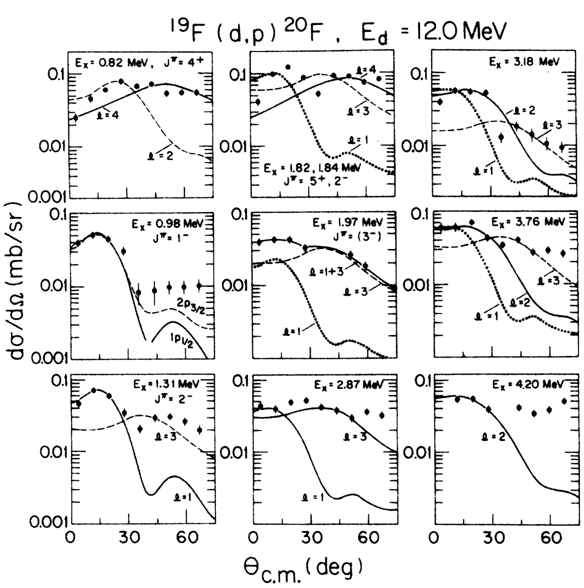

FIG. 4. Angular distributions of weak states.

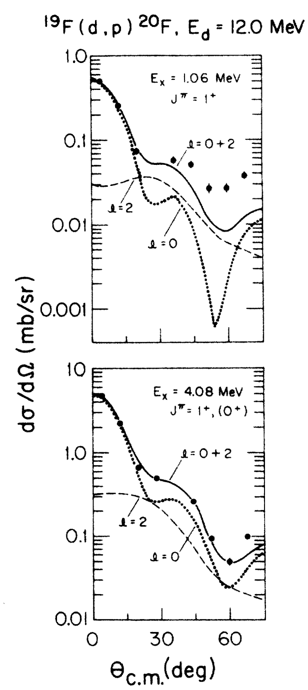

FIG. 5. Angular distributions characteristic of mixed $l = 0+2$.

observed γ decay[18,19] is to the 1^- state at 0.98 MeV. No state is observed to decay by emitting a γ ray to it. At $E_d = 12$ MeV, the $^{19}F(d,p)^{20}F$ angular distribution (Fig. 4) for this state is best fitted with $l = 2$. The spectroscopic strength thus extracted agrees with the 16-MeV result, even though at 16 MeV, the $l = 2$ shape did not give a good fit.

3.59 MeV. This state is populated largely via $l = 2$ (see Fig. 2) at both 12 and 16 MeV. However, at both energies there is a hint of a small $l = 0$ component. The decomposition into $l = 0$ and 2 gives consistent results at the two energies, but the evidence for $l = 0$ is too small to allow an unambiguous assignment of 1^+. If only a single state exists here, then the (d,p) results limit J to 1, 2, and 3, with positive parity. If a doublet exists, then one member has $J^\pi = (1, 2, 3)^+$. A group at 3.59 MeV was observed to have an $L = 2 + 4$ angular distribution in the $^{18}O(^3He,p)^{20}F$ reaction.[9] Thus, if only a single state exists here, it must have $J^\pi = 3^+$. The only γ decays observed[19,20] from this state are to 2^+ states at $E_x = 0$ and 2.04 MeV.

3.68 MeV. The angular distribution for this state (Fig. 2) is reasonably well fitted by an $l = 2$ shape. There is a hint of a small $l = 0$ component, but at the sensitivity of the present experiment it is not required. A state at this excitation energy was populated via $L = 4$ in the $^{18}O(^3He,p)^{20}F$ reaction.[9] If a single state exists at this energy, then $l = 2$ in (d,p) and $L = 4$ in $(^3He,p)$ would require $J^\pi = 3^+$. It is unlikely, however, that a 3^+ state would not contain an $L = 2$ component in $(^3He,p)$. The spectroscopic strength obtained in (d,p) is extremely small, and the state may be populated via a two-step or nondirect process, in which case the l value extracted is meaningless. This possibility is strengthened by the fact that the angular distribution measured for this state at 16 MeV is not well fitted by $l = 2$. Also, the spectroscopic strengths extracted at the two energies, for $l = 2$, differ by more than a factor of 2. One possibility is that this state is actually a $1^+, 4^+$ doublet. A state at this energy has been observed[20] to decay by emitting a γ ray only to the 2^+ ground state and 3^+ first excited state.

3.76 MeV. The angular distribution for this state is displayed in Fig. 4. It is not well fitted by any single l value, though $l = 2$ gives a reasonable fit at forward angles. There is no independent evidence on the parity of this state.

3.97 MeV. A state at this energy decays by emitting a γ ray[21] predominantly to the 2^+ ground state, with weak branches reported to the 0.98

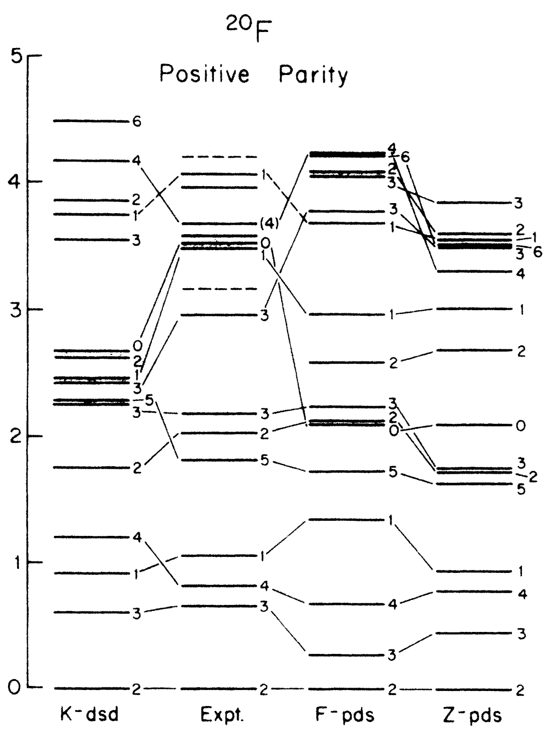

FIG. 6. Comparison of experimental and theoretical level schemes for positive-parity states in ^{20}F.

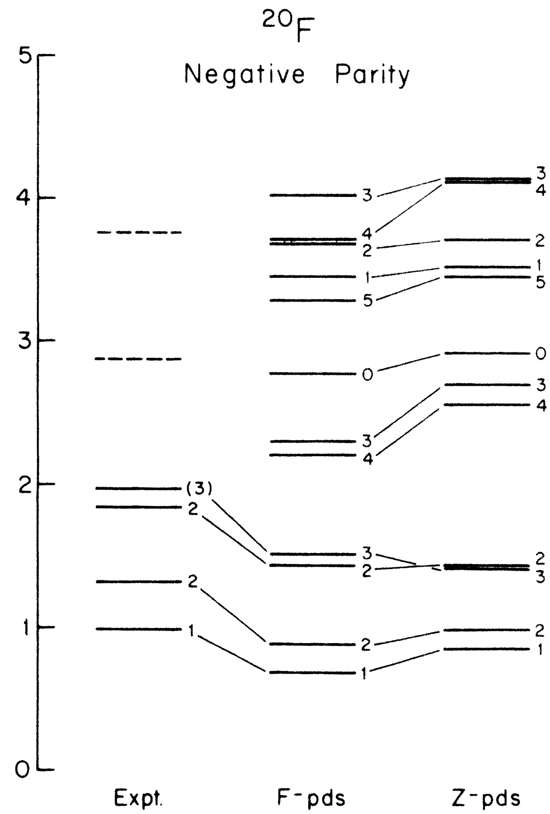

FIG. 7. Comparison of experimental and theoretical level schemes for negative-parity states in ^{20}F.

TABLE II. Results of the $^{19}F(d,p)^{20}F$ reaction.

E_x (MeV) Present	Lit. [a]	J^{π}	nlj	$(2J+1)S$ $E_d=12$ MeV	$E_d=16$ MeV [b]
0.00	0.00	2^+	$1d_{5/2}$	0.054	$\lesssim 0.06$
0.655	0.656	3^+	$1d_{5/2}$	2.32	2.59
0.822	0.823	(4^+)	$(1d_{5/2})$	(0.042)	(0.031)
			$1g_{9/2}$	0.32	0.36
0.980	0.984	1^-	$1p_{3/2}$	0.012	...
			$1p_{1/2}$	0.014	0.016
			$2p_{3/2}$	0.0043	0.006
1.057	1.057	1^+	$2s_{1/2}$	0.013	0.019
			$1d_{3/2}$	0.022	$\lesssim 0.03$
1.311	1.309	2^-	$1p_{3/2}$	0.017	0.013
			$2p_{3/2}$	0.0053	0.005
			$1f_{5/2}$	0.04	...
1.832	{1.824	(5^+)	$1g_{9/2}$	0.35	0.32
	1.843}	2^-	$2p_{3/2}$	0.007	0.03
			$1f_{5/2}$	0.12	...
1.969	1.971	(3^-)	$(2p_{3/2})$	(0.0016)	(0.0080)
			$1f_{7/2}$	0.038	0.042
2.044	2.044	2^+	$1d_{5/2}$	2.32	2.32
2.198	2.195	3^+	$1d_{5/2}$	0.55	0.50
2.867	2.865		$(2p_{3/2})$	$\lesssim 0.002$	...
			$1f_{7/2}$	0.044	...
2.971	2.966	3^+	$1d_{5/2}$	0.38	0.36
3.175	3.175		$1d_{5/2}$	0.019	0.014
			$2p_{3/2}$	0.0032	0.003
			$1f_{7/2}$	0.021	0.039
3.498	3.488	1^+	$2s_{1/2}$	...	1.20
3.533	3.526	0^+	$2s_{1/2}$	...	0.28
3.595	3.587		$2s_{1/2}$	$\lesssim 0.0065$	$\lesssim 0.09$
			$1d_{3/2}$	0.38	0.42
3.687	3.681		$1d_{5/2}$	0.031	$\lesssim 0.04$
3.769	3.761		$2p_{3/2}$	$\lesssim 0.0032$	...
			$1d_{5/2}$	$\lesssim 0.017$	...
			$1f_{7/2}$	$\lesssim 0.044$	...
3.974	3.966		$1d_{5/2}$	0.036	0.043
4.090	4.082		$1s_{1/2}$	0.13	0.18
			$1d_{3/2}$	0.083	0.10
4.212	{4.199, 4.208}		$(1d_{5/2})$	0.013	...

[a] See Ref. 8.
[b] Data of Ref. 1.

MeV, 1^- and 1.31 MeV, 2^- states. The present angular distribution (Fig. 2) is reasonably well fitted with $l=2$, thus suggesting positive parity. As for the 3.68-MeV state, the spectroscopic strength extracted for $l=2$ transfer is quite small. However, in this case, the 12- and 16-MeV results agree. We thus tentatively assign $J^{\pi}=(1, 2, 3)^+$ to the 3.97-MeV state.

4.08 MeV. The angular distribution is dominated by $l=0$ at both 12 and 16 MeV. The 12-MeV data are displayed in Fig. 5. At both energies there is a hint of a small, but detectable, $l=2$ component. Furthermore, the decompositions into $l=0$ and 2 at the two energies are consistent. A mixture of $l=0$ and 2 for a single state requires $J^{\pi}=1^+$. If the state is a doublet, then one member is 0^+ or 1^+, and the other member, if excited, is 1^+, 2^+, or 3^+.

4.20 MeV. A doublet is known[8] to exist here, at 4.1989 MeV ± 2.7 keV and 4.2077 MeV ± 2.6 keV. The $^{14}N(^7Li,p)^{20}F$ results[16] suggest that at least one member has high spin. The present angular distribution (Fig. 4) is not well fitted by any l value.

III. COMPARISON WITH SHELL-MODEL CALCULATIONS

Shell-model calculations for ^{20}F have been performed in a complete $1d_{5/2}$-$2s_{1/2}$-$1d_{3/2}$ basis[2] and in a $1p_{1/2}$-$1d_{5/2}$-$2s_{1/2}$ basis.[4] Predictions from some of those calculations are displayed in Figs. 6 (positive parity) and 7 (negative parity).

Positive-parity states. There is good over-all agreement between experiment and theory for the positive-parity states. Of the 13 experimental states below 4.0 MeV in excitation that are known to have positive parity, 10 of them have obvious shell-model counterparts. These include the 0^+ state at 3.53 MeV, 1^+ states at 1.06 and 3.49 MeV, 2^+ states at 0.0 and 2.04 MeV, 3^+ states at 0.66, 2.19, and 2.97 MeV, the 4^+ state at 0.82 MeV, and the 5^+ state at 1.82 MeV. Excitation energies and spectroscopic strengths for these states are compared with theory in Table III. The only outstanding failure of the calculations is in the predicted positions of the 3.49, 1^+ and 3.53, 0^+ states.

Not yet identified in the experimental spectrum are the states corresponding to the predicted third 1^+ state, third and fourth 2^+ states, fourth 3^+ state, and second 4^+ state. As discussed in Ref. 7, the 3.68-MeV state is an excellent candidate for the second 4^+ state. The 3.59-MeV state has a well-defined $l=2$ stripping angular distribution in (d,p), and hence has $J^\pi=(1,2,3)^+$. It thus probably corresponds to either the ${1^+}_3$, ${2^+}_3$, ${2^+}_4$, or ${3^+}_4$ state. It most likely is the 3^+ state predicted in the *K-dsd* calculations to lie at $E_x=3.55$ MeV and to have a spectroscopic strength of 0.4.

The state at 4.08 MeV is dominated by $l=0$ and hence has $J^\pi=(0,1)^+$. The apparent $l=2$ contribution in its angular distribution would require $J^\pi=1^+$. This state may thus be the third 1^+ state. However, the third theoretical 1^+ state is predicted to be dominated by $l=2$, rather than $l=0$. Hence, it is still possible that a 1^+ state (dominated by $l=2$) remains to be identified below 4.0 MeV.

States at 3.18, 3.68, and 3.97 MeV are reasonably well fitted by $l=2$. However, the extracted spectroscopic strengths are all quite small. The weakness of the cross section makes the identification of l values ambiguous. These states could presumably be populated via some two-step or nondirect process. There is independent evidence from the $^{18}O(^3He,p)^{20}F$ reaction[9] that the 3.68-MeV state has positive parity. But that study favors $J^\pi=4^+$, inconsistent with an $l=2$ angular distribution in (d,p). There is no independent evidence on the parity of the 3.18- and 3.97-MeV states. If they indeed have positive parity, then they are candidates for the two missing 2^+ states predicted below 4 MeV. However, both states are significantly weaker than the predictions for these two 2^+ states. More detailed comparison clearly awaits further experimental information concerning these states.

Negative-parity states. The *F-pds* and *Z-pds* calculations[4] assumed a closed ^{12}C core and allowed particles to occupy the $1p_{1/2}$, $1d_{5/2}$, and $2s_{1/2}$ orbitals. A large number of low-lying negative-parity states are predicted in ^{20}F. The lowest set of states has the dominant configuration of a $p_{1/2}$ hole coupled to the various excited states of ^{21}Ne. For example,[3] a $p_{1/2}$ hole coupled to the $\frac{3}{2}^+$ ground state of ^{21}Ne gives rise to a $1^-, 2^-$ doublet, predicted just below 1 MeV. The $\frac{5}{2}^+$ first excited state of ^{21}Ne gives rise to a $2^-, 3^-$ doublet, predicted near 1.5 MeV, and similarly for the higher

TABLE III. Comparison of experiment and theory for low-lying positive-parity states in ^{20}F.

		E_x (MeV)					$(2J+1)S$	
		K-dsd	*Z-pds*	*F-pds*			*K-dsd*	*F-pds*
J^π	Expt.	(Ref. 2)	(Ref. 4)	(Ref. 4)	l	Expt.	(Ref. 2)	(Ref. 4)
0^+	3.53	2.68	2.11	2.59	0	0.3	0.6	0.5
1^+	1.06	0.92	1.36	0.94	0	0.01	0.0	0.0
					2	≤0.02	0.0	0.0
	3.49	2.47	2.98	3.03	0	1.2	1.7	1.2
					2	0.0	0.0	0.0
	(4.08)	3.75	3.70	3.57	0	0.13	0.0	0.0
					2	0.08	0.2	n.c.
2^+	0.0	0.0	0.0	0.0	2	0.05	0.0	0.3
	2.04	1.76	2.14	1.73	2	2.32	3.3	2.4
		2.63	2.60	2.70	2		0.1	0.5
		3.86	4.10	3.62	2		0.2	0.0
3^+	0.66	0.61	0.27	0.45	2	2.32	4.7	3.9
	2.19	2.26	2.25	1.76	2	0.55	0.1	0.4
	2.97	2.43	3.79	3.51	2	0.38	0.1	0.2
	(3.59)	3.55	4.06	3.86	2	0.38	0.4	0.0
4^+	0.82	1.21	0.68	0.78				
	(3.68)	4.17	4.25	3.32				
5^+	1.82	2.29	1.74	1.64				

states. It can be seen from Fig. 7 that the calculations[4] predict too high a density of low-lying negative-parity states. Ten or eleven negative-parity states are predicted below 4 MeV, whereas only four states in this region are known to have negative parity. These are the 1^- state at 0.98 MeV, the 2^- states at 1.31 and 1.84 MeV, and a suspected 3^- state at 1.97 MeV. Additionally, candidates for negative-parity states below 4 MeV exist at 2.87, 2.97 (unresolved from the 3^+ state there), and 3.76 MeV.

In the shell-model calculations,[4] only the 1^- state has a nonzero predicted spectroscopic strength, since $p_{3/2}$ and $1f$ orbitals are not included. This 1^- state is predicted to be only weakly excited in (d,p)—consistent with the observations. A more stringent test of the model for negative-parity states would be proton pickup from ^{21}Ne. A preliminary report of the ^{21}Ne$(d, {}^3$He$)^{20}$F reaction appeared,[15] but in that work only the first three negative-parity states were observed. Clearly, an extension of that work to higher excitation energies is very desirable.

IV. CONCLUSION

A reinvestigation of the ^{19}F$(d,p)^{20}$F reaction, with special emphasis on the weak states, has helped to clarify the experimental situation for several additional levels of ^{20}F. Results are in reasonable agreement with shell-model predictions—even for these weak states. However, several problems remain. In spite of the wealth of information now becoming available on ^{20}F, it is clear that significantly more work is necessary before this odd-odd nucleus becomes well understood.

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†Work supported by the National Science Foundation.

*Present address: Niels Bohr Institutet, Copenhagen Ø, Denmark.

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