States at E_x = 4–6 MeV from ^{19}F(d,p)^{20}F†

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The ^{19}F(d,p)^{20}F reaction has been used to investigate the 4–6 MeV region of excitation of ^{20}F. Excitation energies were obtained for 26 levels and angular distributions for 23. A distorted-wave Born-approximation analysis yielded l values and spectroscopic strengths for several of these.

[NUCLEAR REACTIONS ^{19}F(d,p), E=12.0 MeV, E_x=4–6 MeV, measured E_x, $\sigma(\theta)$, DWBA analysis.]

A recent study of the ^{19}F(d,p)^{20}F reaction[1] summarized the spins, parities, and other features of states in ^{20}F below 4.2 MeV excitation. We have subsequently analyzed data from the same reaction for states between 4 and 6 MeV in excitation. We report on that analysis here.

The experimental details have been described previously.[1] A spectrum showing the 4-6 MeV region is displayed in Fig. 1. Average excitation energies are listed in Table I, where they are compared with the values from the literature.[2-4] Discounting doublets, our energies agree with previous results within the combined uncertainties for 74% of the states. In fact, the average of the absolute magnitudes of the deviations is 4.3 keV, whereas the average of the combined uncertainties is 6.0 keV.

Data were collected at nine angles between 3.75° and 63.75° (lab), and at 168.75°. The back-angle data were used to investigate the degree of 90° symmetry of the angular distributions. Angular distributions from direct reactions are typically forward peaked while those from compound-nucleus (CN) processes are roughly symmetric about 90°. The presence of an ^{16}O impurity in the target provided a calibration of the technique, since the first two states of ^{17}O have near unit spectroscopic factors, and hence should be populated in (d,p) mainly by a direct reaction. The backward-to-forward ratio for these two states is 0.12 and 0.16, respectively. We present this ratio for the ^{20}F states in Table I. A large ratio implies a non-negligible CN contribution, while small ratios are probably indicative of a direct process.

Angular distributions were analyzed with the aid of distorted-wave Born-approximation (DWBA) calculations using the optical-model parameters of Ref. 1. These angular distributions are displayed in Figs. 2 and 3. Spectroscopic strengths were extracted by normalizing experimental and theoretical angular distributions at angles near where the cross section is maximum. These also are given in Table I.

The j values listed in Table I merely indicate for a given l which j value was used in the computation of strength. If the nlj value is in parentheses, the presence of this l value cannot be definitely established. Nevertheless, the strength of that l value extracted from the curve as shown in the figures is given. Each of the states is discussed in turn below.

4279 keV

The angular distribution for this state is well fitted by $l=2$, consistent with the $J^\pi = 1^+, 2^+$ assignment in the compilation.[2]

4315 keV

The angular distribution for this state is dominated by $l=0$, requiring $J^\pi = 0^+$ or 1^+. The $l=2$ strength is less than 0.15. The best fit admixture has a small $l=2$ component $(2J+1)S = 0.049$. But this is not considered large enough to make a def-

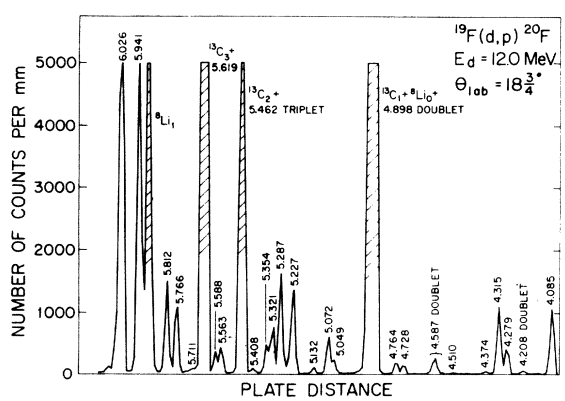

FIG. 1. Spectrum of the ^{19}F(d,p)^{20}F reaction for 4–6 MeV of excitation.

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

E_x (keV) present	Lit.[a]	J^π[a]	nlj	$(2J+1)S$	R[b]
4279.0 ±2.0	4276.6 ±0.5	$1^+, 2^+$	$1d_{5/2}$	0.087	0.16
4315.4 ±2.0	4311.5 ±2.6	$0^+, 1^+$	$2s_{1/2}$	0.20	0.009
			$(1d_{3/2}$	(0.049)	
4374.5 ±2.0	4372 ±4[c]	low spin[d]	$(2p_{3/2})$	(0.003)	0.42
			$(1d_{5/2})$	(0.008)	
			$(1f_{7/2})$	(0.008)	
4509.5 ±3.0	4518 ±4[c]	$(3-5)^-$[d]	$(2s_{1/2})$	(0.001)	0.76
		or $(5-7)^+$	$(2p_{3/2})$	(0.001)	
			$(1d_{5/2})$	(0.005)	
			$(1f_{7/2})$	(0.011)	
4587.4 ±1.5	4583.8 ±3.0 4592.2 ±2.9	$(0-2)$[e]	$2p_{3/2}$	0.02	0.14
			$(1f_{7/2})$	(<0.05)	
4728.9 ±4.0	4730.2 ±2.9	$(1,2,3)^+$[e]	$(1d_{5/2})$	(0.025)	0.24
		or $(2,3,4)^-$	$(1f_{7/2})$	(0.062)	
4763.7 ±2.5	4763.8 ±2.7	high spin[d]	$(1d_{5/2})$	(0.032)	0.31
			$(1f_{7/2})$	(0.038)	
4898.1 ±4.0	4891.6 ±2.8 4898.2 ±2.8		$(1d_{5/2})$	(0.048)	0.37
			$(1f_{7/2})$	(0.082)	
			$(2p_{3/2})$	(<0.024)	
5048.7 ±1.5	5040.2 ±3.1	$(0,1,2)^-$[a]	$(2p_{3/2})$	(0.026)	0.28
			$(1f_{7/2})$	(0.080)	
			$(1d_{5/2})$	(0.042)	
5072.0 ±3.0	5065.5 ±3.1	$(1,2,3)^+$[e]	$1d_{5/2}$	0.09	0.08
5132.4 ±3.5	5131 ±5[c]		$(1d_{5/2})$	(0.019)	0.47
			$(1f_{7/2})$	(<0.039)	
5226.7 ±3.5	5224.0 ±3.1	$(0,1,2)^-$[a]	$2p_{3/2}$	0.09	0.05
			$(1f_{7/2})$	(0.19)	
			$(2s_{1/2})$	(<0.15)	
			$(1d_{5/2})$	(<0.21)	
	5281.0 ±3.3	$(0,1,2)^-$[a]			
5287.2 ±3.5		$(1,0)^+$[e]	$2s_{1/2}$	0.34	0.02
			$(1d_{5/2})$	(<0.22)	

inite 1^+ assignment. This state was previously known to have $J^\pi = 0^+$ or 1^+.

4374 keV

This state is not in the compilation,[2] but is probably the state observed at $E_x = 4360 \pm 10$ keV in ^{14}N(^{7}Li,p)^{20}F [3] and at 4372 ± 4 keV in ^{22}Ne(d,α).[4] It is very weak in (d,p) and has a non-characteristic angular distribution. The curve for $l=1$ gives a marginal fit at forward angles, but no l value produces a good fit. The backward-forward ratio indicates a substantial CN contribution.

4510 keV

This state is also not in the compilation,[2] but was observed in ^{14}N(^{7}Li,p)^{20}F [3] with $E_x = 4513 \pm 5$ keV, and in ^{22}Ne(d,α) [4] with $E_x = 4518 \pm 4$ keV. The (^{7}Li,p) results[3] suggest high spin [$(3-5)^-$ or $(5-7)^+$] if it is a single state. The present (d,p) angular distribution is not well fitted by any single l value. The back-angle cross section implies a large CN component for this state.

4587 keV

The state we observe at 4587.4 ± 1.5 keV is midway between two known states[2] at 4583.8 ± 3.0 and 4592.2 ± 2.9 keV, at least one of which must have high spin.[3] The (d,p) angular distribution is well fitted at forward angles by $l=1$, but appears to also contain a contribution from a large l value (l = 3 or 4). The presence of $l=1$ requires $J^\pi = (0-2)^-$ for one member of the doublet. The evidence for $l=3$ is not sufficiently strong to make a 2^- assignment.

4729 keV

The backward-forward ratio for this state is only slightly larger than that expected for a direct

TABLE I. (*Continued*)

E_x (keV) present	Lit.[a]	J^{π} [a]	nlj	$(2J+1)S$	R[b]
5320.6 ±3.5	5317.1 ±2.7	$(1,2,3)^+$	$1d_{5/2}$	0.10	0.09
		or 2^{-}[e]	or $\{2p_{3/2}$	0.033	
			$1f_{7/2}$	0.10	
5353.9 ±3.0	5344.5 ±3.3	$(1,2,3)^+$[e]	$1d_{5/2}$	0.06	0.12
5408.2 ±2.5	5413.1 ±0.6		$(2p_{3/2})$	(0.007)	~1
			$(1d_{5/2})$	(0.016)	
			$(1f_{7/2})$	(0.033)	
	5450.3 ±3.8				
	5455.4 ±3.2		$1d_{5/2}$	0.27	0.11
5461.7 ±4.0	5463.4 ±3.3	$(1,2,3)^+$[e]	$(2p_{3/2})$	(<0.07)	
			$(1f_{7/2})$	(<0.26)	
5562.9 ±2.0	5554.7 ±0.6	$(0,1,2)^-$[e]	$(2s_{1/2})$	(0.05)	0.05
			$2p_{3/2}$	0.03	
			$(1d_{5/2})$	(0.11)	
5588.1 ±1.5	5574 ±6[c]		$(1f_{7/2})$	(0.13)	0.30
5618.8 ±4.0	5620.3 ±3.3		weak		
5710.8 ±6.0	(5713 ±2)		weak		~0.2
5766.1 ±4	5762.8 ±3.4)	$(1-3)^+$[e]	$1d_{5/2}$	0.15	0.06
5811.7 ±4	5809.1 ±2.9	$(0-2)^-$[a]	$\{2p_{3/2}$	0.10	0.16
		(2^-)[e]	$1f_{7/2}$	0.18	
		or (1^+)[e]	or $\{2s_{1/2}$	0.18	
			$1d_{5/2}$	0.18	
5940.7 ±5	5936.1 ±0.3	$1^-, 2^-$[a]	$2p_{3/2}$	0.43	0.07
			$(1f_{7/2})$	(0.64)	
			$(2s_{1/2})$	(<0.7)	
6025.8 ±7	6017.3 ±0.3	$1^-, 2^-$[a]	$\{2p_{3/2}$	0.68	0.01
		(2^-)[e]	$1f_{7/2}$	1.40	

[a] Reference 2 unless otherwise noted.
[b] Ratio of cross section at lab angle of 168.75° to that of 11.25°.
[c] Reference 4.
[d] Reference 3.
[e] From the present analysis.

process. The angular distribution would appear to require $l=2$ or $l=3$. If the process is direct, $J^{\pi}=(1,2,3)^+$ or $(2,3,4)^-$, with perhaps some preference for the latter.

4764 keV

From the forward-angle data, we prefer $l=2$, implying $J^{\pi}=(1,2,3)^+$. The curve for $l=3$ gives a poorer fit. However, the (^{7}Li,p) results[3] indicate high spin $[(3-5)^-$ or $(5-7)^+]$ if this is a single state. The backward-forward ratio indicates a significant CN component.

4898 keV

Two states are known[2] near this energy— at 4891.6 ± 2.8 and 4898.2 ± 2.8 keV. The (d,p) angular distribution appears to arise from a non-direct process. The (^{7}Li,p) results[3] suggest that the sum of J for the two members is 2–6.

5049 keV

This may be the state of 5040.2 ± 3.1 keV in the compilation[2] with $J^{\pi}=(0,1,2)^-$. The presence of an impurity prevents extraction of data at three angles. The present data do not allow an l determination. Again, a non-direct mechanism appears to be present.

5072 keV

This state has an $l=2$ angular distribution, requiring $J^{\pi}=(1,2,3)^+$.

5132 keV

There is no state near here in the compilation,[2] but a state has been observed at $E_x = 5131 \pm 5$ keV in ^{22}Ne(d,α)[4] and at 5130 ± 5 keV in ^{14}N(^{7}Li,p).[3] There is some indication from the (d,p) spectra that this state may actually be a doublet. The back-angle cross section is almost half the for-

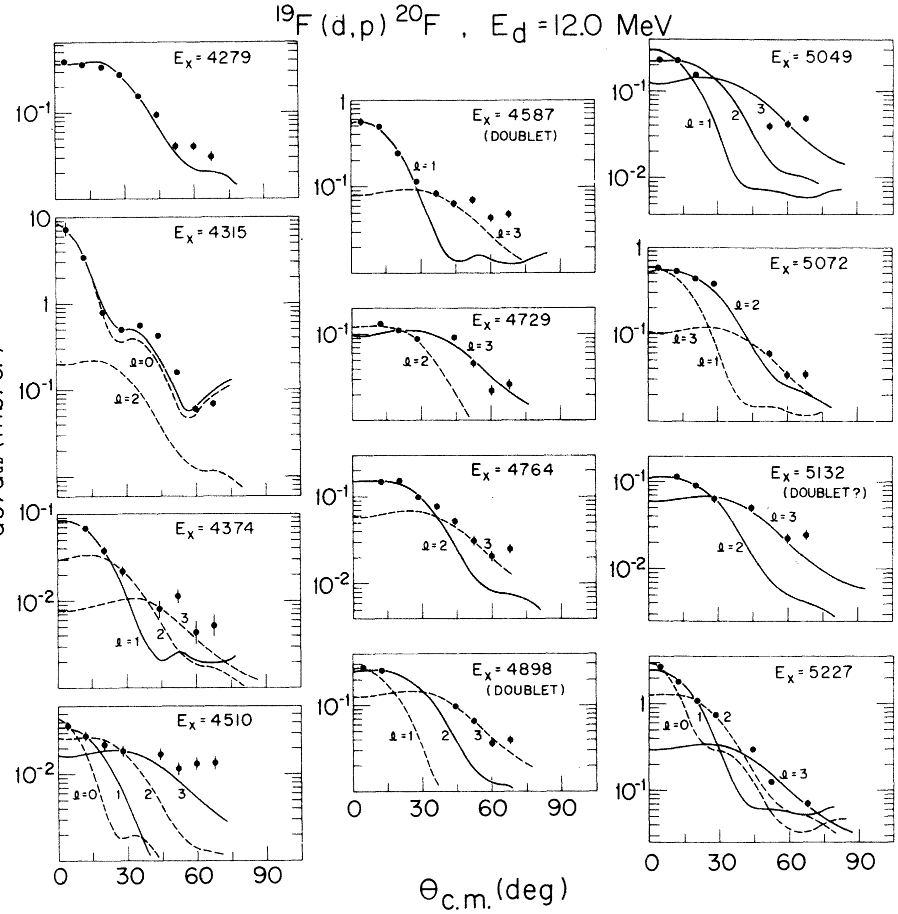

FIG. 2. Angular distributions with DWBA curves for ^{19}F$(d,p)^{20}$F. E_x = 4.20–5.23 MeV.

ward-angle cross section, implying a large CN contribution. We place no J^π restrictions on this state.

5227 keV

This fairly strong state is reasonably well fitted by $l=1$ at forward angles, with a hint of $l=3$ at larger angles. The backward-forward ratio implies a direct process. A state at 5224.0 ± 3.1 keV in the compilation[2] has a $(0,1,2)^-$ assignment. If $l=3$ is indeed present, then this is a 2^- state.

5287 keV

This state is also quite strong, with an obvious $l=0$ angular distribution, with a hint of a small $l=2$ contribution. The magnitude of the possible $l=2$ component is not sufficient to rule out a pure $l=0$. Hence, we assign $J^\pi=(1,0)^+$. A state at 5281.0 ± 3.3 keV in the compilation[2] has a $(0,1,2)^-$ assignment. If this is the same state as the one we observe, then the old assignment is incorrect.

5321 keV

The angular distribution for this state, which appears to be largely direct, requires $l=2$ or a mixture of $1+3$, with slight preference for the latter. Thus $J^\pi=2^-$ or $(1,2,3)^+$.

5354 keV

This state has a very good $l=2$ angular distribution, requiring $J^\pi=(1,2,3)^+$.

5408 keV

The data for this state do not allow an l value determination. The backward-forward ratio is consistent with a pure CN process. This is probably the state at 5413.1 ± 0.6 keV in the compilation.[2]

5462 keV

The state we observe here has a reasonably good $l=2$ angular distribution, requiring $J^\pi=(1-3)^+$.

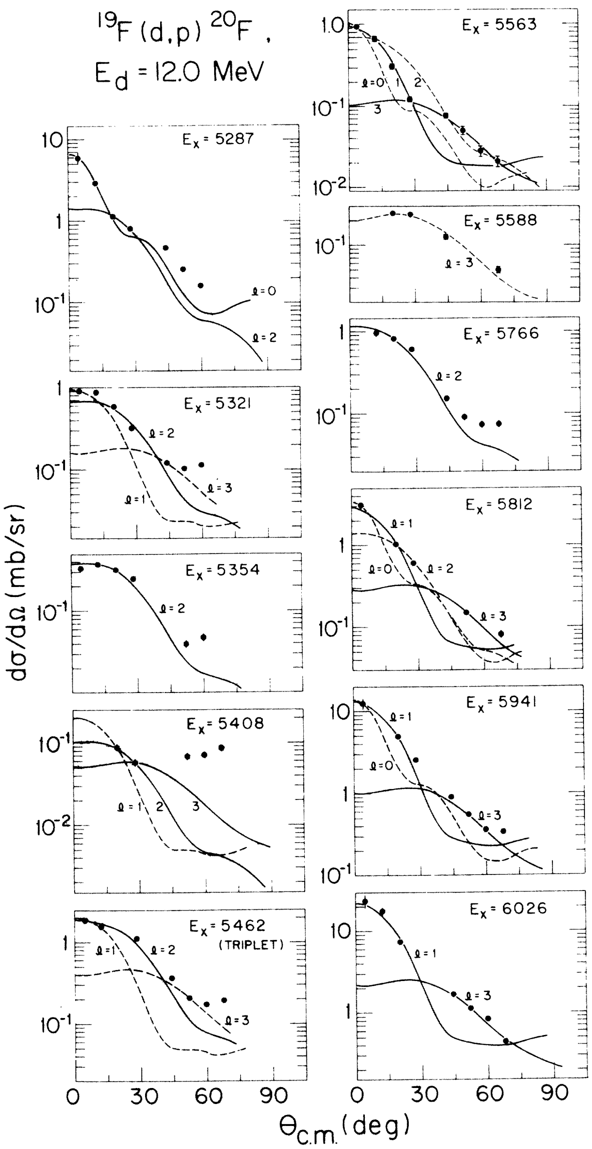

FIG. 3. Same as Fig. 2, but E_x = 5.28–6.03 MeV.

TABLE II. Summary of spectroscopic strengths in $^{19}F(d,p)^{20}F$ from Ref. 1 and the present work. $G = [(2J_f+1)/(2J_i+1)]S$.

l	Definite E_x (MeV)	Definite G		Possible E_x (MeV)	Possible G
0	1.06	0.0065			
	3.49	0.60			
	3.53	0.14			
	4.08	0.065			
	4.32	0.10			
	5.29	0.17			
	Sum = 1.08				
1	0.98	0.007			
	1.31	0.008	$1p_{1/2}$		
	1.84	0.010			
	Sum = 0.025				
	4.59	0.01		3.76	0.002
	5.23	0.045		4.37	0.0015
	5.56	0.03		4.89	0.012
	5.81	0.05	$2p_{3/2}$	5.05	0.013
	5.94	0.22		5.32	0.016
	6.02	0.34		5.46	0.035
	Sum = 0.69			Sum = 0.08	
2	0.00	0.027			
	0.66	1.16			
	1.06	0.011			
	2.04	1.16			
	2.19	0.275			
	2.97	0.19		3.76	0.008
	3.18	0.011		4.31	0.024
	3.59	0.19		4.37	0.004
	3.68	0.016		4.73	0.012
	3.97	0.018		4.76	0.016
	4.08	0.042		4.89	0.024
	4.28	0.044		5.05	0.021
	5.07	0.045		5.13	0.010
	5.32	0.05		5.29	(0.11)
	5.35	0.03		Sum = 0.37	
	5.46	0.14			
	5.77	0.08			
	Sum = 3.49				
3	1.31	0.02		3.76	0.022
	1.84	0.06		4.59	0.020
	1.97	0.02		4.73	0.03
	2.87	0.02		4.76	0.019
	5.81	0.09		4.89	0.041
	5.94	0.32		5.05	0.040
	6.02	0.70		5.23	0.10
	Sum = 1.23			Sum = 0.17	

The compilation[2] lists three states near here, at 5450.3 ± 3.8, 5455.4 ± 3.2, and 5463.4 ± 3.3 keV, none of which have any information on J^π.

5563 keV

The state we observe at 5563 ± 2 keV may be the state at 5554.7 ± 0.6 keV in the compilation and at 5557 ± 5 keV in $^{22}Ne(d,\alpha)$. It has a small backward-forward ratio and its angular distribution is reasonably well fitted by $l = 1$, with a hint of $l = 3$. We thus prefer negative parity and $J = 0, 1, 2$ for this state. If $l = 3$ is indeed present, the state has $J^\pi = 2^-$.

5588 keV

This state has no counterpart in the compilation, but may be the state observed at 5574 ± 6 keV in $^{22}Ne(d,\alpha)$. Its backward-forward ratio is rather large, so we make no l assignment even though $l = 3$ appears to fit the angular distribution reasonably well.

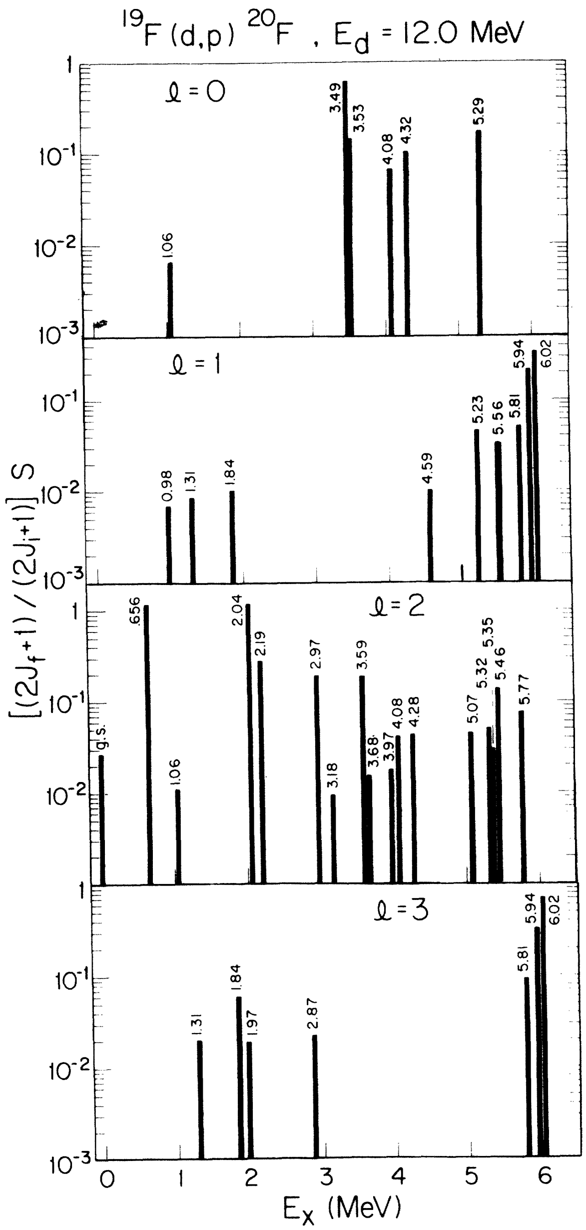

FIG. 4. Distribution of spectroscopic strengths $G_l = [(2J_f+1)/(2J_i+1)]\,S_l$ vs. excitation energy for $l=0$, 1, 2, and 3. For $l=1$, the strengths below 2 MeV are for $1p_{1/2}$, and those above 4 MeV are for $2p_{3/2}$.

5619 and 5711 keV

These two states are too weak at all angles to allow extraction of angular distributions.

5766 keV

This state possesses a good $l=2$ angular distribution, allowing an assignment of $J^\pi=(1,2,3)^+$.

5812 keV

The angular distribution can be fitted either with a sum of $l=0+2$ or a sum of $l=1+3$, suggesting $J^\pi=1^+$ or 2^-. A state at 5809.1 ± 2.9 keV in the compilation[2] has $J^\pi=(0-2)^-$. If that assignment is correct and if we see the same state, we can tentatively assign $J^\pi=(2^-)$.

5941 keV

This state possesses an $l=1$ angular distribution at forward angles, with a hint of a small $l=3$ contribution at larger angles consistent with the previous assignment[2] of $1^-, 2^-$.

6026 keV

This angular distribution appears to require an admixture of $l=1$ and 3, implying $J^\pi=2^-$. A state at 6017.3 ± 0.3 keV has a previous $1^-, 2^-$ assignment.[2]

In summary, the present analysis yields l assignments for 14 levels between 4.2 and 6.1 MeV of excitation in ^{20}F. The spectroscopic strengths

$$G_l = \frac{(2J_f+1)}{(2J_i+1)}\,S_l$$

from the present and previous work are summarized in Table II and Fig. 4 for $l=0$, 1, 2, and 3.

For $l=1$, the strengths were calculated for $1p_{1/2}$ transfer below 2 MeV in excitation and for $2p_{3/2}$ transfer above 4 MeV. The summed strengths indicate we have probably observed most of the $1d_{5/2}$ and $2s_{1/2}$ strength, but little of the $1d_{3/2}$ strength. Of course, below 6 MeV, we are just seeing the beginning of the $2p$ and $1f$ strength.

The centroid energy

$$E_c = \frac{\sum EG}{\sum G}$$

is found to occur at 2.2 MeV for the observed $l=2$ strength, and 3.8 MeV for $l=0$. The widths of the strength distribution

$$\Gamma = \left(\frac{\sum G(E-E_c)^2}{\sum G}\right)^{1/2}$$

are 1.5 MeV for $l=2$ and 0.9 MeV for $l=0$.

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[2]F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972).
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[4]H. T. Fortune and J. D. Garrett, Phys. Rev. C 14, 1695 (1976).