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States at high excitation in ^{20}Ne†

L. R. Medsker, H. T. Fortune, R. R. Betts,* and R. Middleton
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19174
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The ^{12}C(^{12}C, α)^{20}Ne reaction has been studied at bombarding energies of 36.0, 36.5, and 37.0 MeV. States up to 16 MeV excitation in ^{20}Ne were identified. Several previously unreported levels were observed, a number of which are excellent candidates for missing unnatural-parity states. We summarize existing spin-parity information for several "elusive" states.

[NUCLEAR REACTIONS ^{12}C(^{12}C, α), $E_{^{12}C}$=36.0, 36.5, 37.0 MeV, enriched target, measured $\sigma(\theta)$; deduced ^{20}Ne levels.]

I. INTRODUCTION

Very few unnatural-parity $[\pi=-(-1)^J]$ states are known in ^{20}Ne. In fact, below an excitation energy of 16 MeV, the only positive-parity $T=0$ states with definite odd-spin assignments[1] (see Table I) are three 1^+ states at 13.304, 13.733, and 14.197 MeV. And yet unnatural-parity states must exist. Typical shell-model calculations[2] for ^{20}Ne predict two 1^+, six 3^+, and four 5^+ states below 14.2 MeV in excitation.

The situation is equally bad for even-spin negative-parity states. Aside from members of the 5p-1h $K^\pi=2^-$ band (bandhead at 4.968 MeV) the only negative-parity $T=0$, states below 15 MeV with definite even-spin assignments[1] are five 2^- states, all above 13 MeV in excitation. A shell-model calculation[3] that includes only $1p_{1/2}$ holes, and no fp-shell particles, predicts (excluding the above 2^- band) one 0^-, five 2^-, and three 4^- states below 14 MeV. The inclusion of fp-shell excitations would provide several additional states in this energy region.

The fact that these unnatural-parity states have not been observed is understandable in view of the reactions that have been used to investigate ^{20}Ne. Selection rules forbid the population of unnatural-parity states as resonances in the ^{16}O + α reaction, since both the ^{16}O(g.s.) and the α particle have spin zero. These states would be only weakly excited in reactions such as ^{16}O(^{6}Li, d)^{20}Ne and ^{16}O-(^{7}Li, t)^{20}Ne, since population of them is forbidden if the mechanism is direct α transfer. Two-particle transfer experiments are of little help, since the direct component of both ^{18}O(^{3}He, n) and ^{22}Ne-(p, t) can populate only natural-parity states. Single-particle transfer reactions (proton stripping on ^{19}F and neutron pickup from ^{21}Ne) can populate both natural- and unnatural-parity states, but yield no direct evidence as to whether a given state has natural or unnatural parity. In addition, these reactions cannot directly populate high-spin states. For excitation energies above 12.84 MeV, proton capture on ^{19}F provides a means of populating unnatural-parity states, and indeed it is this process that has led to the existing unnatural-parity assignments.

Among the known levels of ^{20}Ne there exist several good candidates for unnatural-parity states. Below 10.86 MeV (the threshold for α decay to the 3^- 6.13-MeV state of ^{16}O), unnatural-parity states can have no natural width, except for γ decay. Table II lists all known states below 15 MeV that are not known to be $T=1$ and that have unknown or uncertain spin assignments. In addition to these states, a recent study[4] of the ^{19}F(^{3}He, d)^{20}Ne reaction populated a few states in this region of excitation that had not been previously observed. These are listed in Table III. Arguments presented there strongly imply that these states are all $T=0$, ex-

TABLE I. States below 15 MeV in ^{20}Ne (Refs. 1 and 4) that are known to have unnatural parity and $T=0$.

E_x (MeV ± keV)	J^π
4.9682 ± 0.8	2^-
7.0055 ± 2.8	4^-
10.609 ± 7	6^-
12.367 ± 10	1^+
12.823 ± 10	1^+
13.060 ± 4	2^-
13.304 ± 1	1^+
13.135 ± 10	1^+
13.411	2^-
13.673 ± 1	2^-
13.733 ± 1.5	1^+
14.124 ± 1.2	2^-
14.148 ± 1.2	2^-
14.197	1^+

TABLE II. States below 15 MeV in ^{20}Ne that are not known to be $T=1$, and that have unknown or uncertain spin assignments.

E_x (MeV ± keV)	J^π	$\Gamma_{c.m.}$ or τ_m (keV)	Decay	Reaction
(9.34 ± 30)	···	···	···	3, 26
9.950 ± 6	(1$^+$)	$\tau_m < 35$ fsec	γ	3, 19
10.920 ± 7	···	$\tau_m < 30$ fsec	γ	3
11.528 ± 6	≤4	$\tau_m < 30$ fsec	γ, α	3, 8, 19
11.549 ± 10	($T=1$)	···	···	26, 34
12.086 ± 10	($T=1$)	···	(α)	9, 26
12.200 ± 10	($T=1$)	···	···	26
12.61 ± 100	···	···	α	9
12.83 ± 30	···	55	α	9, 19
12.98 ± 75	(4$^+$)	60	α	9
13.086 ± 15	(4$^+$)	70	α	9, 26
13.168 ± 1	1$^+$ ($T=1$)	2.3 ± 0.2	γ, p, α	20, 21, 22, 26
13.18 ± 75	(4$^+$)	60	α	9
13.42 ± 140	(4$^+$)	110	α	9
13.523	(1$^-$)	190	p, α	21, 22
13.63 ± 30	···	7.9	p	19, 21
13.699		4.6	p	21
13.7 ± 400	(3, 7$^-$)	320	α	9
13.775	···	···	γ, p	20
(13.87)	(1$^-$)	190	p, α	22
13.882 ± 15	···	~1	γ, p	20, 21, 26
13.924	···	3.5	p	21
14.065	···	18	γ, p	20, 21
14.098	···	3.8	γ, p	20
14.373	···	~5	p	21
14.421	···	···	p	21
14.523 ± 2	···	33 ± 3	p, α	21, 22
14.6 ± 300	(4$^+$)	240	α	9
14.695 ± 2.6	(1$^+$)	38 ± 10	p, α	21, 22
14.772 ± 3	···	95 ± 20	p, α	21, 22
14.85 ± 150	(2$^+$, 4$^+$)	~100	p, α	9, 22

[a] Reactions labeled according to convention of Ref. 1.
(3) ^{12}C(^{12}C, α); (19) ^{18}O(^{3}He, n); (22) ^{19}F(p, α);
(8) ^{16}O(α, γ); (20) ^{19}F(p, γ); (26) ^{19}F(d, n);
(9) ^{16}O(α, α); (21) ^{19}F(p, p); (27) ^{19}F(^{3}He, d);
(34) ^{20}Ne(e, e).

TABLE III. Previously unreported states in ^{20}Ne that were populated in the ^{19}F(^{3}He, d) reaction (Ref. 4).

E_x	J^π, T	Γ (keV)	Remarks
9.305	(1, 2, 3)$^+$	···	Probably the (9.34) state?
10.951	···	···	The 10.92-MeV state?
11.549	3$^+$ (1, 2)$^+$ $T=0$	···	The 11.549 ($T=1$) state?
11.992	($T=1$?)	···	···
12.367	1$^+$	···	···
12.423	2$^+$ (1, 3)$^+$	160	···
12.503	(1, 2, 3)$^+$	···	···
12.823	1$^+$	···	···
13.037	(1, 2, 3)$^+$	···	···
13.135	1$^+$	···	State at 13.168 ± 1 has 1$^+$ ($T=1$)
13.270	···	···	···

cept possibly for the states at 11.992 and 13.135 MeV.

Of the states listed in Table II, any state that has been observed as a resonance in either reaction 8 [$^{16}O(\alpha,\gamma)$] or reaction 9 [$^{16}O(\alpha,\alpha)$] can be removed from consideration as a candidate for unnatural parity. This eliminates states at 11.528, 12.086, 12.61, 12.83, 12.98, 13.086, 13.18, 13.42, 13.7, 14.6, and 14.85 MeV.

γ decays provide some additional information. For example, the state at 9.95 MeV decays[1] >90% to the 1.63-MeV 2^+ state, with no other measured branches. The lifetime limit and the $\Delta T = 0$ $E1$ selection rule require positive parity. The 10.92-MeV state decays[1] 25% to the 1.63-MeV state and 75% to the 4.25-MeV 4^+ state. The lifetime restricts the parity to positive. The state at 11.53 MeV, which must have natural parity, decays[1] 34% to the 4.25-MeV state and 66% to the 4.97-MeV 2^- state. Finally, the state at 13.88 MeV decays[1] 20% to the 1.63-MeV state and 80% to the 4.97-MeV state. We thus expect $J^\pi(9.95) = 1^+, 2^+, 3^+$; $J^\pi(10.92) = 2^+, 3^+, 4^+$; $J^\pi(11.53) = 2^+, 3^-$ (4^+ is ruled out by the lifetime) and $J(13.88) = 1, 2, 3$. Since the 9.95-MeV state has no measured width, it is likely an unnatural-parity state, $J^\pi = 1^+$ or 3^+. Similarly, the lack of a measurable width for the 10.92-MeV state implies $J^\pi = 3^+$. The absence of any α width for the 13.88-MeV state implies $J^\pi = 1^+, 2^-, 3^+$.

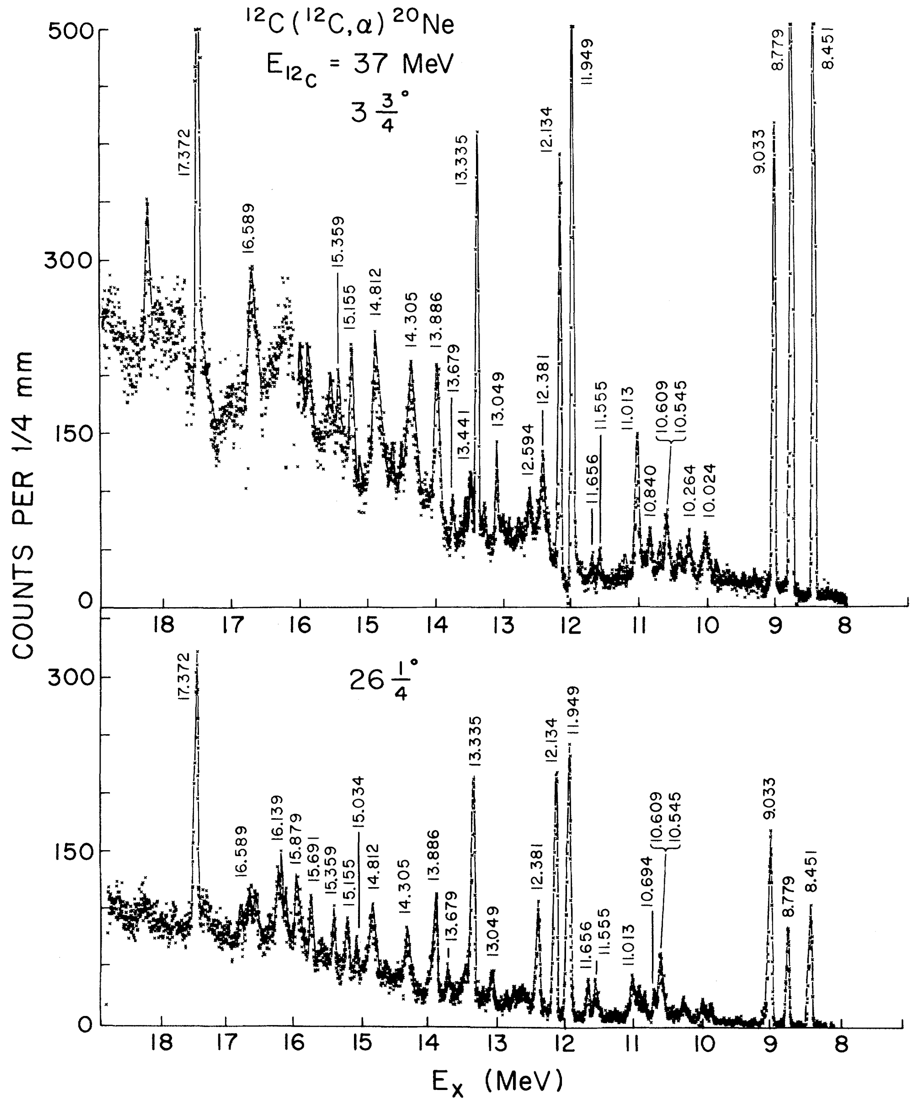

FIG. 1. The high excitation portion of spectra from the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction at a bombarding energy of 37.0 MeV and laboratory angles of 3.75° (top) and 26.25° (bottom).

TABLE IV. Excitation energies, integrated cross sections (σ_{total}), and $\sigma_{\text{total}}/(2J+1)$ from the present ^{12}C(^{12}C, α) experiment at 37 MeV. Energies and J^{π} of previously observed states in ^{20}Ne are shown in the first two columns.

Previous[a]				^{12}C(^{12}C, α)^{20}Ne				
E_x (MeV)	± (keV)	J^{π}	K^{π}	E_x[b]	σ_{total} (mb/sr)	± (mb/sr)	$\sigma_{\text{total}}/(2J+1)$ (mb/sr)	± (mb/sr)
0.0		0^+	0_1^+					
1.6338	0.4	2^+	0_1^+					
4.2473	1.8	4^+	0_1^+					
4.9682	0.8	2^-	2^-	4.968	0.54	0.04	0.11	0.006
5.6217	2.0	3^-	2^-	5.618	1.56	0.04	0.22	0.006
5.785	3	1^-	0^-	5.774	0.77	0.03	0.26	0.01
6.722	3	0^+	0_2^+	6.725	1.54	0.07	1.54	0.07
7.0055	2.8	4^-	2^-	7.004	1.31	0.04	0.15	0.004
7.166	4	3^-	0^-	7.169 }	2.86	0.06		
7.196	4	0^+	0_3^+	7.196 }				
7.424	4	2^+	0_2^+	7.435	0.76	0.03	0.15	0.006
7.834	4	2^+	0_3^+	7.835	4.09	0.07	0.82	0.01
8.447	3	5^-	2^-	8.451	7.28	0.09	0.66	0.008
~8.6		0^+	0_4^+					
8.72	20	1^-		8.694	1.13	0.03	0.38	0.01
8.7750	2.2	6^+	0_1^+	8.779	5.73	0.08	0.44	0.006
~8.8		2^+	0_4^+					
8.82		(5^-)						
8.850	5	1^-		8.85				
9.040	5	4^+	0_3^+	9.033	12.1	0.14	1.34	0.01
9.117	5	3^-		9.110	0.77	0.04	0.11	0.005
(9.34	30)			9.318	0.53	0.03		
9.489	9	2^+		9.533	1.02	0.09	0.20	0.02
				9.872				
9.950	6	(1^+)						
9.99	10	4^+	0_2^+					
				10.024	1.87	0.04		
10.257	5	5^-	0^-	10.264	2.17	0.04	0.20	0.004
10.26	20	2^+, $T=1$						
10.401	5	3^-		10.407	1.46	0.04	0.21	0.005
10.548	5	4^+		10.545	1.19	0.06	0.13	0.006
10.579	10	2^+						
10.609	7	6^-	2^-	10.609	4.49	0.11	0.35	0.009
				10.694	2.17	0.05		
10.79	100	4^+						
10.836	5	2^+						
10.836		3^-		10.840	1.73	0.04	0.25	0.006
10.853	10	(2^+), $T=1$						
10.920	7	3^+		10.915	1.34	0.03	0.19	0.005
10.97	150	0^+						
11.015	10	4^+		11.013	3.12	0.06	0.35	0.006
11.08	20	(4^+), $(T=1)$						
11.23	30	1^-						
11.233	10	1^+, $T=1$						
11.27	30	2^+						
11.324	10	2^+						
11.528	6	≤ 4						

TABLE IV *(Continued)*

Previous [a] E_x (MeV)	± (keV)	J^π	K^π	$^{12}C(^{12}C, \alpha)^{20}Ne$ E_x [b]	σ_{total} (mb/sr)	± (mb/sr)	$\sigma_{total}/(2J+1)$ (mb/sr)	± (mb/sr)
11.549	15	$3^+(1^+, 2^+)$						
				11.555	2.04	0.04		
				11.656	2.44	0.05		
11.871	20	2^+						
				11.871				
11.925	5	4^+						
11.948	5	8^+	0_1^+	11.949	12.47	0.16	0.73	0.01
11.953	10	1^-						
11.971	8	1^-						
12.086	10	$T=1$						
12.150	10	6^+	0_3^+	12.134	10.42	0.12	0.80	0.009
(12.200	10)	$(T=1)$						
12.224	10	4^+						
12.245	15	(2^+), $T=1$						
12.35	100	2^+						
12.367	10	3^-		12.381	6.81	0.09	0.97	0.01
12.367 [c]	15	1^+						
12.410	5	0^+						
12.559	10	6^+	0_2^+					
12.61	100			12.594	3.59	0.06		
12.682	15	5^-						
				12.730	2.72	0.05		
12.77	100	4^+						
12.830	30							
				12.919	0.76	0.03		
12.980	74	(4^+)						
				13.010	1.10	0.04		
13.060	4	2^-		13.049	4.88	0.07	0.98	0.01
13.086	15	(4^+)						
13.168	1	1^+, $(T=1)$						
13.18		(4^+)		13.190	0.68	0.03	(0.14	0.006)
13.224		1^-						
13.224		0^+						
				13.277	0.84	0.04		
13.304	1	1^+						
13.333	6	7^-		13.335	9.78	0.12	0.65	0.08
13.342		4^+						
13.411		2^-						
13.42	140	(4^+)						
				13.441	3.18	0.06		
13.462	20	1^-						
13.479	1.5	1^+, $T=1$						
13.523		(1^-)						
13.541		2^+						
13.584		2^+		13.569	0.99	0.04	0.20	0.008
13.63	30			13.631	0.60	0.03		
13.650	15	0^+, $T=1$						
(13.66)		1^-						
13.673	1	2^-		13.679	1.63	0.05	0.33	0.01
13.699								
13.7	400	$(3,7)^-$						
(13.73)		0^+						

TABLE IV *(Continued)*

Previous [a] E_x (MeV)	± (keV)	J^π	K^π	^{12}C(^{12}C, α)^{20}Ne E_x [b]	σ_{total} (mb/sr)	± (mb/sr)	$\sigma_{total}/(2J+1)$ (mb/sr)	± (mb/sr)
13.733	1.5	1^+						
13.775								
(13.87)		(1^-)		13.845	0.76	0.03	(0.25	0.01)
13.88	30	(6^+)		13.886	8.80	0.11	(0.68	0.008)
13.882	15							
13.903		2^+						
13.924								
13.946		0^+						
14.017		1^-						
14.03		2^+						
14.065								
14.098								
14.124	1.2	2^-						
14.134		2^+						
14.148	1.2	2^-		14.144	1.12	0.04	0.55	0.008
14.197		1^+						
14.3	300	6^+		14.305	7.24	0.10	0.56	0.007
14.373								
14.421								
14.453	2			14.44	1.37	0.05		
14.467		0^+						
14.6	300	(4^+)						
14.604		1^-		14.60	1.54	0.06	0.51	0.02
14.695	2.6	(1^+)						
14.772	3.0							
14.85	150	(2^+, 4^+)		14.812	9.32	0.12		
15.03	150	(2^+)						
				15.034	2.09	0.06		
15.18	40	6^+		15.155	4.19	0.08	0.32	0.006
15.23								
15.26		(1^-)						
15.30		(0^+)						
				15.359	3.54	0.07		
15.39								
15.44								
15.52				15.50				
15.59								
15.618		(8^-)	2^-					
15.71				15.691	4.50	0.04		
				15.879	6.33	0.10		
15.9	40	5^-						
15.9	40	8^+						
16.02								
				16.139	8.65	0.12		
16.24								
16.34								
16.49				16.50				
16.59				16.589	5.05	0.05		
16.728	4	0^+, $T=2$						
16.77								
16.98								
17.08								

TABLE IV (*Continued*)

Previous [a] E_x (MeV)	± (keV)	J^π	K^π	E_x [b]	$^{12}C(^{12}C, \alpha)^{20}Ne$ σ_{total} (mb/sr)	± (mb/sr)	$\sigma_{total}/(2J+1)$ (mb/sr)	± (mb/sr)
17.30								
17.40		9^-		17.372	12.31	0.56	0.65	0.03
17.50								
17.58								
17.76								
18.08	180	$(6^+, 7^-)$		18.11				
18.31	300	(6^+)						

[a] Reference 1 unless otherwise indicated.
[b] Uncertainties in E_x are about 6 keV below 13.5 MeV excitation and 15 keV above there.
[c] Reference 4.

Thus, several states that do not have unique J^π assignments are candidates for some of the missing unnatural-parity states. However, it is obvious that many of the expected unnatural-parity states are still unknown because they have not been populated in any of the reactions discussed above.

We have investigated this region of excitation in ^{20}Ne by means of the reaction $^{12}C(^{12}C, \alpha)^{20}Ne$. The motivation was twofold: (1) to try to locate previously unknown states, and (2) to try to delineate which states are good candidates for unnatural parity. Since the target, projectile, and outgoing α particle all have spin zero, the cross section for this reaction at 0° will be identically zero for states of unnatural parity. In practice, this means that the angular distribution for such states will turn downward at extreme forward angles. Of course, the angular distributions for natural-parity states can also turn downward. But, if the angular distribution of a given state continues to rise at forward angles, then that state must have $\pi = (-1)^J$.

II. EXPERIMENTAL

The experiment was performed with the $^{12}C^{5+}$ beam from the University of Pennsylvania EN tandem. The target was a 10-μg/cm^2 self-supporting foil enriched to 99.99% in ^{12}C. Outgoing particles were momentum analyzed in a multiangle magnetic spectrograph and detected in photographic emulsions. Angular distributions were measured at bombarding energies of 36.0, 36.5, and 37.0 MeV. Typical spectra are displayed in Fig. 1.

Accurate excitation energies and the exact beam energy were obtained from the known magnet calibration and the positions of peaks corresponding to states whose excitation energies were accurately known[1] previously. Our extracted excitation energies are listed in Table IV. The uncertainty is about 6 keV below $E_x = 13.5$ MeV, and 15 keV above that energy. Whenever a state has an obvious counterpart from the literature,[1] the previously known excitation energy is shown for comparison. Whenever such a correspondence can be made, our energies agree quite well with the literature values, usually to within a few keV.

It can be seen that we observe several states not previously known. These include states at excitation energies of 9.872, 10.024, 10.694, 11.555, 11.656, 13.441, 15.034, 15.359, and 15.879 MeV. In addition, for several states, we have more accurate energies than those previously known.

Angular distributions were extracted for all strong states and are displayed in Figs. 2 and 3. Data beyond a center of mass angle of 90° is not required since the presence of two identical nuclei in the incident channel guarantees symmetry about 90°. Several of the angular distributions are indeed observed to turn over at forward angles, as required for unnatural-parity states.

For essentially all states observed, we have extracted the ratio of cross sections at the two most forward angles ($\theta_{lab} = 3\frac{3}{4}°$ and $11\frac{1}{4}°$). These are listed in Table V for all three bombarding energies. Hauser-Feshbach calculations suggest that for unnatural-parity states this ratio will be about $\frac{1}{2}$ of the ratio for a natural-parity state of the same spin. It is interesting to note that this ratio, $R = [\sigma(3\frac{3}{4}°)]/[\sigma(11\frac{1}{4}°)]$ is substantially less than unity for all but two of the new states. There is some evidence that one of them (at 10.024 MeV) may be a doublet. For most, but certainly not all, of the states that are known to have natural parity, this ratio is substantially greater than unity. The average ratio for all known natural-parity states is 1.50. We thus expect a ratio of roughly 0.8 for unnatural-parity states.

We have also obtained total cross sections by integrating the 37-MeV angular distributions. These are also listed in Table IV. We expect, generally, that higher-spin states will have larger cross sections, though deviations of a factor of 2 or 3 can easily be caused by fluctuations.

III. RESULTS

Below 9.2 MeV we observe all states previously known[1] [except for a (5^-) state at 8.82 MeV] and no others. The two broad states near $8.3(0^+)$ and $8.6(2^+)$ MeV are too broad to allow their yield to be extracted from the background. For the other known states in this region, our extracted excitation energies agree reasonably well with the values from the compilation.[1] As can be seen in Table IV our energies overlap those from the literature, to within the combined uncertainties, for most states below 9.2 MeV.

Above this energy, things are less clear. We observe clearly a state at 9.318 MeV which was not previously known, although it may be identified with a tentative state at 9.34 ± 0.03 MeV from the compilation[1] and/or with a state recently observed at 9.357 ± 0.017 MeV in the ^{21}Ne$(d, t)^{20}$Ne reaction.[5] In the latter reaction, the angular distribution was characteristic of $l = 1$, implying $J^\pi = (0-3)^-$, with 2^- preferred although the authors state that the level could arise from a ^{22}Ne impurity in their target. In ^{19}F$(^3$He$, d)$, a state at $E_x = 9.305$ MeV was observed[4] to be populated via $l = 2$, implying $J^\pi = (1, 2, 3)^+$, and the absence of a measurable width made 2^+ unlikely. In the ^{12}C$(^{12}$C$, \alpha)$ reaction, the average ratio R is 1.66, implying natural parity. However, this state could actually be a doublet, especially in view of the divergent excitation energies measured in different reactions.

The next state we observe is at 9.533 MeV. A 2^+ state is known near here, with $E_x = 9.489 \pm 0.009$

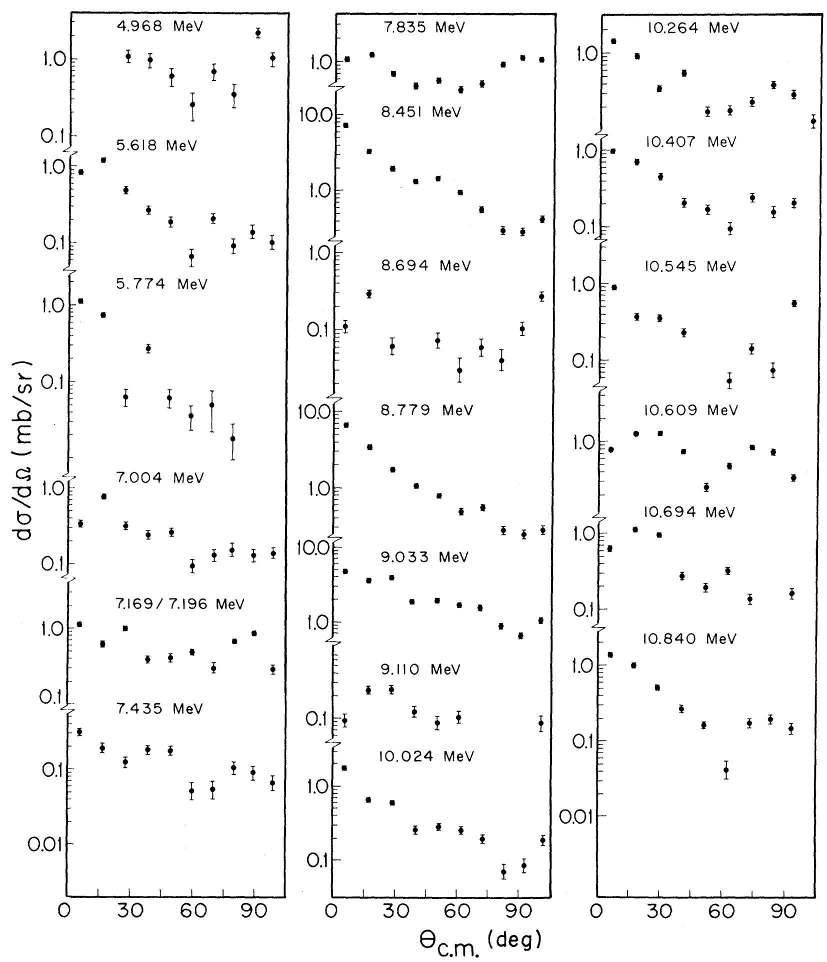

FIG. 2. Angular distributions for states in ^{20}Ne populated in the reaction ^{12}C$(^{12}$C$, \alpha)^{20}$Ne. The bombarding energy was 37.0 MeV.

MeV from the compilation.[1] A weak state was observed[4] in ^{19}F(^{3}He, d) at 9.469 MeV. These may all be the same state, though if so, the spread in measured excitation energies is perplexing. Our ratio $R = 2.38$ is consistent with natural parity.

We observe a state at 9.872 MeV, with $R = 0.61$, consistent with unnatural parity. This state is not in the compilation, but a state at 9.859 MeV was populated[4] with a strong $l = 2$ in ^{19}F(^{3}He, d). That work favored $J^\pi = 3^+$, with 1^+, 2^+ also possible. If this is the same state, the absence of natural width and the forward dip in ^{12}C(^{12}C, α) make a 2^+ assignment very unlikely.

A state at 9.950 ± 0.006 MeV in the compilation, tentatively assigned (1^+), was not observed here nor in ^{19}F(^{3}He, d), though possibly in ^{21}Ne(d, t).[5]

A known 4^+ state at 9.99 MeV, with $\Gamma = 150 \pm 50$ keV was not observed with sufficient strength to allow extraction of its yield. However, we observe a new narrow state at 10.024 MeV, with $R = 1.97$. Among the new states that we observe, this state and the one at 9.318 MeV are the only ones with $R > 1$. This new state, therefore, probably has natural parity, although it could be a doublet.

States we observe at 10.264, 10.407, 10.545, and 10.609 MeV are probably to be identified with 5^-, 3^-, 4^+, and 6^- states previously known[1] at energies of 10.257 ± 0.005, 10.401 ± 0.005, 10.548 ± 0.005, and 10.609 ± 0.007 MeV, respectively. As expected, we do not observe the 2^+ $T = 1$ state at 10.26 ± 0.02 MeV, which is the analog of the ground state of ^{20}F, nor do we observe any higher-lying $T = 1$ states. A state at 10.694 MeV, not previously reported, is observed here with $R = 0.64$, mak-

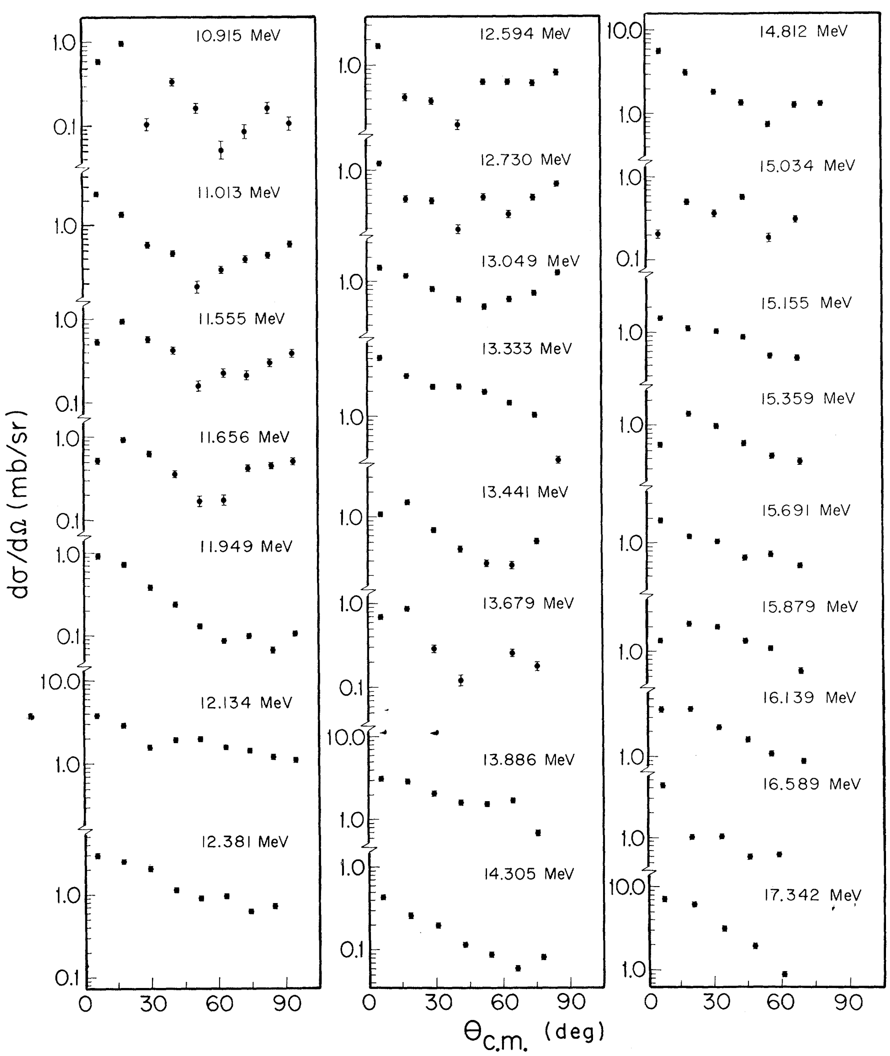

FIG. 3. Angular distributions for states in ^{20}Ne populated in the ^{12}C(^{12}C, α) reaction. The bombarding energy was 37.0 MeV.

TABLE V. Ratios of cross sections at $3\frac{3}{4}$ and $11\frac{1}{4}°$ for states observed with the $^{12}C(^{12}C, \alpha)^{20}Ne$ reaction at $E_{^{12}C}$=36.0, 36.5, and 37.0 MeV.

E_x	J^π	$\sigma(3\frac{3}{4}°)/\sigma(11\frac{1}{4}°)$ 36 MeV	36.5 MeV	37 MeV	$\frac{\sum\sigma(3\frac{3}{4}°)}{\sum\sigma(11\frac{1}{4}°)}$
7.435	2^+	2.75	1.36	1.61	2.25
7.835	2^+	1.15	1.20	0.87	1.12
8.451	5^-	2.56	2.56	2.20	2.34
8.694	1^-	...	...	0.38	0.38
8.779	6^+	1.32	1.92	1.96	1.88
8.85	1^-	2.66	2.71	1.58	2.44
9.033	4^+	1.21	2.15	1.31	1.61
9.110	3^-	(3.07)	0.26	1.28	0.51
9.318		...	1.47	2.00	1.66
9.533	2^+	...	...	2.38	2.38
9.872		0.28	0.92	0.79	0.61
10.024		1.16	1.98	2.68	1.97
10.264	5^-	1.64	1.07	1.57	1.35
10.407	3^-	1.18	1.73	1.45	1.44
10.545	4^+	2.07	1.66	2.42	2.04
10.609	6^-	0.69	1.28	0.58	0.80
10.694			0.69	0.58	0.64
10.840	3^-	1.38	0.79	1.37	1.20
10.915	3^+	(1.34)	(1.55)	0.60	0.70
11.013	4^+	1.61	1.50	1.77	1.63
11.555		0.78	0.61	0.56	0.61
11.656		0.27	0.47	0.55	0.46
11.871		...	0.45	0.74	0.53
11.949	8^+	0.76	0.98	1.27	1.05
12.134	6^+	0.80	1.14	1.33	1.09
12.381	3^-	0.96	1.73	1.17	1.01
12.594		(0.52)	(0.59)	(4.09)	1.19
12.730		1.10	2.06	2.71	1.76
12.919		...	0.78	3.27	
13.010		...	...	2.55	
13.049	2^-	0.74	1.26	1.28	1.13
13.190		0.97	0.79	0.57	
13.277		1.63	0.62	2.85	
13.335	7^-	0.93	1.04	1.68	1.30
13.441		1.07	0.66	0.73	0.77
13.569	2^+	...	0.68	2.68	
13.631		...	...	1.88	1.88
13.679	2^-	0.57	1.80	0.79	0.88
13.845	(1^-)	...	...	1.20	1.20
13.886	(6^+)	1.16	2.62	1.08	1.19
14.144	2^-	...	...	0.95	0.95
14.305	6^+	1.39	...	1.68	1.47
14.44		...	...	...	...
14.60	1^-	...	...	...	...
14.812	$(2^+, 4^+)$	...	1.70	1.82	1.77
15.034		1.01	2.47	0.41	1.09
15.155	6^+	2.22	1.93	1.35	1.83
15.359		(0.92)	...	0.43	0.62
15.50		(0.90)	(1.92)	...	1.32
15.691		0.76	(0.75)	1.58	0.95
15.879		0.79	...	0.63	
16.139			...	(<1.02)	

TABLE V *(Continued)*

E_x	J^{π}	$\sigma(3\frac{3}{4}^{\circ})/\sigma(11\frac{1}{4}^{\circ})$ 36 MeV	36.5 MeV	37 MeV	$\frac{\sum\sigma(3\frac{3}{4}^{\circ})}{\sum\sigma(11\frac{1}{4}^{\circ})}$
16.50		1.22	...	...	
16.589		0.53	0.91	(4.14)	(1.52)
17.372	9^-	1.29	1.93	1.15	1.34

ing it a candidate for unnatural parity.

Broad 4^+ and 0^+ states at 10.79 ± 0.10 and 10.97 ± 0.15 MeV, respectively, were not observed here, presumably because of their large widths. Neither was the $T = 1$ state at 10.853 MeV, assigned 2^+ in the compilation,[1] but now known[4,6] to be 3^+. A state we observe at 10.840 MeV probably corresponds to one or both of the two states (2^+ and 3^-) known at 10.836 MeV. However, the small width of the peak in our spectrum would rule out a large contribution from the 3^- state, which has $\Gamma = 45$ keV. Our results for states we observe at 10.915 and 11.013 MeV are consistent with their being the 3^+ and 4^+ states previously known at 10.920 ± 0.007 and 11.015 ± 0.010 MeV, respectively.

Between 11.05 and 11.55 MeV, the compilation[1] lists seven states, none of which are clearly observed here. Some of these states have $T = 1$ and should be absent in $^{12}C(^{12}C, \alpha)$, but the absence of the others is puzzling.

We observe two new states at 11.555 and 11.656 MeV, with ratios $R = 0.61$ and 0.46, respectively, making both excellent candidates for unnatural parity. A state we observe at 11.871 MeV has a very small ratio, $R = 0.53$, which is unexpected if this is the 2^+ state previously known at this energy. However, in the $^{19}F(^3He, d)$ reaction,[4] a peak at this energy had a width significantly larger than the measured width of the known state. Thus, this "state" may actually be a doublet.

The 8^+ state at 11.948 MeV and the 6^+ state at 12.150 MeV are strong in the present reaction. We see no evidence of known 4^+, 1^-, and 1^- states reported at 11.925, 11.953, and 11.971 MeV, respectively. Though unlikely, it is possible that they are obscured by the strong 8^+ state. The $T = 1$ states at 12.086, 12.200, and 12.245 MeV are absent, as expected.

Above 12.2 MeV, the situation becomes very complicated. In general, it is difficult to make a correspondence between the levels we see and the ones in the compilation. In what follows, we discuss primarily the levels we observe and comment only briefly on other known levels.

We observe a strong state at 12.381 MeV, with R close to 1.0. It is not clear which of the experimentally known states near here (2^+ at 12.35 ± 0.10, 3^- at 12.367 ± 0.010, and 0^+ at 12.410 ± 0.005 MeV) we are populating, though its excitation energy would favor the 3^-. A 1^+ state was observed[4] at 12.367 MeV in $^{19}F(^3He, d)$.

The state we observe at 12.594 MeV may be the 6^+ state at 12.559 ± 0.010 MeV or a state listed as 12.61 ± 0.10 MeV, or a combination of the two. The apparent width of this state and the ratio R both differ greatly for different bombarding energies, perhaps implying the presence of at least two states.

A state we observed at 12.730 MeV with $R = 1.76$ lies between known 5^- and 4^+ states at 12.682 ± 0.015 and 12.77 ± 0.10 MeV, respectively, both with $\Gamma \approx 100$ keV. Likewise, our states at 12.919 and 13.010 lie between previously known states. The state we observe at 13.190 MeV may be the state at 13.18 ± 0.075 MeV in the compilation which has a tentative assignment of (4^+, $T = 0$). However, the ratio R is less than 1 at all three bombarding energies, making it a candidate for an unnatural-parity state.

The strong state we observe at 13.335 MeV is undoubtedly the 7^- state known at 13.333 ± 0.006 MeV. The 13.277- and 13.441-MeV states have no obvious counterparts in the compilation.

Between 13.5 and 14.0 MeV, we observe five states, each of which can be identified with a known level. However, we fail to observe a number of known states in this region. Furthermore, the 13.679-MeV state has $R > 1$ at one bombarding energy, uncharacteristic of unnatural parity. (A state at 13.673 ± 0.001 MeV has a 2^- assignment.)

Above 14 MeV, the density of levels is so great that we do not present a state-by-state evaluation. We see strongly states at 14.305 (14.3 ± 0.3, 6^+), 14.812 [14.85 ± 0.15, ($2^+, 4^+$)], 15.034 [15.03 ± 0.15, (2^+)], 15.155 (15.18 ± 0.04, 6^+), 15.359, 15.691 (15.71), 15.879 (15.9 ± 0.04), 5^-), 16.139, 16.589, 17.372 (17.40, 9^-), and 18.11 MeV [18.08 ± 0.18 ($6^+, 7^-$)], where the numbers in parentheses refer to possible identifications with previously known levels.

We do not observe any state near 15.618 MeV, even though a state at this excitation energy was observed strongly at higher bombarding energies, in the same reaction, and assigned[7] $J^{\pi} = 8^-$. The

TABLE VI. Results for members of three $K^\pi = 0^+$ bands.

J^π	E_x (MeV)	$\frac{\sigma(3\frac{3}{4}°)}{\sigma(11\frac{1}{4}°)}$	$\frac{\sigma_{tot}}{2J+1}$
6^+	8.78	1.88	0.44
8^+	11.95	1.05	0.73
0^+	6.72	···	1.54
2^+	7.43	2.25	0.15
4^+	9.99	···	···
6^+	12.40	···	···
0^+	7.20	···	~1.5
2^+	7.84	1.12	0.82
4^+	9.03	1.61	1.34
6^+	12.16	1.09	0.80

nearest states in our spectrum that behave like unnatural-parity states are at 15.359 and 15.879 MeV. It would seem unlikely that the previous calibration[7] was incorrect by that large an amount. It may simply be that the 8^- state is populated only at higher bombarding energies.

IV. DISCUSSION

It is tempting to try to place the known states into rotational bands. For five low-lying bands with $K^\pi = 0^+$, 2^-, 0^-, 0^+, and 0^+ this is simple. (See Tables VI–VIII.) Above that things are more complicated.

Two 1^- states exist near 9 MeV—at 8.72 and 8.850 MeV. One of these is most likely the bandhead of the $K^\pi = 1^-$ band expected from the five-particle one-hole (5p-1h) configuration $(sd)^5p^{-1}$. The 2^- bandhead of this configuration is at 4.97 MeV. Pickup reactions[5,8] favor the 8.85-MeV state as the 1^- 5p-1h state, since it is much stronger than the 8.72-MeV 1^- state. This 1^- band should contain all spins 2^-, 3^-, etc. up to 10^- or 11^-. The first candidates for the 2^- member are at 9.3 and 9.9 MeV. The 9.3-MeV state was suggested[5] as the 2^- member from an $l = 1$ angular distribution in ^{21}Ne(d, t). However, a positive-parity state was observed[4] there in ^{19}F(^{3}He$, d)$, with $J^\pi = (1, 2, 3)^+$. This state may, in fact, be a doublet. The other candidate, at 9.87 MeV, appears from the present work to be an excellent candidate for unnatural parity and hence may be the 2^- 5p-1h state. However, ^{19}F(^{3}He$, d)$ favors $J^\pi = 3^+$ for a state near here. Again, we have the possibility of a doublet. Two 3^- states are known at 10.401 and 10.836 MeV. If either is in the band built on the 8.85-MeV state, then the 2^- member of this band should lie below it, and the only two candidates are those at 9.3 and 9.9 MeV. In fact, if the 1^- state at 8.72 MeV is also a bandhead, the other 3^- may be in that band, in which case two 2^- states are needed.

TABLE VIII. Results for the $K^\pi = 0^-$ band.

J^π	E_x (MeV)	$\frac{\sigma(3\frac{3}{4}°)}{\sigma(11\frac{1}{4}°)}$	$\frac{\sigma_{tot}}{2J+1}$
1^-	5.78	···	0.26
3^-	7.17	···	~0.2
5^-	10.26	1.35	0.20

TABLE VII. Results for the $K^\pi = 2^-$ band.

J^π	E_x (MeV)	$\frac{\sigma(3\frac{3}{4}°)}{\sigma(11\frac{1}{4}°)}$	$\frac{\sigma_{tot}}{2J+1}$
2^-	4.97	···	0.11
3^-	5.62	0.69	0.22
4^-	7.00	0.44	0.15
5^-	8.45	2.34	0.66
6^-	10.61	0.80	0.35
7^-	13.33	1.30	0.65
8^-	(15.37)	0.62	(0.21)
	(15.88)	0.71	(0.37)
9^-	17.40	1.15	0.65

The 3^- state at 9.12 MeV may be the beginning of a $K^\pi = 3^-$ band. If so, it should also possess both natural- and unnatural-parity members. No 4^- states are known. The next candidate for an unnatural-parity state is the previously unreported state at 10.694 MeV. The fact that it was observed in neither proton stripping nor neutron pickup suggests that it has $J \geq 4$. Hence, it is a good candidate for a 4^- state. If so, its energy suggests it as the 4^- member of the 3^- band, beginning at 9.12 MeV.

The next candidate for unnatural parity is at 10.915 MeV. But this is probably a 3^+ state. Additional candidates for unnatural parity exist

TABLE IX. Results for possible members of the first $K^\pi = 1^-$ band.

J^π	E_x (MeV)	$\frac{\sigma(3\frac{3}{4}°)}{\sigma(11\frac{1}{4}°)}$	$\frac{\sigma_{tot}}{2J+1}$
1^-	8.72	0.38	0.38
2^-	(9.34)	1.66	(0.11)
	(9.87)	0.61	···
3^-	10.40	1.44	0.21
	10.84	1.20	0.25
4^-	(11.56)	0.61	(0.23)
	(11.66)	0.46	(0.27)
	(11.87)	0.53	···
5^-	(13.44)	0.77	(0.29)
6^-	(15.37)	0.62	(0.27)
	(15.88)	0.71	(0.49)

TABLE X. Results for possible members of the second $K^{\pi}=1^-$ band.

J^{π}	E_x (MeV)	$\sigma(3\frac{3}{4}°)/\sigma(11\frac{1}{4}°)$	$\sigma_{tot}/(2J+1)$
1^-	8.85	2.44	...
2^-	(9.34)	1.66	(0.11)
	(9.87)	0.61	...
3^-	10.40	1.44	0.21
	10.84	1.20	0.25
4^-	(11.56)	0.61	(0.23)
	(11.66)	0.46	(0.27)
	(11.87)	0.53	...
5^-	(13.44)	0.77	(0.29)
6^-	(15.37)	0.62	(0.27)
	(15.88)	0.71	(0.49)

at 11.555, 11.656, and 11.871 MeV. The first two of these were observed here for the first time and the third may actually be a member of a doublet. These states have about the right energy for the 4^- members of the two 1^- bands. Thus it is possible that two of these three states are 4^-.

Except for the 5^- state at 8.45 MeV, which is in the 2^- band, and a possible (5^-) state at 8.85 MeV, the only 5^- state known below 15 MeV is at 12.682 MeV. This state has the appropriate energy to be the 5^- member of the 3^- band. A new state at 15.034 MeV, which probably has unnatural parity and high spin, is an excellent candidate for the 6^- member of this band.

Additional candidates for unnatural-parity states are the two new states at 15.359 and 15.879 MeV. If neither is the 8^- state of the 2^- band, then they are possible candidates for the 6^- members of the two 1^- bands. If so, the 5^- members of these two bands should lie near 13–14 MeV. One possibility is the new state we observe at 13.441 MeV. However, the present results give $R\sim 1$, so it may

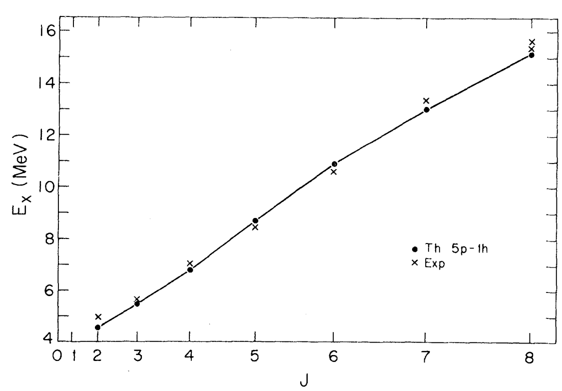

FIG. 4. Experimental (crosses) and theoretical (dots connected by lines) exictation energies for the lowest 2^- band in ^{20}Ne.

TABLE XI. Results for possible members of the $K^{\pi}=3^-$ band.

J^{π}	E_x (MeV)	$\sigma(3\frac{3}{4}°)/\sigma(11\frac{1}{4}°)$	$\sigma_{tot}/(2J+1)$
3^-	9.12	0.51	0.11
4^-	(10.69)	0.64	(0.24)
5^-	12.68	1.76	0.25
6^-	(15.03)	1.09	(0.16)

have either natural or unnatural parity. Its complete absence in single-particle transfer argues in favor of high spin. These results are summarized in Tables IX–XI.

Some of these conjectures are compared with the results of shell-model calculations[3] in Figs. 4–6. These calculations assumed an inert $1p_{3/2}$ core and allowed particles to occupy the $1p_{1/2}$, $1d_{5/2}$, and $2s_{1/2}$ orbitals. The agreement between theoretical and experimental excitation energies for the previously known low-lying 2^- band is remarkably good as depicted in Fig. 4. The 1^- band of the same 5p-1h configuration is predicted several MeV too low. In Fig. 5, we have plotted (as dots) the predicted energies for the members of this band after shifting it so as to line up the 1^- state with the experimental 1^- state at 8.85 MeV. Plotted as crosses in Fig. 5 are the two known 1^- states at 8.72 and 8.85 MeV, the three known 3^- states at 9.12, 10.401, and 10.830 MeV, and sever-

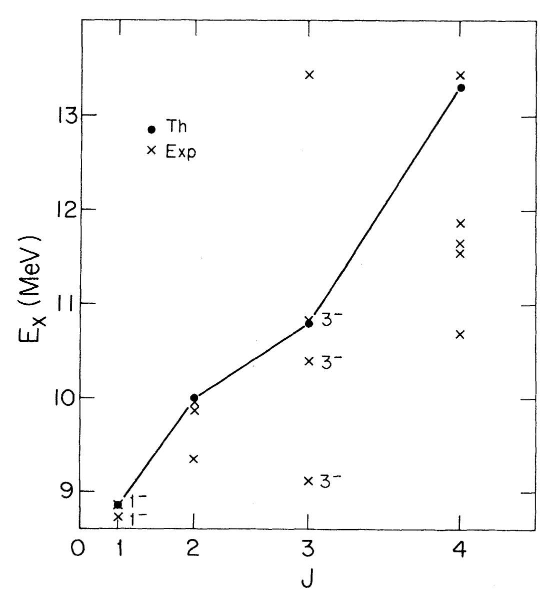

FIG. 5. Same as Fig. 4 but for known and suspected members of the excited 1^- band. The theoretical levels have all been shifted by the same amount to align the band heads.

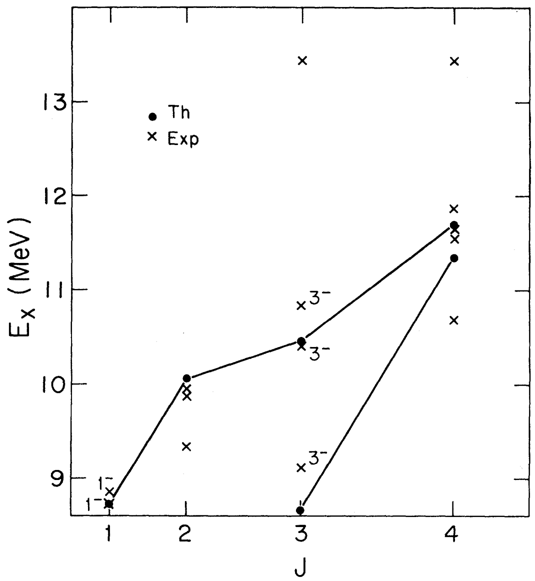

FIG. 6. Same as Fig. 4, but for the known and suspected members of a higher 1^- and a 3^- band. All theoretical energies have been shifted by the same amount to align the two 1^- states.

al of the candidates for unnatural-parity states. We emphasize that none of these latter have definite spin-parity assignments. However, the comparison suggests that one of the unnatural-parity states near 9.9 MeV is very likely the 2^- member of this band. Similarly, we might guess that the state at 13.441 MeV is a good candidate for the 4^- member of this band and that it is the upper of the three 3^- states that belongs in this band.

Those same calculations predict another low-lying 1^- band and a 3^- band. In Fig. 6 we have plotted the theoretical excitation energies for those two bands, after a uniform shift to align the 1^- bandhead with the experimental 1^- state at 8.72 MeV. The experimental states plotted are the same as for Fig. 5. Again, the comparison favors a 2^- state near 10 MeV, though, of course, in the absence of the kinking predicted by the calculations, the state at 9.3 MeV is a better candidate. Here, it is the second of the three 3^- states that appears to belong to this second 1^- band while the 3^- state at 9.12 MeV is relatively close to the expected position of the 3^- bandhead. Finally, the calculation appears to favor one of the unnatural-parity states near 11.5–12 MeV as the 4^- member of the second 1^- band, with a lower one possibly being the 4^- member of the 3^- band.

It is obvious that a detailed study of the decay properties of these states is necessary for spin-parity assignments and band identifications. We believe that the present results provide strong hints as to which states are candidates for having unnatural parity. If the spin-parity of some of these states can be established, a more meaningful test can be made between the structure of ^{20}Ne as found experimentally and as produced in a shell-model calculation.

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*Present address: Niels Bohr Institute, 2100 Copenhagen, Denmark.
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