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Rotational bands in ^{20}Ne

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Assignments to the $K^\pi = 0_2^+$, 0_4^+, 0_5^+, and 0_1^- rotational bands of ^{20}Ne (all characterized by large reduced width for alpha decay to the ground state of ^{16}O) are critically discussed. Some past assignments seem to be in error. The 0_5^+ band is new. Promising candidates are suggested for gaps in the $K^\pi = 1^-$ and 2^- bands. Verification of assignments and conjectures needs more work, both experimental and theoretical.

[NUCLEAR STRUCTURE Assignments of ^{20}Ne levels to rotational bands.]

I. INTRODUCTION

The literature[1] lists many empirical rotational bands in ^{20}Ne. Besides displaying a $J(J+1)$ energy dependence, band members must have common characteristics such as reduced widths, interband $B(E)$ values, etc. Although doubt has been expressed as to whether these empirical bands in ^{20}Ne correspond to any real rotational motion,[2] theoretical calculations[3,4] (both shell model and cluster models) have had relatively good success in accounting for many of the band characteristics.

II. THE POSITIVE PARITY ROTATIONAL BANDS

In contrast to the 0_3^+ band of ^{20}Ne, the 0_2^+ and 0_4^+ bands (with heads at 6.7 and ~8.5 MeV) have unusually large reduced widths, $\theta_{\alpha_0}^2$, for alpha emission to the ground state of ^{16}O, and so should be well described by cluster models. The 0_5^+ level at 10.97 MeV also has a large $\theta_{\alpha_0}^2$ of 0.14, but no higher band members have been identified. In recent years heavy-ion transfer reactions,[5-7] and especially some extensive and accurate ^{16}O(α,α_0) data and analyses,[8-10] have given enough new information, especially about reduced widths, to warrant a reexamination of previous assignments and to start a search for possible members of the unidentified $K^\pi = 0_5^+$ band. Table I summarizes all known ^{20}Ne levels whose reduced width and energy location make them possible candidates for any of these with positive parity bands. Somewhat arbitrarily I have required that $\theta_{\alpha_0}^2 \geq 0.04$ if they are to be considered. Reduced width values are sensitive to the assumed radius. In this paper I choose $R = 1.25(4^{1/3} + 16^{1/3})$ fm $= 5.134$ fm to facilitate comparison with other work. Our dimensionless reduced widths are defined as $\theta^2 = \gamma^2/(3\hbar^2/2\mu R^2)$.

A. The 0_2^+ band

The 0_2^+ band head at $E_x = 6.724$ MeV has $\theta_\alpha^2 \approx = 0.17 \pm 0.08$. As Table I and Fig. 1 show, the 2^+ and 4^+ assignments are unambiguous. However, the higher spin members are in dispute. Recently at Yale, Hindi *et al.*[7] proposed the 13.9 MeV 6^+ state as a member and then suggested a new state at 20.478 MeV which they tentatively assigned as 8^+ (with $\theta_{\alpha_0}^2 = 0.11$) for the 8^+ member. However, their evidence, via ^{12}C(^{12}C,α)^{20}Ne, for the tentative (8^+) assignment is not persuasive. In fact, their double correlation fit has a reduced $\chi^2 = 15$. Even the admixture of another state still gives $\chi^2 \sim 9$. Quite convincing evidence that the spin assignment is wrong or that $\Gamma_{\alpha_0}/\Gamma \ll 0.66$ comes from the old ^{16}O(α,α_0) data of Bergman and Hobbie,[11] which at this excitation energy show nearly zero cross sections at angles where $P_8(\cos\theta)$ is large (e.g., their Figs. 1 and 2 at $\theta = 158.8°$, $154.0°$, $149.4°$, and $125.2°$), whereas the cross sections are nonnegligible at $\theta = 163.9°$, where $P_8(\cos\theta) = 0$. The much more extensive 1979 ^{16}O(α,α_0) data of Billen[8] at 20 angles agree with the data of Bergman and Hobbie in the region of overlap. Riedhauser[9] (1983) has analyzed Billen's data, and his fit with $\chi^2 = 2.69$ for $20.1 < E_x < 21.05$ MeV shows unequivocably the absence of any appreciable 8^+ resonance strength in this region. We must therefore abandon the Yale 8^+ assignment with $\Gamma_{\alpha_0}/\Gamma \sim 0.66$.

Hindi *et al.*[7] extrapolated to the 13.9 MeV state for the 6^+ member because it had reasonable $\theta_{\alpha_0}^2$ and was of suitable energy. They ignored the obviously appropriate 12.6 MeV 6^+ state because they believed it belonged to the 0_4^+ band, although originally Hunt, Mehta, and Davis[12] assigned it to the 0_2^+ band. Fujiwara *et al.*[4] also tentatively assigned the 12.6 MeV state to the 0_2^+ band because the reduced widths fit better with their cluster calculations. Caskey's recent ^{16}O(α,α_0) data and analysis[10] give a smaller $\theta_{\alpha_0}^2 = 0.069 \pm 0.01$ for the 13.9 MeV 6^+ state compared with the value of Hindi *et al.*, $\theta_{\alpha_0}^2 = 0.10 \pm 0.015$. Furthermore, Caskey's work reveals a new 6^+ at 13.1 MeV with $\theta_{\alpha_0}^2 = 0.11 \pm 0.02$, and shows that the old 6^+ state at 12.6 MeV has a $\theta_{\alpha_0}^2 = 0.14 \pm 0.03$ rather than the 0.26 ± 0.10 quoted by Sanders *et al.*[6] This decrease in $\theta_{\alpha_0}^2$ strengthens the argument of Ref. 4 that the 12.6 MeV state does not belong to the 0_4^+ band. Since Caskey's new 6^+ level at 13.1 MeV and the old 6^+ level at 12.6 MeV both have suitable reduced widths for the 0_2^+ band, and since both lie close to the $J(J+1)$ extrapolation from the 0^+, 2^+, and 4^+ members, either one would be a suitable 0_2^+ band member.

To locate the 8^+ member one may continue the extrapolation from the lower band members. The literature

TABLE I. ^{20}Ne levels with energy and reduced widths suitable for consideration as $K^\pi = 0_2^+$, 0_4^+, and 0_5^+ band members.

J^π	E_x (MeV±keV)	Γ (keV)	Γ_{α_0} (keV)	$\theta^2_{\alpha_0}$	Ref.	K^π assignment
0^+	6.724±5	15±7		0.17±0.08[a]	1	0_2^+
	~8.3–8.6	~800		0.70[a]	1	0_4^+
	10.97±150	576		0.14[a]	1	0_5^+
2^+	7.4214±1	8		0.047[a]	1	0_2^+
	~8.8	>800		0.95[a]	1	0_4^+
	12.324±10	388±46	357 ±58	0.08±0.02	10,13,14	0_5^+
4^+	9.984±8	97		0.17[a]	1(13)	0_2^+
	10.79±100	349		0.33[a]	1	0_4^+
	12.251±7	153±13	136 ±19	0.068±0.01	10,13,14	
	12.943±13	578±53	532 ±112	0.19±0.04	10[b]	(0_5^+)
	14.585±16	262±34	191 ±43	0.052±0.012	10	
		240			1	
6^+	12.582±5	72±9	49 ±10	0.14±0.03	10	(0_2^+)
				[0.26±0.10]	6	
	13.102±4	102±5	53 ±7	0.11±0.02	10[c]	
	13.926±2	68±5	57 ±7	0.069±0.01	10	
		113±7	81 ±12	0.10±0.015	7	
	14.309±5	117±8	96 ±11	0.096±0.01	10	
		240			1	
	14.804±5	86±12	80 ±18	0.064±0.015	10[c]	
	15.72	(~300 keV)[d]	(large)[d]	?	15	(0_5^+)
	15.97	(~300 keV)[d]	(large)[d]	?	15	
	16.868±20	353±45	99 ±23	0.039±0.01	9,12	
8^+	15.874±9	100±15	24 ±9	0.047±0.017	7	
			9 ±4[e]	0.02±0.01[e]	5	0_3^+
	17.292±14	196±18	51 ±9	0.12±0.02	9,8	(0_2^+)
		220±40	88 ±38	0.20±0.06	6	
	18.617±18	185±30	44 ±13	0.06±0.02	9[c]	(0_5^+)
	18.957±23	196±62	29.4±13	0.03±0.02	9[c]	
	19.727±23	328±56	75 ±19	0.06±0.02	9[c]	
	22.03±100	630±80			7[f]	
	23.3±250	500			11[g]	
	24.24±150	350			11[g]	
	25.4±300	600			11	

[a] With Γ_{α_0} assumed equal to Γ.

[b] A new level with tentative assignment. See text.

[c] A new level.

[d] Visual estimate by Richards from data of Ref. 15.

[e] Based upon $\Gamma_{\alpha_0}/\Gamma = 9\pm2\,\%$ of Ref. 5 and $\Gamma = 100\pm15$ keV of Ref. 7.

[f] The 8^+ assignment is tentative.

[g] Also reported by Minoru Tokeda, Syokei Dato, and Tabashi Jamazaki, J. Phys. Soc. Jpn. 30, 56 (1971).

(Table I and Fig. 1) indicate that two 8^+ states can be considered, one at 15.9 MeV and the other at 17.3 MeV. The former state has been studied only in heavy-ion transfer reactions[1] and the assignment to the $K^\pi = 0_3^+$ band is usually made, even though the recent value[7] given by Hindi *et al.* for $\theta^2_{\alpha_0}$ (0.047±0.017) is several times that of any other 0_3^+ band member. However, if one instead combines the branching ratio $\Gamma_{\alpha_0}/\Gamma = 0.09\pm0.02$ reported by Young *et al.*[5] with $\Gamma = 100\pm15$ keV reported by Hindi *et al.*, then $\theta^2_{\alpha_0}$ drops to 0.02±0.01, a value consistent with the other 0_3^+ band members and one which would exclude it from the 0_2^+ band. That the state has not been reported via ^{16}O(α,α_0) is not surprising since the excitation energy lies in the middle of a 1 MeV data gap between the recent careful work of Caskey[10] and the earlier study of Billen.[8] In fact, this gap, poorly studied by ^{16}O(α,α_0), may well contain one (or more) 8^+ states of large $\theta^2_{\alpha_0}$ suitable for either the 0_2^+, or particularly the 0_4^+, band (see the discus-

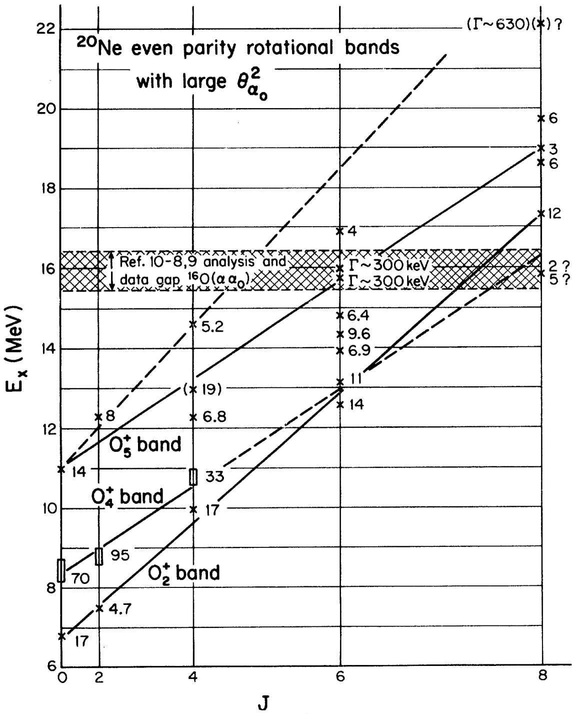

FIG. 1. E_x vs $J(J+1)$ plot of ^{20}Ne levels which might belong to the even parity rotational bands characterized by large reduced width for alpha decay to the ground state of ^{16}O. The plotted numbers are the reduced widths (in %) except for the two 6^+ levels, where only an approximate total width (Γ) is known. Solid lines are likely band slopes. Dotted band slopes indicate missing band members or less likely band slopes.

sion below), since the heavy-ion transfer reactions which have spanned this region have not reported[1] the broad lower 0_4^+ band members.

The other state, 8^+ at 17.3 MeV, Sanders *et al.*[6] assign to the 0_4^+ band because of their ^{16}O(^{12}C,^{8}Be)^{20}Ne (α) data from which they argue $\theta^2_{\alpha_0} \geq 0.20 \pm 0.06$. However, the more direct measurement from Billen's ^{16}O(α,α$_0$) data[8] (as reanalyzed by Riedhauser[9]) gives $\theta^2_{\alpha_0} = 0.12 \pm 0.02$. This lower value corresponds better to those of the other 0_2^+ members, and so I tentatively assign the 17.3 MeV 8^+ state to the 0_2^+ band instead of the 0_4^+ band. I cannot, however, exclude it as belonging to the new 0_5^+ band (see the discussion later).

B. The 0_4^+ band

The chief characteristic of the 0_4^+ band is that the reduced widths are nearly the single particle limit. Only the 0^+, 2^+, and 4^+ members seem well established (see Fig. 1), and they have $\theta^2_{\alpha_0} = 0.70$, 0.95, and 0.33, respectively.[1] With such reduced widths one may view this band as an alpha cluster orbiting around an ^{16}O core at a relatively large separation distance (perhaps 4.6–4.9 fm according to Fujiwara *et al.*[4]), and thus the band corresponds to a well-developed dinuclear molecular type of structure. According to Fujiwara *et al.*,[4] for the higher spin states all models gave values of $\theta^2_{\alpha_0}$ which are comparable to the lower band members. In fact, Tomoda and Arima[3] suggest that the observed 4^+ member at 10.79 MeV with $\theta^2_{\alpha_0} \sim 0.33$ may *not* belong to the band because they can account for its properties mainly in terms of $(sd)^4$ [31] (61) components (40%), plus a large admixture (40%) of the ^{16}O + α cluster components.

So the higher spin members remain unidentified (perhaps even the 4^+), and one may be tempted to doubt their existence. However, the expected very broad states are hard to separate from background and potential scattering except through the careful phase shift analyses of ^{16}O(α,α$_0$) data. Indeed, such analyses provided most of the information about the low band members. At the high excitation energies of the higher spin members many inelastic channels are open and the needed complex phase shift analyses are usually not feasible.[8] However, a computer program where the scattering amplitude has been written as a background term plus a sum over many resonant terms each containing a Γ_{α_0}/Γ factor has been very successful[8–10] in this energy range in identifying and parametrizing ^{20}Ne resonances, but only when the resonant widths are not large compared to the fitting interval. Otherwise the slowly varying background term simulates the broad resonance. Unfortunately, Caskey's[10] fitting intervals were typically only ~300–500 keV. Hence, broad 0_4^+ band states could have been missed. Therefore, the possibility is large that a broad 6^+ state of the 0_4^+ band exists undetected around $12.5 < E_x < 14.5$ MeV. In fact, mixing of such a state with other 6^+ levels in the vicinity may account for the cluster (in Fig. 1) of 6^+ states with enhanced reduced widths. Perhaps a proper energy averaging of Caskey's data to remove the narrower structure would permit his program to fit a large enough energy interval ($\Delta E \sim 1200$ keV) that such a broad resonance could be identified. Even at $E_x = 14.0$ MeV a 6^+ state with a $\theta^2_{\alpha_0} \approx 1$ would have a $\Gamma_\alpha \sim 800$ keV.

For the 8^+ member with $\theta^2_{\alpha_0} \approx 1$, the laboratory width may still be large enough (the increase in E_x balances the decrease in penetrability because of the higher l) that the analysis limitations discussed above will still apply. However, Riedhauser's[9] fitting regions ($E_x > 16.5$ MeV) were generally wider than those of Caskey. But unfortunately, the 1 MeV gap between Caskey's[10] and Billen's[8] data occurs close to where a $J(J+1)$ extrapolation would predict the 8^+ member.

To resolve the question of whether broad 6^+ and 8^+ members exist, Caskey's high resolution data[10] should be energy averaged and reanalyzed; in addition, the data gap between $15.4 < E_x < 16.5$ MeV should be filled in.

C. The new 0_5^+ band

The choice for the 2^+ member is unambiguous, as it is the only 2^+ state with requisite reduced width. This broad 2^+ state at 12.3 MeV was first reported by John, Aldridge, and Davis[13]; Steck[14] estimated its width as 500 keV. The parameters in Table I are from Caskey's recent data and analysis.[10] His analysis could separate such a broad level (Γ = 388 keV) from background only because the fitted region in this case was ~600 keV wide and because he knew that the early phase shift analysis[13,14] required a broad 2^+ member in the middle of the region.

For the 4^+ member, a new broad 540 keV state at 12.96 MeV, $\theta^2_{\alpha_0}=0.19\pm0.04$, reported by Caskey[10] seems the best choice (both in energy and reduced width) if Caskey's tentative 4^+ assignment is correct. Qualitatively, the broad structure is clearly visible in the data and behaves correctly for a 4^+ assignment in that it vanishes smoothly as zeros of $P_4(\cos\theta)$ are approached. But, including this broad level reduced χ^2 by only 10%. The tentative nature of the assignment relates more to the fact that its width, $\Gamma=580$ keV, is comparable to the fitting region ($\Delta E=550$ keV), and so a slowly varying background can simulate the broad resonance and probably explains why including it resulted in only a 10% reduction in χ^2. The level is near the top end of the fitted region, and so the parameters are not well fixed. However, it should exert considerable influence in the next higher region of fitting. Indeed, this was the case, and inclusion of this 4^+ member in the next higher fitting region immediately dropped that χ^2 by 17%. Therefore, although Caskey lists the level as tentative, I believe the chances are reasonably good that it is the 4^+ member of the 0^+_5 band. There are two other possible 4^+ candidates. The lower energy one at 12.25 MeV has $\theta^2_{\alpha_0}=0.07\pm0.01$, but its energy is actually less than that of the 2^+ member. The other one at 14.585 MeV has $\theta^2_{\alpha_0}=0.05\pm0.01$ and its energy fits well with extrapolation from the 0^+ and 2^+ members. The resultant high slope of the $J(J+1)$ band would, however, imply a smaller moment of inertia of the cluster than the 0^+_2 or 0^+_4 bands.

With the above large uncertainty in band slope, identification of the 6^+ and 8^+ members becomes even more speculative, especially since the most likely slope would place the 6^+ level in the gap between Caskey's[10] and Billen's[8] data (see Fig. 1). However, some information exists for this region[15]: an ^{16}O(α,α_0) excitation curve at a back angle and a few angular distributions which have been analyzed by a one Regge-pole model. This analysis[15] suggests two 6^+ resonances at peaks in the excitation curve ($E_x=15.71$ and 15.97 MeV). I visually estimate these peaks as having $\Gamma\approx300$ keV. If $\Gamma_{\alpha_0}\approx\Gamma$, then these overlapping resonances would certainly qualify as ideal 6^+ candidates. The observed strength in the α_0 channel certainly means that Γ_{α_0}/Γ is *not* $\ll1$.

For either of these 6^+ choices, the 0^+_5 band slope would be similar to that of the 0^+_4 bands (see Fig. 1). Such a slope also predicts the 8^+ member to be at ~19 MeV. Riedhauser's[9] analysis of Billen's data[8] reveals only four 8^+ states for $16.5<E_x<21.5$ MeV. One is the 17.3 MeV state already discussed and tentatively assigned to the 0^+_2 band but which would be suitable for an 0^+_5 band of smaller slope or one which shows an "antistretching" droop at $J=8^+$ like the 0^+_1 band. The other three are within 700 keV of ~19 MeV. One at 18.957 MeV is approximately 200 keV wide but has a Γ_{α_0}~29 ± 13 keV to give $\theta^2_{\alpha_0}$~0.03. The second one at 18.617 MeV has a similar total width but a somewhat larger $\Gamma_{\alpha_0}=44\pm13$ keV and $\theta^2_{\alpha_0}=0.06$. The third one at 19.727 MeV has $\Gamma_{\alpha_0}=75\pm19$ keV, and $\theta^2_{\alpha_0}=0.06$. Hence, there is no obvious choice, although certainly 8^+ strength exists in this region. (The two states at 18.6 and 18.9 MeV overlap in total width and presumably mix strongly.)

The only other 8^+ states reported in the literature are at much higher energies (>22 MeV) and so are not of interest for this band unless one chooses the 14.6 MeV state as the 4^+ band member and thus has the much steeper band slope.

If one were to choose the steeper slope, there indeed seems to be adequate 8^+ strength at the appropriate energies (~24 MeV), but a 6^+ member of reasonable reduced width is missing, even though the region has been well studied by Billen[8] and Riedhauser.[9] In fact, Riedhauser identifies about fourteen 6^+ levels between $17<E_x<21$ MeV, but the one with the largest $\theta^2_{\alpha_0}$ (=0.022 and located at 19.16 MeV) has a value a bit small for a band member. For this reason, I tentatively choose the smaller slope for the band.

III. THE NEGATIVE PARITY ROTATIONAL BANDS

A. $K^\pi=0^-$ band

According to Horiuchi and Ikeda,[16] this band is the inversion doublet of the $K^\pi=0^+_1$ ground state band. The empirically very large reduced widths definitely imply an α-^{16}O molecularlike structure. In fact, new data on the width of the 1^- band head ($E_x=5.785$ MeV) give a reduced width equal to the Wigner limit (see Table II). The 3^- and 5^- states also approach the Wigner limit.

The previous selections (by Sanders *et al.*[6]) of the 7^- and 9^- members as the 15.34 and 22.9 MeV ^{20}Ne states do not seem to be good choices. Such assignments force a quite steep upward kink for the higher band members, and the reduced widths (0.62 ± 0.12 and 0.17 ± 0.04) are both on the small side. Caskey's recent ^{16}O(α,α_0) data[10] provide a much more likely 7^- member. In the region ~13.7 MeV, where Mehta *et al.*[12] had suggested a tentative ($3^-,7^-$), Caskey found the 7^- assignment definitely preferred. The main limitation to his analysis is that the level width is again comparable to the fitting region. However, he needed the broad 7^- level also for a lower but overlapping fitting region to give the best χ^2. The energy location and reduced width agree beautifully with the lower band members (see Fig. 2). A $J(J+1)$ extrapolation predicts the 9^- member at ~19 MeV, but Billen's data[8] (and Riedhauser's analysis[9]) reveal absolutely *no* 9^- strength around 19 ± 1 MeV. In fact, the only 9^- level they see with $\theta^2_{\alpha_0}>0.05$ is at 17.427 MeV, where the reduced width is 0.48. However, there are reasons for thinking that this *is* the appropriate 9^- member: Since the 0^- band is the inversion doublet of the 0^+_1 band, then one may expect the same antistretching effect at high spins (e.g., see Ref. 4) which causes the well-known droop in location for the 8^+ member of the 0^+_1 band. This effect may give a similar droop for the 9^- member of the 0^- band. Also the 8^+ member of the 0^+_1 band has (both theoretically[4] and experimentally) an appreciably lower reduced width than the other band members. Tomoda and Arima,[3] using a modified resonating group method (MRGM), also predict an appreciable drop in $\theta^2_{\alpha_0}$ for the 9^- member of the 0^-

TABLE II. Negative parity bands $K^\pi=0^-,1^-,2^-$ (unless otherwise noted, data are from Ref. 1).

K^π	J^π	E_x (MeV)	Γ (keV)	Γ_{α_0} (keV)	$\theta^2_{\alpha_0}=\gamma^2\Big/\frac{3}{2}\left[\frac{\hbar^2}{\mu R^2}\right]$
0^-	1^-	5.785	0.028 ± 0.003^{a}	b	1.03 ± 0.11
	3^-	7.1563	8.1 ± 0.3^{a}	b	0.87 ± 0.03
	5^-	10.261	145 ± 40^{c}	b	0.90 ± 0.25
	7^-	13.689^{d}	310 ± 28^{d}	158 ± 24^{d}	0.84 ± 0.13^{d}
	9^-	17.427^{c}	219 ± 25^{e}	53 ± 9^{e}	0.48 ± 0.08^{e}
1^-	1^-	8.848 ± 5	19^{f}	b	0.011^{f}
	2^-	$9.446\pm7^{g,h}$			
	3^-	10.403 ± 5	81^{f}	b	0.048^{f}
	4^-	11.528 ± 6^{i}			
	5^-	12.710 ± 5^{d}	84 ± 8^{d}	84 ± 12	0.073 ± 0.010^{d}
	6^-	$14.367\pm2^{j,k}$	4.5 ± 0.3	~0	
	7^-	16.578 ± 12^{e}	92 ± 8^{e}	41 ± 7^{e}	0.041 ± 0.006^{e}
	8^-	$18.323\pm20^{l,m}$	$\leq70^{m}$		
	9^-	20.683 ± 34^{e}	78 ± 11^{e}	26 ± 6^{e}	0.045 ± 0.010^{e}
		21.059 ± 6^{e}	60 ± 6^{e}	28 ± 5^{e}	0.041 ± 0.007^{e}
2^-	2^-	4.9665			
	3^-	5.6214	$(3.1\pm0.7)\times10^{-6}$	b	0.038 ± 0.009^{n}
	4^-	7.004			
	5^-	8.4486	0.013 ± 0.004	b	0.0016 ± 0.005^{o}
	6^-	10.609			
	7^-	13.334	0.08 ± 0.003	0.034 ± 0.014^{p}	$0.0003\pm0.0001^{o,p}$
	8^-	$(15.70)^{q}$			
	9^-	17.385^{r}	<10 keV^{r}	$<0.1^{s}$	<0.0009

[a] J. D. MacArthur, H. C. Evans, J. R. Leslie, and H. B. Mak, Phys. Rev. C 22, 356 (1980).

[b] $\Gamma_\alpha=\Gamma$ assumed.

[c] Reference 6.

[d] Reference 10.

[e] Reference 9.

[f] Reference 13.

[g] Conjectured 2^- assignment; see text.

[h] Reference 21.

[i] Tentative 4^- assignment; see text and Ref. 20.

[j] Conjectured 6^- assignment; see text.

[k] Reference 24.

[l] Conjectured 8^-; see text.

[m] Reference 25.

[n] O. Häusser, A. J. Ferguson, A. B. McDonald, I. M. Szöghy, T. K. Alexander, and D. L. Disdier, Nucl. Phys. A179, 465 (1972), but with $\theta^2=\gamma^2/(3/2)(\hbar^2/\mu R^2)$.

[o] Reference 18, but with $\theta^2=\gamma^2/(3/2)(\hbar^2/\mu R^2)$.

[p] Using $\Gamma_{\alpha_0}/\Gamma=0.43\pm0.01$ from Ref. 5.

[q] Unnatural parity from Ref. 29 ($E_x=15.62$ MeV); also from absence in Fig. 2 of Ref. 5; $E_x=15.691$ MeV from Ref. 19. $E_x=15.707$ MeV and spin from Fig. 14 of Ref. 25.

[r] Parameters from Ref. 18, but J^π from Ref. 17.

[s] With $\Gamma_{\alpha_0}/\Gamma<0.01$, from Ref. 17.

band.

Incidentally, this broad 9^- level seen by Billen[8] and Riedhauser[9] in the α_0 channel should not be confused with the 9^- state at 17.40±0.02 MeV seen by Fifield *et al.*[17] via $^{12}C(^{12}C,\alpha)^{20}Ne$ which decays >99% to the ^{16}O(6.13 MeV) state. This latter 17.40 MeV 9^- state is probably the same as the narrow ($\Gamma<10$ keV) unassigned one at 17.385 MeV which Häusser *et al.*,[18] via $^{16}O(\alpha,\alpha_i)$, saw only in the unresolved $\alpha_1+\alpha_2$ channel, and which is usually thought to belong to the $K^\pi=2^-$ band of small reduced widths for ground state alpha decay. Unfortunately, the most recent compilation[1] omits this state in the master table and inappropriately lists the *broad* 9^- state as the $K^\pi=2^-$ band member.

B. The $K^\pi=1^-$ band

The 1979 assignments[5] of Young *et al.* for the 1^-, 3^-, 5^-, 7^-, and 9^- members of the band are supported by

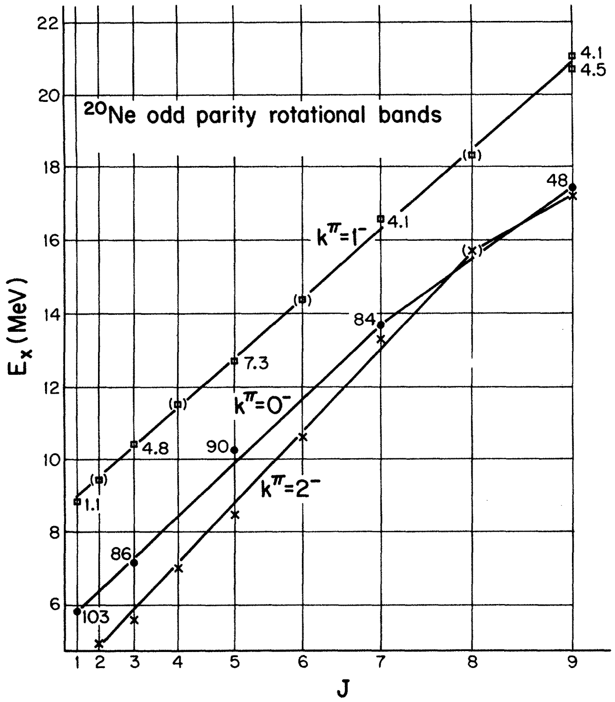

FIG. 2. E_x vs $J(J+1)$ plot of ^{20}Ne levels believed to be members of the odd parity rotational bands. For the natural parity members, α decay to the ^{16}O ground state is permitted, and the corresponding reduced widths (in %) are listed for $K^\pi=0^-$ and 1^-. Levels in parentheses are the presently proposed unnatural parity band members for which further work is needed to unambiguously establish either the unnatural parity or the J assignment. See text.

more recent data (see Table II and Fig. 2) except that now there are two choices for the 9^- member. However, a $K^\pi=1^-$ band should also contain the unnatural parity levels 2^-, 4^-, 6^-, and 8^-. Except for some early speculations by Medsker *et al.*,[19] these unnatural parity members have been generally ignored, although Fifield, Zurmühle, and Balamuth[20] argued for a probable 4^- level at 11.53 MeV and noted that it fit the 1^- band. Since energy locations are now relatively well fixed from the $J(J+1)$ plot of the natural parity members 1^-, 3^-, etc., it seems worthwhile to search the literature for possible unnatural parity members, 2^-, 4^-, etc. The 2^- level should lie $\sim$9.5 MeV, and, indeed, in 1981 Vermeulen *et al.*,[21] via the ^{24}Mg(d,^{6}Li)^{20}Ne reaction, reported a "new" state at 9.466±0.007 MeV whose angular distribution was *not* that of the nearby 2^+ state at 9.493 MeV seen in ^{16}O(α,α_0). In fact, the new state is probably the same one seen earlier by Betts *et al.*[22] via ^{19}F(^{3}He,d)^{20}Ne at 9.469±0.010 MeV but believed to correspond to the well-known 2^+ state although the angular distribution (their Fig. 3) did not agree with a 2^+ assignment. The fact that the state is not seen via ^{16}O(α,α_0) strongly supports the unnatural parity assignment. Furthermore, although Vermeulen *et al.*[21] did not attempt to fit the ^{6}Li angular distribution, it is so very similar to the angular distribution which they reported for the known 2^- level at 4.968 MeV (see their Fig. 2) that a 2^- assignment seems very probable. Such an assignment forbids alpha decay to the 0^+ ground state and there is insufficient energy for any other decay. Hence, one should look for gamma decay which probably will preferentially go to the lower 2^- state at 4.97 MeV, since a dipole transition to the 2^+ state at 1.63 MeV is hindered by isospin conservation.

The 4^- band member at 11.53 MeV, suggested in Ref. 20 in 1976, is a state whose decay modes and lifetime restrict its spin and parity to 3^+ or 4^-. In fact, the absence of any branch to the 2^+ state at 1.63 MeV strongly favors the 4^- choice. Subsequently the nearby level at 11.56 MeV has been given a firm 3^+ assignment by Marrs *et al.*[23] Since it is unlikely that there are two 3^+ levels so close to each other, I believe that the 4^- assignment is almost certain. [Vermeulen *et al.*[21] did not resolve the 11.56-11.53 MeV doublet, but the width of the 11.56 MeV peak in their Fig. 1 suggests they also see the 11.53 MeV state in the ^{24}Mg(d,^{6}Li) reaction.]

The $J(J+1)$ interpolation would locate the 6^- level at $\sim$14.5 MeV. Search of the literature turns up only a few possibilities. The first is a very narrow ($\Gamma=4.5\pm0.3$ keV) state at 14.367±0.002 MeV seen[24] via ^{19}F(p,$\alpha\gamma$)^{16}O ($E_\gamma>4.7$ MeV) which is not observed in ^{19}F(p,α_0) or ^{19}F(p,α_π). The lack of any alpha decay to the spin zero states of ^{16}O is consistent with unnatural parity, and the small width favors high spin. (There will be <3.5 MeV total energy available for decay to nonspin zero states in ^{16}O.) Klapdor *et al.*,[25] via ^{10}B(^{12}C,d)^{20}Ne, also claim an unidentified level at 14.36±0.02 Mev, and this reaction experimentally seems selective for high spin states. However, many years ago (1955) Barnes[26] reported a $\Gamma\sim5$ keV resonance at $E_x=14.37\pm0.01$ MeV in ^{19}F(p,p$_1$)^{19}F but not in ^{19}F(p,p$_2$)^{19}F, and he suggested it was likely a 0^- state. (A high spin resonance should favor the p_2 decay because of the different J^π of the residual ^{19}F states.) Clearly, more experimental work is needed to elucidate the level parameters of the one or more ^{20}Ne states at $\sim$14.37 MeV. Incidentally, a recent data compilation[1] erroneously lists (in the master $A=20$ table) this 14.37 MeV state as 0^+ and $\Gamma=86\pm5$ keV and lists one of the relevant reactions as seven instead of six; in tracking down this error, I also found that all recent compilations neglect an early and quite careful study of this state via ^{19}F(p,$\alpha\gamma$)^{16}O which Hunt and Firth[27] made in 1955 using both LiF and CaF thin targets, heated to 200 °C and with an adjacent liquid nitrogen trap to prevent carbon buildup.

If the 14.37 MeV state turns out not to be 6^-, consideration should be given to unidentified and undiscussed structure around 14.6 MeV in Fig. 14 of Ref. 25 and to the $\Gamma=23$ keV wide state at 14.45 MeV seen[24] in the ^{19}F(p,$\alpha\gamma$)^{16}O reactions.

The $J(J+1)$ interpolation predicts the 8^- state to be $\sim$18.5 MeV. Klapdor *et al.*,[25] by the high spin selective reaction ^{10}B(^{12}C,d)^{20}Ne, see a strong state at 18.32±0.02 MeV which appears to be no wider than their experimental resolution ($\sim$70 keV). Clearly, this state is not the broad $\sim$240 keV (6^+) one reported at 18.32 MeV by Mehta *et al.*[12] via ^{16}O(α,α_0). Examination of Fig. 14 from Klapdor *et al.*[25] shows that the ^{10}B(^{12}C,d)^{20}Ne reaction probably also populates all of my proposed lower

$K^\pi=1^-$ band members whose $J\geq 4$, although the 7^- and 4^- states appear somewhat weaker and are not labeled in their Fig. 14 nor listed in their Table V. Another studied reaction where an 8^- state of proper energy could have been seen is $^{12}C(^{12}C,\alpha)^{20}Ne$. Hindi *et al.*[7] report nothing below the 8^+ state at 18.54 MeV, but their angle of observation ($\theta=4°$) is not favorable for seeing unnatural parity states. Young *et al.*[5] see a strong yield from a state at $\sim$18.4 MeV, but the $\theta=0°$ data require natural parity. The state is fairly broad, so it is probably the 7^- state Riedhauser[9] deduces from his analysis of Billen's data.[8] Greenwood *et al.*[28] report an unidentified sharp level at 18.50 MeV for $E_{\text{lab}}=42$ MeV and $\theta_{\text{lab}}=5°$ which may, however, be the same as the 18.54 MeV 8^+ state of Hindi *et al.* I feel that the 18.32 MeV state (Klapdor *et al.*[25]) is a more likely candidate for the 8^- member, but the evidence is meager.

Young *et al.*[5] also speculated upon another $K^\pi=1^-$ band based on a 1^- state at 8.69 MeV. They thought this alleged nearby second $K^\pi=1^-$ band was characterized by the small alpha reduced widths (for the natural parity members) corresponding to the $\theta^2_{\alpha_0}=0.0015$ of the band head and by very little mixing between the other nearby 1^- band. Unfortunately, they used a wrong experimental width for the proposed 3^- state at 10.84 MeV. The correct $\Gamma=45$ keV from Ref. 13 gives $\theta^2\sim 0.021$, well over an order of magnitude larger than that of the band head. Hence, an appropriate 3^- member is missing (as are all the unnatural parity members). The recent measurements[10] of Caskey on their proposed 5^- member at 13.44 MeV also gives too large a $\theta^2_{\alpha_0}$ (0.011); however, he does see a new, very narrow 5^- state at 13.674 MeV with $\theta^2=0.0021\pm 0.007$, which would be suitable. The new 7^- level which Young *et al.*[5] report at 16.68 MeV via $^{12}C(^{12}C,\alpha)^{20}Ne$ has a suitable width ($\Gamma_{\alpha_0}<8$ keV), but it has not been reported elsewhere. (This state unfortunately is missing from the latest $A=20$ compilation.[1]) Also, no candidate of suitable θ^2_α and energy is known for the 9^- member. Hence, the band remains so speculative that I have not included it in Fig. 2.

C. The $K^\pi=2^-$ band

The $K^\pi=2^-$ band is one of the oldest and best-established bands. All members 2^- through 9^- have been identified with the exception of the unnatural parity 8^- state. Also, except for the 9^- member, they fall remarkably close to a straight $J(J+1)$ line (see Fig. 2). All the natural parity members show $\theta^2_{\alpha_0}\leq 0.04$. The 9^- member deserves comment because of the confusion in the latest $A=20$ data compilation.[1] The confusion arises because there are, in fact, two nearby 9^- levels, a broad one ($\Gamma\sim 240$ keV) at $\sim$17.4 MeV seen[8,9] in $^{16}O(\alpha,\alpha_0)$ with $\Gamma_{\alpha_0}/\Gamma\sim 0.25$ to give $\theta^2_{\alpha_0}\sim 0.5$. The compilation erroneously attributes this state to the $K^\pi=2^-$ band, whereas with such a $\theta^2_{\alpha_0}$ it should belong to the $K^\pi=0^-$ band (where I have placed it). The other 9^- level at 17.40 MeV, according to the discussion about the $K^\pi=0^-$ band, probably has $\Gamma<10$ keV and $\Gamma_{\alpha_{1,2}}/\Gamma>0.99$ to give $\theta^2_{\alpha_0}<9\times 10^{-4}$ and, of course, is the one that belongs to the $K^\pi=2^-$ band.

The question of a possible 8^- member remains. In 1970, Panagiotou[29] reported, via $^{12}C(^{12}C,\alpha)^{20}Ne$, a strong narrow alpha yield from a ^{20}Ne state at 15.618 MeV for which the yield vanished at $\theta=0°$, thereby implying unnatural parity. Although no information about its J value existed, the excellent fit to the $J(J+1)$ line (see Fig. 2) suggested it for the missing member. In a later work, Medsker *et al.*[19] claimed via the same reaction not to see the level, although, in fact, they reported a level at 15.691 MeV which to me seems likely to be the same state since it is within the combined calibration uncertainties of the two measurements (as I infer them from the comparison of their quoted E_x for other states). Apparently, the reason Medsker *et al.*[19] ignored this possibility is that they earlier identified this 15.691 MeV state as being the same as a level reported by Mehta, Hunt, and Davis[12] at 15.71 MeV via $^{16}O(\alpha,\alpha_0)$ and hence of natural parity. However, the subsequent high resolution work of Young *et al.*[5] at 0° for $^{12}C(^{12}C,\alpha)^{20}Ne$ showed no 15.691 MeV state (see their Fig. 2), a result consistent with Panagiotou's[29] unnatural parity assignment. Furthermore, Klapdor *et al.*,[25] via the high spin selective reaction $^{12}B(^{12}C,d)^{20}Ne$, see a state at 15.707 ± 0.020 MeV, which on the basis of Hauser-Feshbach calculations they feel is either a 7^- or 8^- (see their Fig. 16). I therefore feel the evidence is sufficient to make a tentative 8^- assignment to a state at $\sim$15.7 MeV which belongs to the $K^\pi=2^-$ band.

IV. CONCLUSION

In summary, several errors in recent assignments for ^{20}Ne rotational bands have been noted and new assignments suggested; reasons are advanced why the higher spin members of the 0_4^+ band have not been seen experimentally; likely candidates for a new 0_5^+ band have been located; and finally, possible unnatural parity members of the $K^\pi=1^-$ and 2^- bands are explored. Some assignments seem very likely, but in some cases further experiments are needed to fix J^π unambiguously. Suggestions are made for further experimental studies and analyses.

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