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Natural parity levels in ^{16}O

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Absolute cross section data at over a thousand energies [$15 < E_x(^{16}O) < 22$ MeV], usually at 18 angles and for as many as four reactions [$^{12}C(\alpha,\alpha_i)^{12}C$ with $0 \le i \le 2$ and $^{12}C(\alpha,p_0)^{15}N$], reveal much alpha cluster and other level structure in ^{16}O. A differentially pumped methane gas target allowed laboratory energy resolution better than 10 keV. The author critically discusses problems in past and present data analyses and introduces some new techniques. With the aid of these techniques and a resonance shape fitting program, all of the α_0 data (plus some of the α_2 and (α,p_0) data) were fitted and resonant parameters to over 50 states in ^{16}O were assigned. These levels often correspond to families of excited ^{12}C core states. Clear absence of an 8^+ state at $E_x(^{16}O) \approx 20$ MeV makes questionable early rotational band assignments. Instead evidence is cited supporting Robson's predictions of ^{16}O as a tetrehedral rotor.

NUCLEAR REACTIONS $^{12}C(\alpha,\alpha_i)$, (α,p_0), $E=10.5-20$ MeV measured $\sigma(E,\theta)$; deduced ^{16}O level parameters; new analysis techniques, resolution 10 keV, $\theta_{lab}=30-170°$.
NUCLEAR STRUCTURE Alpha cluster structure of ^{16}O; excited core states.

INTRODUCTION

The last systematic study of ^{16}O levels by the $^{12}C+\alpha$ reaction in the $15 \le E_x \le 22$ MeV range was by Carter *et al.*[1] in 1964, and involved 50 keV (laboratory) steps. While this and other work[2] showed numerous ^{16}O levels of various widths,[3] some were narrower than the experimental resolution. Later work by Marvin and Singh[4] overlapped part of this energy range but failed to confirm some of the levels. Since then, experimental conditions have improved considerably: The University of Wisconsin α source delivers about 25 times more beam on target than Ref. 1 had, and our differentially pumped methane gas target permitted 10 times better energy resolution than either group's solid targets. In addition, analysis techniques have improved dramatically (see discussion by Billen[5] for the similar problem of $^{16}O+\alpha$ scattering where many open channels preclude a simple unique phase shift analysis). Therefore restudy of this region was desirable to overlap the fine-resolution work of Martin and Ophel[6] (on the low side), and Morgan and Hobbie[7] (on the high side). The $^{12}C(\alpha,p_0)^{15}N$ data augment those of Black *et al.*[8]

EXPERIMENTAL TECHNIQUES

The experimental procedures are similar to those of Billen[5] and are discussed in detail in various University of Wisconsin theses.[9–12] The ~11 Torr pressure of "ultra-high purity" methane gas in the target chamber gave a target thickness of about 2–3 keV, and a total laboratory-energy resolution[9] of about 10 keV. A new beam entrance snout to the chamber and reduced gas pressure were used to remeasure a very narrow resonance with an over-all energy resolution of 4–5 keV.

The use of a gas target resulted in especially clean spectra (see Fig. 1). Alphas elastically scattered from the naturally occurring ^{13}C were kinematically separated from the peaks of interest and excluded from the cross section determinations. Because the target gas pressure was accurately measured and controlled,[10] the absolute cross sections had small (+1.2/−1.5%) total systematic error, and the random uncertainties (including statistical errors) were also small (generally 2–4%). The absolute energy calibration[13] of the accelerator was good to ±6 keV, with relative uncertainties about half of that.

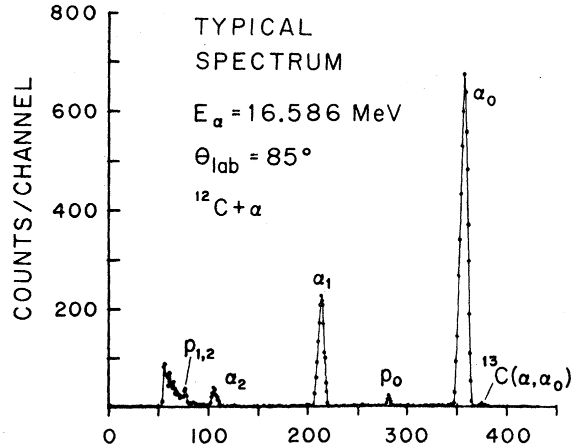

FIG. 1. Typical spectrum. The reaction groups were assigned by kinematic calculations.

The simultaneous use of up to 18 surface barrier ion detectors gave fine enough angular distributions for spin assignments. The detector's signals, after processing and digitizing, were stored directly in the computer's memory. Runs generally consisted of collecting 200 μC of charge on the target chamber's Faraday cup at which time the spectra were recorded on tape for later analysis.

RESULTS

Figure 2 shows the extracted c.m. elastic scattering cross sections as a function of energy for 18 angles. Figure 3 displays similar data for the alphas inelastically scattered from the 2^+ first excited state of ^{12}C (the α_1 group of Fig. 1). Figures 4 and 5 relate to inelastic alpha scattering from the

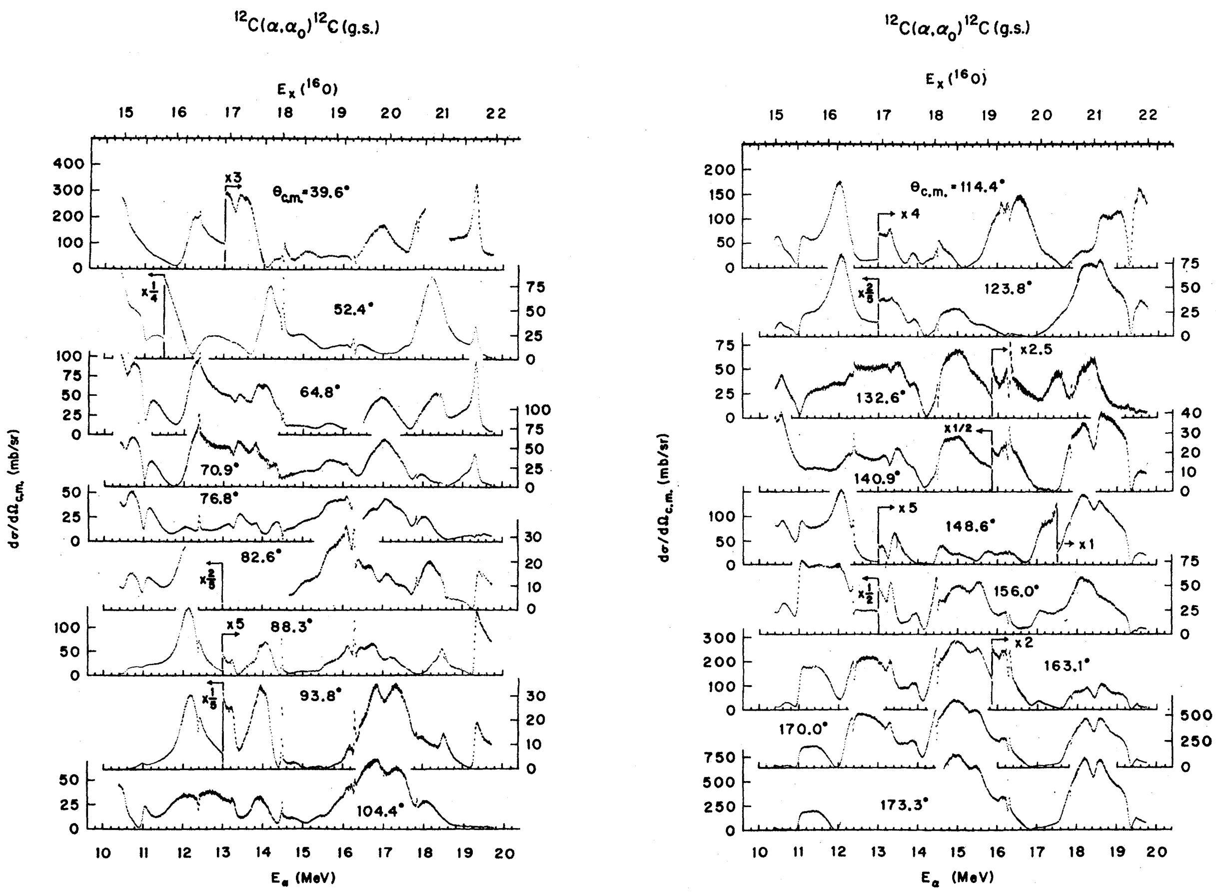

FIG. 2. $^{12}C(\alpha,\alpha_0)^{12}C$ cross sections. The size of each datum point represents statistical and background uncertainty. All angles θ are in the center of mass, but E_α is the laboratory energy. The ^{16}O excitation energies, E_x, are at the top.

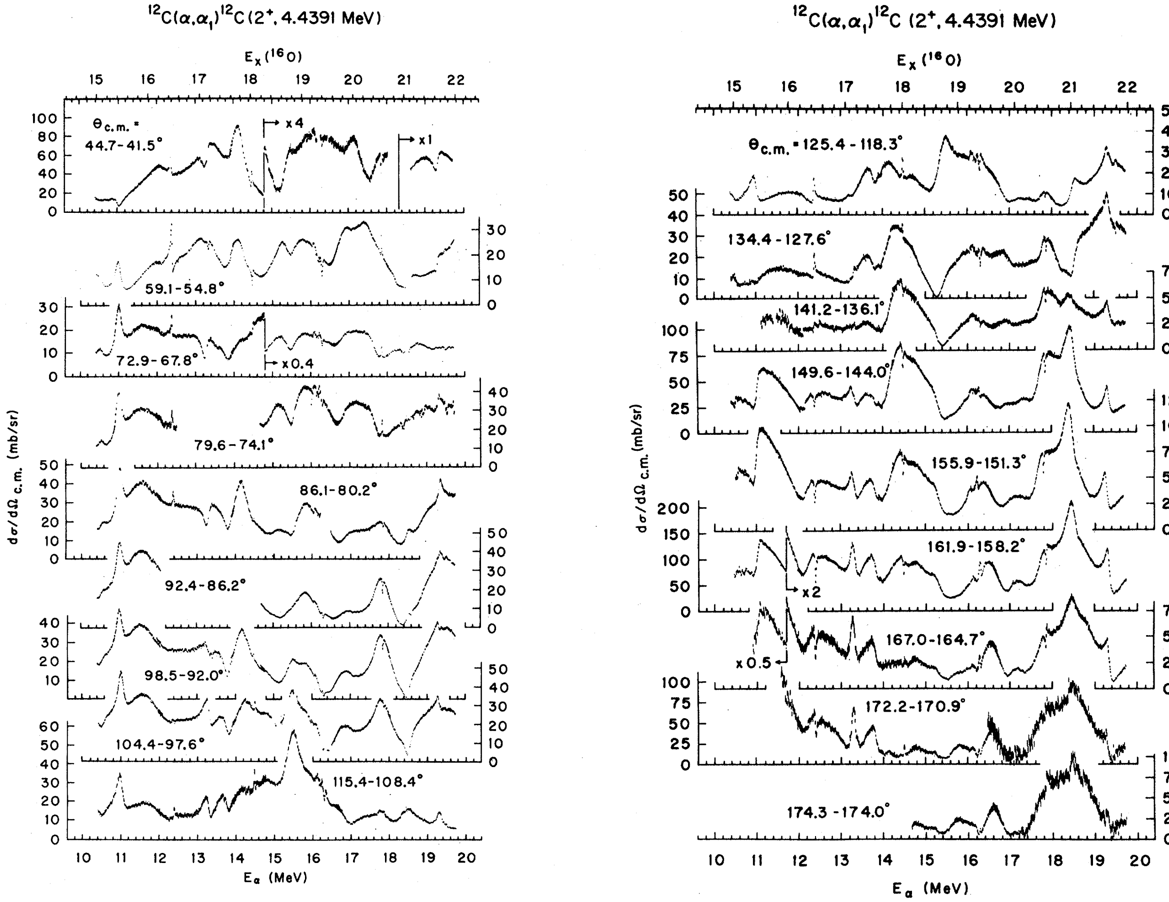

FIG. 3. $^{12}C(\alpha,\alpha_1)^{12}C$(4.439 MeV) cross sections. The data, taken at fixed laboratory angles simultaneously with Fig. 2 data, correspond to c.m. angles which vary with energy as shown. For further details see Fig. 2 caption.

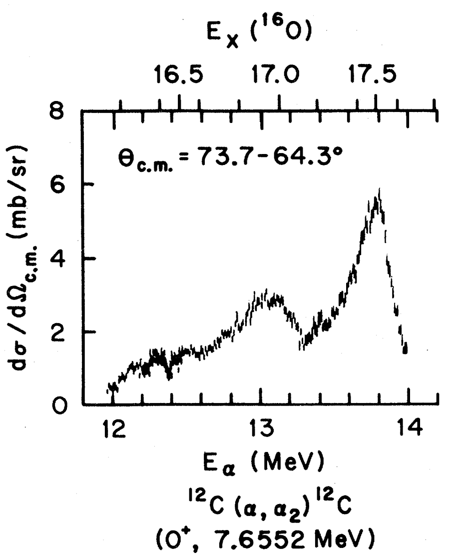

FIG. 4. $^{12}C(\alpha,\alpha_2)^{12}C$(7.655 MeV) cross sections for low E_α. See also Fig. 3 caption.

0^+ second excited state of ^{12}C, and unfortunately are much less complete since the α_2 group was often lost in proton groups or detectors noise. The cross sections on the $^{12}C(\alpha,p_0)^{15}N$ reaction (Fig. 6) are also limited because the detector thicknesses and biases were optimized for alphas rather than protons, but they still contain useful information. Numerical values of the 50 000 cross sections are available from the American Institute of Physics Depository Service (PAPS).[14]

DISCUSSION OF RESULTS

Where there are overlaps, the α_0 cross sections generally agree with the lower resolution work of Carter *et al.*,[1,15] Marvin and Singh,[4] and Martin and Ophel.[6] The data of Ref. 7 were at different angles, but the resonant structure and cross sections appear consistent. The α_1 and α_2 cross sec-

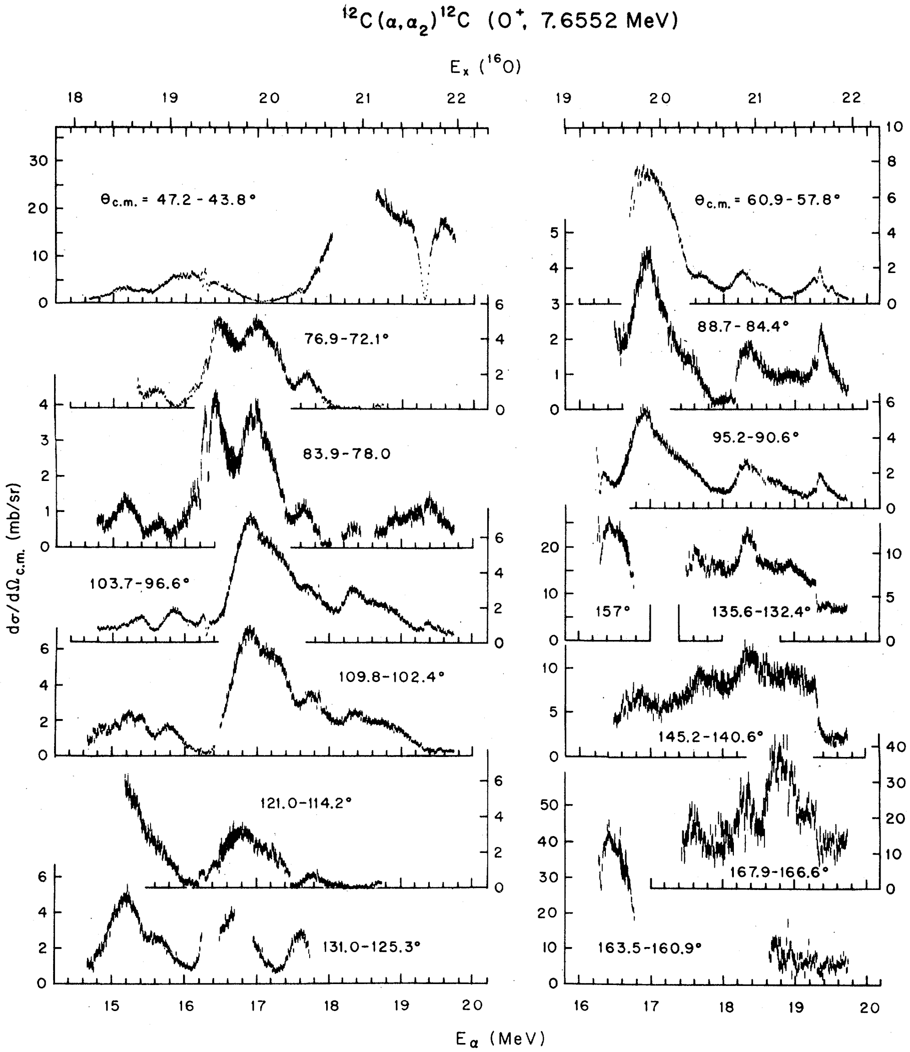

FIG. 5. ^{12}C(α,α_2)^{12}C(7.655 MeV) cross sections for higher E_α. See also Fig. 3 caption.

tions are also mainly consistent with the early work of Mitchell *et al.*[16] However, the present work disagrees with the α_2 cross sections reported by Morgan and Weisser,[17] which they measured for astrophysical purposes. Both excitation functions agree for $E_\alpha < 16.3$ MeV, but Ref. 17 then reports a rise where the present data dip. The angular distribution data at $E_\alpha = 16.0$ MeV agree; at other points (e.g., $E_\alpha = 12.5$ MeV and $\theta = 70°$) the cross section[17] is a factor of 3 smaller or (at $E_\alpha = 16.9$ MeV, $\theta = 45°$) five times larger. Their use of relatively thick targets (~ 100 keV) and nickel foils in front of their 700 μm thick detectors must have resulted in poor spectral resolution and may account for some of their higher cross sections (e.g., if proton groups contaminated their spectra). Their lower cross sections may arise from their subtracting too much background. The α_2 peak was easily resolved from other groups and from background in the present data. Recent low resolution (α,p_0) cross sections ($17.5 \leq E_x \leq 18.7$ MeV) by Möbius and Gruhle[18] show only moderate agreement.

ANALYSIS

Analysis is easiest for the elastically scattered alphas (Fig. 2) since all particles involved are 0^+.

The same is true for the α_2 data (Figs. 4 and 5), but usually there were too few angles to permit quantitative analysis.

Since both incident particles in the $^{12}C+\alpha$ reaction have 0^+ spin parity, only natural parity [i.e., $\pi=(-)^l$] levels of ^{16}O occur, and the J of the ^{16}O state is the same as the orbital angular momentum l. If the level is isolated, then the l (and hence J^π) follow immediately from an inspection of the resonant behavior as a function of incident energy and scattering angle θ: a resonance does not appear where the lth Legendre polynomial $P_l(\cos\theta)$ is 0. The extraction of level parameters E_r, Γ, and Γ_{α_0}/Γ is also relatively straightforward. However, problems arise when several levels overlap which, because of the high density of ^{16}O levels in this energy range, happens often.

To identify levels and to determine their parameters several complimentary techniques were used; two not overly successful complex phase shift programs (called SHIFTS and FAZED), a very successful resonant-shaped fitting routine (PSA), and a graphical method of determining the resonant l's in a region (SUMDIF).

The phase shift analysis SHIFTS used the equation:

$$\frac{d\sigma}{d\Omega}(\theta,E)=|F(\theta,E)|^2 ,$$

where

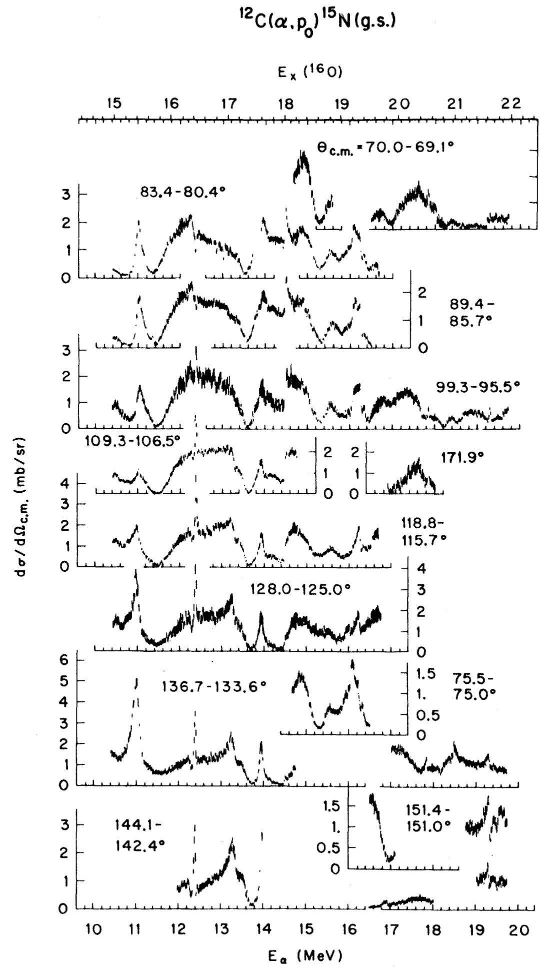

FIG. 6. $^{12}C(\alpha,p_0)^{15}N$(g.s.) cross sections. See also Fig. 3 caption.

$$F(\theta,E)=-\frac{1}{2k}\eta csc^2\left[\frac{\theta}{2}\right]\exp\left[i\eta\ln csc^2\left[\frac{\theta}{2}\right]\right]e^{2i\sigma_0}-\frac{i}{2k}\sum_{l=0}^{L_{max}}(2l+1)P_l(\cos\theta)e^{2i\sigma_l}(e^{2i\delta_l}-1) ,$$

$$k=(2mE)^{1/2}/\hbar ,$$

$$\eta=zZe^2/\hbar v ,$$

σ_l are the Coulomb phases

$$e^{2i(\sigma_l-\sigma_0)}=\prod_{j=1}^{l}(j+i\eta)/(j-i\eta)$$

and δ_l are the complex phases. The summation over l terminates at L_{max} greater or equal to the classical grazing l. The problem is to find the physically correct solution, and to trace it through energy without jumping to one of many ambiguous solutions.

One method of finding an acceptable solution is to input random starting parameters and then see whether the program converges to the same solution with an appropriately small chi squared/degree of freedom (χ^2). Another approach involves following solutions found for low incident energies (where the large Rutherford scattering and the few partial waves minimize amibiguities) to the region of interest and assuming that one has not branched to spurious solutions as the energy increases. Marvin and Singh[4] report following both approaches. While either approach may be reasonable when only elastic scattering is possible (and hence the phases are real), it appears neither can be trusted when numerous complex phases occur. In fact Marvin and Singh's[4] preferred solution is puzzling since it does not fit the data well (e.g., see curves A and B of Fig. 7). However, in his Ph.D.

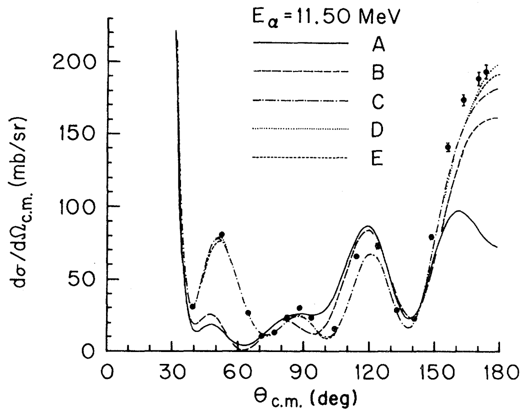

FIG. 7. Present α_0 data at $E_\alpha = 11.50$ MeV ($E_x = 15.78$ MeV) fit with Marvin and Singh's solutions.[4] Curve A uses phases read from their figures; curve B results from biasing curve A phases by maximizing reading errors to reduce χ^2 (see Ref. 9 for details); curves C, D, and E use phases tabulated in Marvin's thesis and which came from random starting phases.

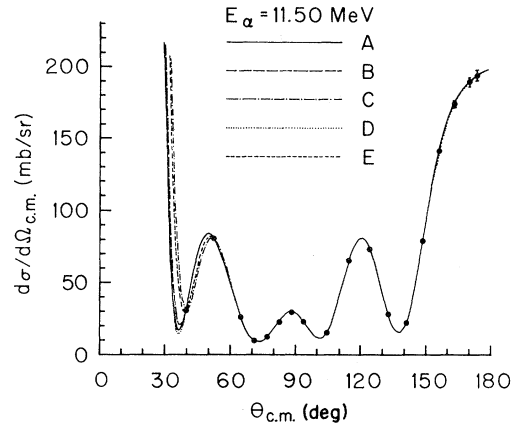

FIG. 8. The same as Fig. 7 except for fits with five typical ambiguous solutions generated with random input phases by the program SHIFTS.

thesis,[4] Marvin has a table of solutions, none even close to their preferred solution, based upon random inputs which give much better fits of my data (see curves *C*, *D*, and *E* of Fig. 7). I, too, tried various random inputs (in all more than 200) but could not find a unique solution (Fig. 8 shows the same as Fig. 7 and five solutions which give equally good fits). Nor could the program trace any of these solutions through an appreciable energy range without jumping to other solutions. Even in the vicinity of resonance of known l, biasing the fitting routine with the known l's had only limited success. For example, the program SHIFTS did generate a reasonable resonant circle on an Argand plot for a known $l=0$ level but had difficulty with the unitary limit (see Fig. 9).

Billen[5,12] successfully used a different approach on his $^{16}O+\alpha$ data. He separates the scattering amplitude for $0^+ + 0^+ \to 0^+ + 0^+$ reactions into resonant and nonresonant terms. Then he searched on various level parameters to fit sections of data, typically an energy interval of ~ 0.3 to 0.8 MeV. His program PSA fits data with the equation:

$$\frac{d\sigma}{d\Omega}(\theta,E) = \left| \rho(\theta) + \frac{i}{2k} \sum_j (2l_j+1) \left[\frac{\Gamma_{\alpha_0}}{\Gamma} \right]_j \times (e^{2i\beta_j(E)} - 1) \times e^{2i\phi_j(\theta)} P_{l_j}(\cos\theta) \right|^2 . \quad (2)$$

The sum is over resonant terms (up to five per interval); the ρ's are the nonresonant amplitudes and the ϕ_j are the relative phases, both assumed linear with energy; l_j and $(\Gamma_{\alpha_0}/\Gamma)$ are the spin and strength of the jth resonance; and

$$\beta_j(E) = \tan^{-1}[(\Gamma_j/2)/(E_{rj}-E)] ,$$

where E_{rj} and Γ_j are the resonant energy and width. If a resonance's level parameters are approximately known in addition to the spin l, PSA determines a more refined set of parameters. If the spin is not known, the correct choice is usually

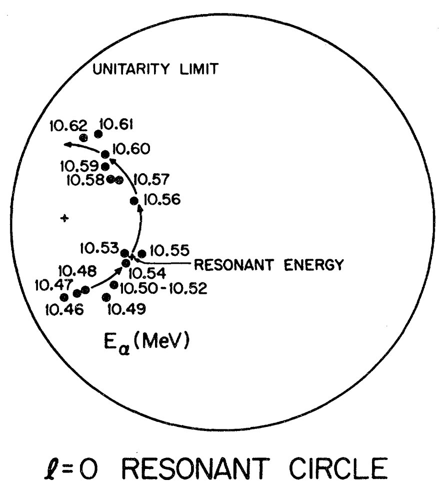

FIG. 9. An Argand plot of $l=0$ phases from SHIFTS when biased toward changes in the $l=0$ phase. Re($2\delta_0$) moves counterclockwise from the bottom and the radial distance is exp($-2\mathrm{Im}\delta_0$). The solution is reasonable except for violating unitarity somewhat.

apparent among several fits attempted with different choices for l [the program cannot fit a resonance at all the angles simultaneously with the wrong l because of the $P_l(\cos\theta)$ term]. This program eventually fit all of the α_0 and part of the α_2 data. However, the program was time consuming and not sensitive to weak broad resonances which it hides in the background terms; and occasionally a region had so many overlapping resonances that good fits were difficult to obtain.

Haeberli suggested[19] that if the phase shift routine were given more information, such as the energy (as well as the angular) dependence of the cross sections, it would be less likely to find multiple solutions. Such information can be provided for a narrow, isolated level by giving the resonance's shape in terms of relative phases ϕ of Eq. (2).

Figure 10 shows a resonance circle in the complex plane for two different scattering angles θ_i and θ_j. By using Eq. (1) SHIFTS gives the cross section, and thus $\nu(\theta,E)$ (which equals arctan $\{\mathrm{Im}[F(\theta,E)]/\mathrm{Re}[F(\theta,E)]\}$) in terms of the phases δ. The program PSA, using Eq. (2), gives ϕ for the different scattering angles, but tells nothing of δ, or the orientation $\mu(\theta)$ of the nonresonant vector $\rho(\theta)$ in the complex plane. However, the resonant circle's orientation ξ is determined only by the σ_l and $\delta_l(E_{\mathrm{or}})$ of Eq. (1), and so is a constant in θ. Here E_{or} is an off resonant energy such that $\nu(\theta,E_{\mathrm{or}})=\mu(\theta)$. One relates the complex phases δ to the relative phases ϕ by taking the difference between the ν's and the ϕ's at a pair of scattering angles θ_i and θ_j:

$$\nu(\theta_i,E_{\mathrm{or}})-\nu(\theta_j,E_{\mathrm{or}})+2[\phi(\theta_i)-\phi(\theta_j)]=0 . \qquad (3)$$

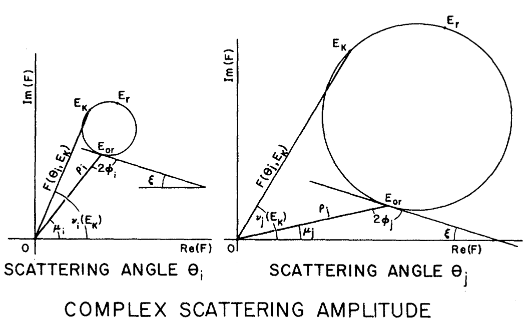

FIG. 10. A plot in the complex plane of the scattering amplitude $F(\theta,E)$ as a function of energy for two arbitrary scattering angles θ_i and θ_j. All angles vary with θ except ξ which gives the orientation of the resonant circle. See text for relations between μ, ν, ϕ, and ξ. [There is no simple relationship between ϕ and $\nu(E_k)$ when $E_k\neq E_{\mathrm{or}}$.]

By adding this difference to the usual $(\sigma_{\mathrm{calc}}-\sigma_{\mathrm{exp}})$ term in the expression for χ^2, and then trying to minimize the sum (see Ref. 9), the program FAZED found solutions that not only fit the angular distribution, but had the correct energy dependence. The solutions were more clustered for random starting parameters for FAZED than SHIFTS, and they exhibited the correct resonant behavior when traced through energy. However, because of the complexity of the level structure at this energy, the program was still unable to trace these solutions very far before jumping to other solutions. But the method is promising and might prove useful for other reactions or at other energies.

A new type of program, SUMDIF, was useful in guessing the l's to try in PSA fits, or in corroborating PSA's assignments of l. Consider an isolated resonance of spin l: As the cross section is constant in energy at those angles θ where $P_l(\cos\theta)=0$, the difference between the cross section at different energies at these angles will be zero whereas at other angles the difference generally will not be zero (see Fig. 11). By adding the absolute values of several such differences together,

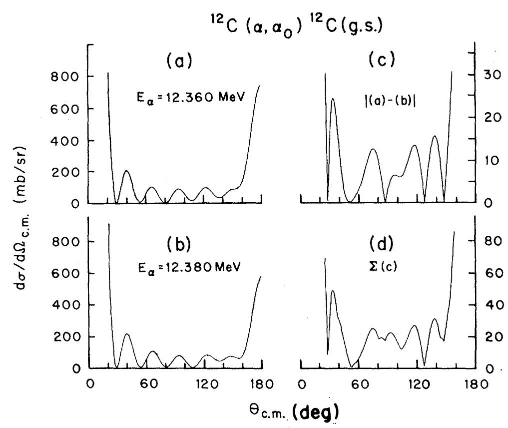

FIG. 11. The making of a SUMDIF plot: Curves (a) and (b) show SHIFTS' fits to α_0 data at two energies near a sharp 2^+ level. The finite width of the fitting curve obscures most of the 16 data points whose size represent statistical uncertainty. Curve (c) is the absolute value of the angle-by-angle difference between curve (a) and (b). Some of the dips in curve (c) result from $P_l(\cos\theta)=0$ while others are accidental because the cross sections happen to be the same at these two energies. However, these accidental dips vanish when several curves like (c) are summed. The result is curve (d) where the zeros at $\theta=55°$ and 125° [where $P_2(\cos\theta)=0$] clearly demonstrate the $l=2$ resonance. Note that the SHIFTS' fits need not be unique; they need only have a small χ^2.

one can eliminate the "accidental zeros", where the cross sections were coincidentally the same. The resonance's l value is then obvious from the angles at which large dips occur in the resulting curve. When there are several resonances in a region, each of the l values affects the plot.

RESULTS OF THE ANALYSES

Table I lists the resultant levels plus previously claimed natural parity levels. All of the present J^{π} assignments with quoted parameters involve at least one PSA fit as well as confirmation by either SUDMIF, SHIFTS, FAZED, and/or visual inspection. The PSA program determined the quoted uncertainties by varying each parameter in turn (with the rest constant) until the χ^2 for the resonance doubled. Unlike the phase shift fits, the PSA results are insensitive to most systematic cross section errors since the adjustable nonresonant terms can often compensate. My estimate of random (including statistical) uncertainties in cross section (2−4 %) was probably too generous at times because PSA often achieved χ^2 appreciably less than one. The parameters for levels whose widths are comparable with the fitting region are less well determined than the assigned errors might indicate because the slowly varying nonresonant term becomes hard to distinguish from effects of a broad resonance.

Below are brief comments about most of the fitted levels. As the level parameters are most accurately determined when the resonance was centered in the fitting region, PSA made numerous overlapping fits (not shown). My thesis[9] has more detailed level discussions.

The region $14.9 \leq E_x \leq 15.5$ MeV. The excellent PSA fit in Fig. 12 shows a 0^+ state at $E_x = 15.066$ MeV. This is the fourth 0^+ excited state[4] in ^{16}O, and the assignment comes originally from Marvin and Singh's[4] questionable phase shift analysis. Frawley *et al.*[22] later found by an R-matrix fit to ^{15}N(p,α) and ^{15}N(p,p) data, a 0^+ state at $E_x = 15.10$ MeV but reported a width ($\Gamma = 327 \pm 100$ keV) larger than Ref. 4 ($\Gamma = 190 \pm 30$ keV), or the present value ($\Gamma = 166 \pm 30$ keV). The branching ratio $\Gamma_{\alpha_0}/\Gamma = 0.46$ of Ref. 22, however, agrees with the present 0.35. A phase shift analysis supports the 0^+ assignment though the solution is not unique and somewhat violates unitary (see Fig. 9). However, the PSA fits are unambiguous and accurately fix the parameters. Although the Ajzenberg-Selove compilations[2] list this level as also seen in ^{13}C(^{12}C,^{9}Be)^{16}O and ^{14}N$(\alpha,d)^{16}$O reactions, these studies make no J^{π} assignments, and are unlikely to show large yields for a 0^+ state. The quoted width, $\Gamma \leq 80$ keV for ^{14}N$(\alpha,d)^{16}$O is also inconsistent with the (α,α_0) data. More likely they see the (unnatural parity) 2^- state, $\Gamma = 70$ keV at $E_x = 15.22$ MeV.

Figure 12 also shows the known prominent 3^- state at $E_x = 15.407$ MeV. The parameters agree well with the best of previous measurements although Frawley *et al.*[22] find [via ^{15}N(p,α)] that $\Gamma = 167 \pm 20$ keV vs $\Gamma = 133 \pm 7$ keV of Table I.

Region $15.4 \leq E_x \leq 16.2$ MeV. Figure 13 shows a good fit of the region which required only a broad 3^- resonance ($E_x = 15.828$ MeV, $\Gamma = 703$ keV) and tails of the previously discussed 0^+ and 3^- states and the tail of a strong higher energy 6^+ level. Two other natural parity levels reported by others were not needed. The program finds excellent fits with or without a broad 2^+ level (with $\Gamma_{\alpha_0}/\Gamma \approx 0.2$) that Snover *et al.*[23] see in (α,γ) experiments, but SUMDIF plots show no need for it. The other unneeded level is a relative narrow ($\Gamma = 96 \pm 16$ keV) level seen in ^{14}N$(\alpha,d)^{16}$O at $E_x = 16.214$ MeV which Lowe and Barnett[24] claim is probably 4^+ but could be 5^+. The lack of any evidence in the alpha data for this state probably indicates the assignment should be 5^+, and hence, forbidden to ^{12}C$+\alpha$. Artemov *et al.*'s result[25] that the $E_x = 16.214$ MeV state found in ^{14}N$(\alpha,d)^{16}$O decays equally to the ground and the first excited state of ^{12}C is inconsistent with the present data. Perhaps the ^{14}N$(\alpha,d)^{16}$O reaction also populates the 6^+ state described next.

Region $16.2 < E_x < 16.6$ MeV. The main structure in Fig. 14 comes from a broad ($\Gamma = 422$ keV) 6^+ state at $E_x = 16.274$ MeV and the sharp ($\Gamma = 22$ keV) 2^+ resonance at $E_x = 16.442$ MeV. By including the tail of the previous broad 3^- state and a weak 0^+ or 1^- state at $E_x = 16.361$ MeV, PSA finds a $\chi^2 = 0.45$ or 0.43.

The broad 6^+ resonance is the strongest level in this experiment, with $\Gamma_{\alpha_0}/\Gamma = 0.93$. This branching ratio also agrees with α transfer data: ^{12}C(^{6}Li,d)^{16}O$\rightarrow$(^{12}C$+\alpha$),1.07$\pm$0.11 (Cunselo *et al.*[20]); 0.80$\pm$0.10, (Artemov *et al.*[25]); and ^{12}C(^{12}C,^{8}Be)^{16}O$\rightarrow$(^{12}C$+\alpha$); 0.90$\pm$0.10 (Sanders *et al.*[21]).

Although Marvin and Singh[4] missed the sharp 2^+ resonance, it appears in the ^{16}O(e,e') results of Miska *et al.*[26] and is probably the same 2^+ state Snover *et al.*[23] report via (α,γ) as $E_x = 16.5$ MeV,

TABLE I. Natural parity ^{16}O states. The uncertainties assigned come from varying each parameter (with the rest constant) until the χ^2 of the fit for the resonance doubled. The E_x's have an additional ±5 keV from the absolute energy scale. The Γ_{α_0}/Γ have no assigned errors because this procedure gave unreasonably small uncertainties (probably because the background was kept constant). However, I estimate Γ_{α_0}/Γ values are good to ±0.10, better for isolated narrow levels, worse for broad levels.

This work						Other work[a]					
E_x (MeV±keV)	E_α (MeV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay	E_x (MeV±keV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay[i]	Ref.
14.620±11[b]	9.948	(4^+)	487± 12	80	α_0	14.63 ±40[b]	4^+	500±100	85±10	$\alpha_0\alpha_1$	
14.660±11[b]	10.002	5^{-c}	672± 11	94	α_0	14.67 ±40[b]	5^-	650±100	95	$\alpha_0\alpha_1$	
						14.805± 2[b]	6^{+d}	70 ± 8	45±5	$\alpha_0\alpha_1$	
						14.917± 5[b,j]	2^{+d}	69 ± 10		$\alpha_0\alpha_1p_0$	22
15.066±11	10.544	0^+	166± 30	35	$\alpha_0\alpha_1p_0$	15.17 ±50	0^+	190± 30		α_0	
						15.26 ±20[j]	2^+	315±100		$\alpha_0\alpha_1p_0\gamma$	22
15.407±2	10.999	3^{-d}	133± 7	58	$\alpha_0\alpha_1p_0$	15.45 ±20	3^-	100± 20	60	$\alpha_0\alpha_1p_0\gamma$	
15.828±30	11.560	3^{-d}	703±113	21	$\alpha_0(\alpha_1)$	15.8	3^-	525		$\alpha_0\alpha_1$	1,16
						15.9	2^+	~600		γ	
						16.214±15[k]	$(4^+,5^+)$	96 ± 16			
16.274±7	12.156	6^{+c}	422± 14	93	α_0	16.29 ±40	6^+	490± 40	80±10	α_0	25
									90±10		21
									107±11		20
16.361±20	12.272	$(0^+,1^-)$	65± 45	7	$\alpha_0(\alpha_1\alpha_2)p_0$	16.33[l]	0^+				28
16.442±2	12.380	2^{+e}	22± 3	28	$\alpha_0\alpha_1\alpha_2p_0$	16.40	2^+	45		$\alpha_0\alpha_1n_1p_0\gamma$	
						16.5		980		α_0p	1
16.843±21	12.915	4^+	567±60	28	α_0	16.8	(4^+)	525		α_0	1
						16.9	5^-	900		α_0	1
16.94[f]	13.05[f]		~280[f]		α_2	16.94	2^+	~280		$\alpha_0{}^8Be$	
						~17	1^{-e}	~1500		γp_0	
17.129±5	13.296	2^+	107±14	37	$\alpha_0\alpha_1p_0$	17.10	$(1^-,2^+,0^+)$	110		$\alpha_0\alpha_1(p_0)n\gamma$	
17.15[f]	13.32[f]		~35[f]		$\alpha_0\alpha_1$	17.14±15[j]	1^{-e}	36±5		$p_0n\gamma$	
17.17[f]	13.35[f]		~150[f]		α_2	17.200±20	2^{+c}	160±60		$\alpha_0{}^8Be$	
						17.29±15[j]	1^{-e}	90±10		$\alpha_0p_0n\gamma$	
						17.35		150		α_1	
17.510±26	13.805	1^{-d}	182±56	16	$\alpha_0(\alpha_1)\alpha_2$						
17.555±21	13.865	(6^+)	178±66	7	$(\alpha_0)(\alpha_1)$	17.55	(4^+)	165		α_0n	
17.617±20	13.948	$(0^+,1^-)$	175±55	32	α_0p_0	17.62[g]		150		α_0p	
17.72[f]	14.08[f]		~75[f]		(p_0)	17.7	$(0^+,2^+)$			^8Be	
17.784±15	14.170	4^+	396± 41	34	$\alpha_0\alpha_1$	17.81	4^+	300		$\alpha_1(^8Be)n$	16

TABLE I. *(Continued.)*

This work: E_x (MeV ± keV)	E_α (MeV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay	Other work[a]: E_x (MeV ± keV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay[i]	Ref.
18.016±1	14.480	4^{+d}	14± 2	36	$\alpha_0\alpha_1p_0$	18.018±15	4^{+c}	14		$\alpha_0\alpha_1p_0{}^8$Be	
						18.06±15	$(2^+,4^+)^e$	26±5		$\alpha_0\alpha_1n(\gamma)$	
18.089±25	14.577	$(0^+,1^-,3^-)$	248±90	31	α_0	18.1^g	(2^+)	220±60		n	
18.12^f	14.62^f	$(\neq 4^+)$	$\sim 45^f$		α_0						
18.25^f	14.8^f		$\sim 380^f$		$(\alpha_1)p_0$	18.29	2^+	370		$(\alpha_0)\alpha_1p_0\gamma$	1,16,23
18.403±12	14.997	5^-	544±39	40	α_0	18.4	5^-	680		$\alpha_0(\alpha_1)$	1
18.55^f	15.20^f		$\sim 150^f$		$(\alpha_1)(\alpha_2)$	18.55	(1^-5^-)	190		$\alpha_0(\alpha_1)$	1
18.6^f	15.25^f	(4^+)	$\sim 300^f$		α_2	18.6	$(0^+,2^+)$			$(^8$Be)	
						18.71	(1^-)	75		α_0	1
18.773±22	15.490	1^-	215±45	26	α_0p_0	18.8	(1^-)	~ 200		$\alpha_0\gamma$	23(Fig. 1)
18.785±6	15.506	4^+	260±16	48	$\alpha_0(\alpha_1)$	18.80	(4^+)	220		$\alpha_0\alpha_1p_0n{}^8$Be	
						$18.99\pm 30^{j,m}$	$3^-(1^-)^h$	240		$p_1\gamma$	38
19.0^f	15.8^f	$(5^-)^d$	$\sim 550^f$		$(\alpha_0)\alpha_1$	19.06		broad		α_1	
						19.09 ± 30^j	2^{+e}	~ 120		$p_0\gamma$	
						19.10±50	(2^+4^+)	55		α_0	1
19.252±30	16.130	(5^-)	50±45	4	(α_0)	19.24	5^-	30		$\alpha_0(n)$	
19.257±9	16.137	2^{+d}	155±23	34	$\alpha_0(\alpha_1)p_0$						
19.319±14	16.219	(6^+)	63±33	7	$(\alpha_0)\alpha_1\alpha_2p_0$	19.34	6^{+c}	50		$\alpha_0(\alpha_2)^8$Be	
19.374±2	16.293	4^+	23±4	23	$\alpha_0\alpha_1\alpha_2p_0$	19.39	(4^+0^+)	30		α_0	1
						19.48 ± 25^j	1^{-e}	250±60		γpn	
19.526±26	16.496	2^+	255±75	20	$\alpha_0(\alpha_1\alpha_2)$	19.5^m	(2^+3^-)	300		α_1	41
						19.63		240		n	8
						19.68	even	22		α_0	1
19.753±16	16.799	2^+	286±44	29	$\alpha_0\alpha_1p_0$						
19.85^f	16.92^f		$\sim 175^f$		α_2						
						19.9	(4^+)	1100		α_0	1
19.94^f	17.05^f	$(\neq 3^-)$	$\sim 30^f$		(α_0)						
20.055±13	17.201	2^+	432±40	43	$\alpha_0(\alpha_1p_0)$	{ 19.98	$(2^+,0^+,1^-)$	190		$\alpha_0\alpha_1$	1
						{ 20.07	2^+	310		γ_0n	
20.11^f	17.27^f	$(\neq 3^-)$	$\sim 45^f$		(α_0)						
						20.3		~ 1500		p_0	
20.40^f	17.66^f	(4^+)	$\sim 150^f$		$(\alpha_0)\alpha_2(p_0)$	20.41		<150		n	8
						20.44	(4^+)	150		α_0	1
$20.50^{f,d}$	17.80^f		$\sim 300^f$		α_1	20.58				α_1	

TABLE I. (*Continued.*)

This work E_x (MeV±keV)	E_α (MeV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay	Other work[a] E_x (MeV±keV)	J^π	$\Gamma_{c.m.}$ (keV)	Γ_{α_0}/Γ %	Decay[i]	Ref.
20.540 ± 2	17.849	5^{-d}	11 ± 2	14	$\alpha_0\alpha_1\alpha_2p_0$						
20.560 ± 2^{f}	17.875	(even)	<5		α_0						
20.614 ± 3^{f}	17.948	(even)	<10		α_0						
20.8^{f}	18.2^{f}		$<60^{f}$		(p_0)						
						20.81		<25		n	
20.856 ± 14	18.271	7^{-c}	904 ± 55	60	α_0	20.9^{n}	7^-	$600-1000$	90 ± 10	α_0	1,20,42
20.9^{f}	18.3^{f}	2^+			α_0	20.9 ± 100^{m}	2^+	350 ± 50	116 ± 23		41
						20.945^{j}	1^{-e}	320 ± 10		γnp_2	
						21.0	(5^-)	1200		α_0	1
21.01^{f}	18.48^{f}		~50		$(\alpha_0)p_0$	21.01		55		n	
21.03	18.50	(1^-)	~175	20	$(\alpha_0)\alpha_1$	21.03 ± 25	1^-	240 ± 80		γ	
21.051 ± 6	18.531	6^{+d}	205 ± 14	50	α_0	(21.1)	(6^+)	450		$\alpha_0\alpha_1n$	
(21.098)	18.593	4^{+d}	306 ± 46	20	(α_0)						
21.623 ± 11	19.294	(7^-)	61 ± 32	<5	$\alpha_0\alpha_2p_0$	21.69	7^-	55		α_2n	48
21.647 ± 3	19.327	6^+	115 ± 8	41	$\alpha_0\alpha_1\alpha_2$	21.8^{n}	6^+		67 ± 13		20
21.776 ± 9	19.498	3^-	43 ± 20	7	$\alpha_0\alpha_1\alpha_2p_0$	21.80		55		n	8

[a]From Ref. 2, Table 16.12 or 16.9 except as noted.
[b]These are below my range of data so only the strong broad levels influence my fits. My uncertainty estimates may be optimistic.
[c]Member of a rotational band.
[d]A possible "excited core" state.
[e]Thought to be $T=1$.
[f]Estimated parameter since no PSA fit was possible.
[g]Alleged member of a T-mixed doublet (Ref. 37).
[h]See Table 16.24 of Ref. 2.
[i]Decay listing excludes entrance channel (usually $^{12}C+\alpha$) unless elastic scattering data were reported.
[j]Entrance channel was $^{15}N+p$.
[k]Seen via $^{14}N(\alpha,d)^{16}O$.
[l]Seen via $^{18}O(p,t)^{16}O$.
[m]Seen via $^{16}O(\alpha,\alpha')^{16}O$.
[n]Seen via $^{12}C(^{6}Li,d)^{16}O$.

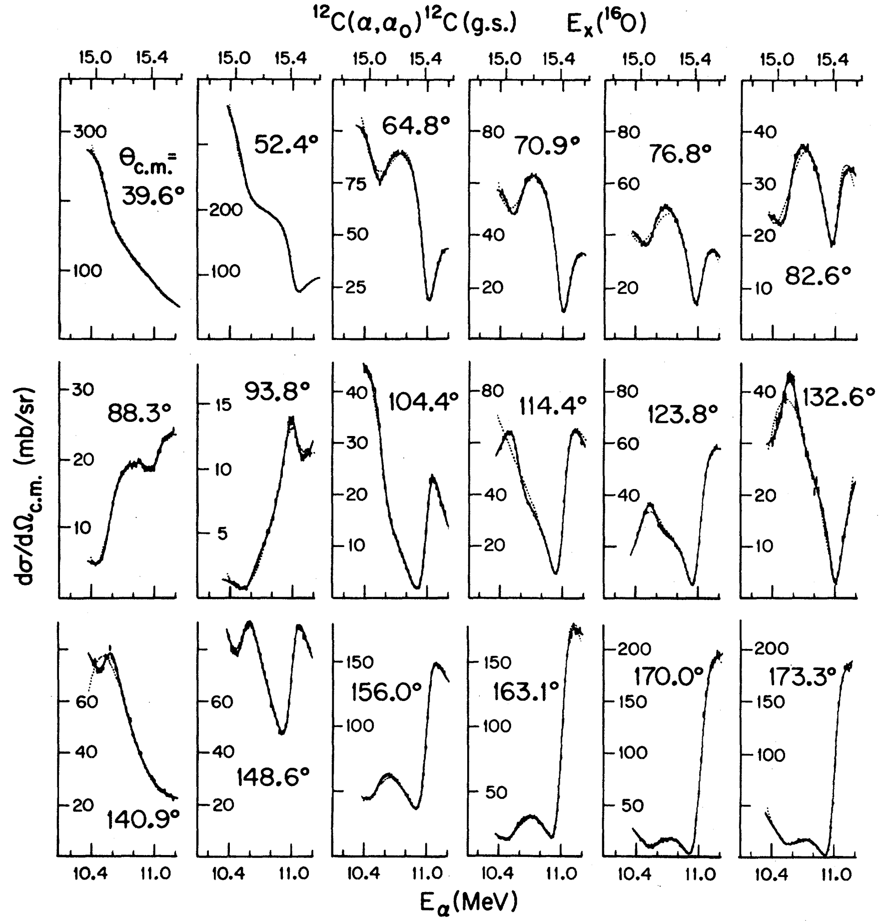

FIG. 12. A PSA fit to α_0 data over $14.9 \le E_x \le 15.5$ MeV. The solid line fit ($\chi^2 = 0.49$) uses four resonances; tails of broad 4^+ and 5^- resonances below the energy range, 0^+ and 3^- states at $E_x = 15.066$ and 15.407 MeV. Table I gives the level parameters. Omitting the 0^+ state raises χ^2 to 2.32 and gives the dotted curve shown at a few angles only. Data point size corresponds to statistical error.

$\Gamma \le 200$ keV. Black *et al.*[8] see an unassigned $\Gamma = 50$ keV state via (α,n) which may correspond to the 2^+ since the resonance also shows in the mirror reaction $^{12}C(\alpha,p_0)^{15}N$ (see Fig. 15). In fact, PSA could fit the (α,p_0) data with level parameters close to those of the α_0 channel (Table I). This use of PSA seems inappropriate because the $p + {}^{15}N$ exit channel does not involve 0^+ particles; instead, the channel spin s equals 1. However, PSA is a phenomenal fitting routine and applies if the resonant scattering amplitudes are proportional to a sum of $P_l(\cos\theta)$ if each resonance has a single l. For the 2^+ level at $E_x = 16.442$ MeV (Fig. 15) only outgoing $l = 1$ or 3 can occur since $J = l + s$ and ^{15}N has negative parity. Experimentally the data have a pure $\cos^2\theta$ angular distribution (i.e., $l = 3$ is negligible), and so PSA gives a good fit. The fits of both the α_0 and p_0 channels (Figs. 14 and 15) not only make the assignment unambiguous but yield $\Gamma_{\alpha_0}/\Gamma = 0.28$ and $(\Gamma_{\alpha_0}\Gamma_{p_0})^{1/2}/\Gamma = 0.17$ (thus $\Gamma_{\alpha_0} \approx 6$ keV and $\Gamma_{p_0} \approx 2$ keV). The small Γ_{α_0} suggests a possible $T = 1$ assignment. Indeed Baxter *et al.*[27] use $^{18}O(\vec{d},\alpha)^{16}N$ to argue persuasively for a firm 2^+ assignment for the $E_x(^{16}N) = 3.519$ MeV which occurs at the proper energy for the analog state. The corresponding ^{16}F state at $E_x = 3.870$ MeV also has a tentative 2^+ assignment.[2]

The possible (weak) 0^+ or 1^- state at $E_x = 16.361$ MeV deserves comment. In a study of the 0^+ states of ^{16}O, Ohanian[28] made a special search for the lowest expected 2p-2h, $T = 1$ state. Use of Zuker-Buck-McGrory wave functions predicts[28] such a state at $E_x = 15.05 - 15.72$ MeV (or with the McGrory-Wildenthal[29] interaction, $E_x \approx 16.56$ MeV). Ohanian used the $^{18}O(p,t)^{16}O$ reaction to select 2p-2h states and claimed a strong

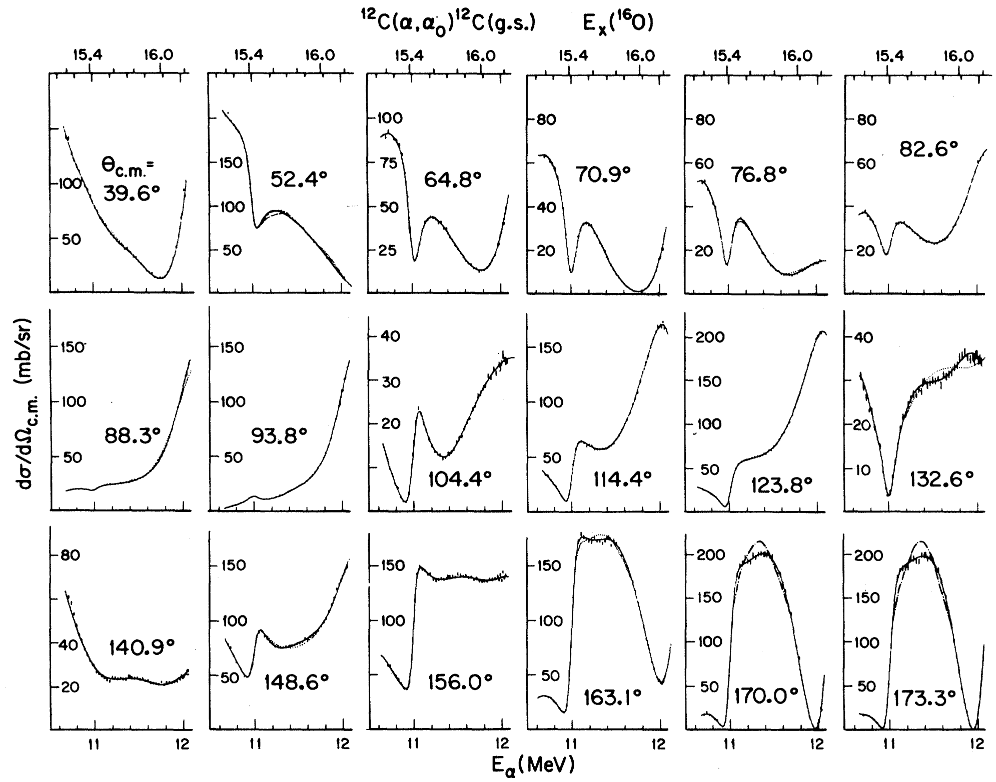

FIG. 13. Like Fig. 12 except for $15.2<E_x<16.2$ MeV. A fit (solid line) with $\chi^2=0.87$ involves tails of the 0^+ and 3^- resonances in Fig. 12, a broad 3^- state at $E_x=15.828$ MeV and the tail of the 6^+ resonance in Fig. 14. At a few angles a dot-dashed line and a dotted line show the best fit if the 3^- state is omitted or if a 2^+ replaces it.

state at $E_x=16.33$ MeV which he fits as 0^+. However, he could not find the corresponding state in ^{16}N via the analog $^{18}O(p,^3He)^{16}N$ reaction which a $T=1$ assignment requires. If it instead is 0^+, $T=0$, the state should also be accessible via the $^{12}C+\alpha$ channel. However, a high resolution search in the neighborhood of $E_x=16.33$ MeV (corresponding to $E_\alpha\approx$ 12.3 MeV) showed nothing obvious in the α_0 channel (e.g., see Fig. 14), but in the $^{12}C(\alpha,p_0)^{15}N$ reaction below the known sharp 2^+ level at $E_x=16.442$ MeV there is possibly a weak resonance (see Fig. 15). In fact, PSA could only obtain the reasonable fit of Fig. 15 by adding to the 2^+ a weak isotropic resonance with $\Gamma=76$ keV at $E_x=16.353$ MeV. Such an isotropic resonance for the $p+{}^{15}N$ exit channel implies either $J=0^+$ or 1^-.

Although a level at $E_x=16.3$ is not needed for the α_0 fit of Fig. 14, adding such a weak 0^+ or a 1^- level did indeed lower the χ^2 of the α_0 fit by about 20% and would suggest a $\Gamma_{\alpha_0}/\Gamma\approx0.07$. If this is indeed the same state Ohanian[28] reports, it could be 0^+ and the small Γ_{α_0} would favor a $T=1$ assignment rather than $T=0$. Yet unexplained would be its absence in the $^{18}O(p,^3He)^{16}N$ reaction. Incidentally, the PSA fit for the 0^+ gives $(\Gamma_{\alpha_0}\Gamma_{p_0})^{1/2}/\Gamma$ as ~0.075 so Γ_{p_0}/Γ is also ~0.08. From the $^{15}N(p,n)^{15}O$ total cross sections Barnett[30] reports a $J=0$ level at $E_x=16.33\pm03$ MeV but with $4\Gamma_p\Gamma_n/\Gamma^2=1$ and $\Gamma=240\pm30$ keV. These parameters are inconsistent with the α_0 data. The earlier $^{15}N(p,n)^{15}O$ data of Jones *et al.*[31] are isotropic (consistent with $J=0$) but show enough scatter that the large width may result from two or more overlapping states. Jones *et al.*'s arguments[31] for a $0^{(-)}$ assignment rely on a strong P_1 term at a lower positive parity level arising from this "broad" J=0 resonance. Bilanink *et al.*[32] see a weak state at $E_x=16.350$ MeV via $^{14}N(^3He,p)^{16}O$ but had inadequate data to attempt a J^π assignment.

There are, however, reasons to expect a $J=0^+$, $T=0$ level in this region. Jäger,[33] using a shell model calculation with pairing plus quadrupole Hamiltonian, predicts such a state at $E_x=16.3$

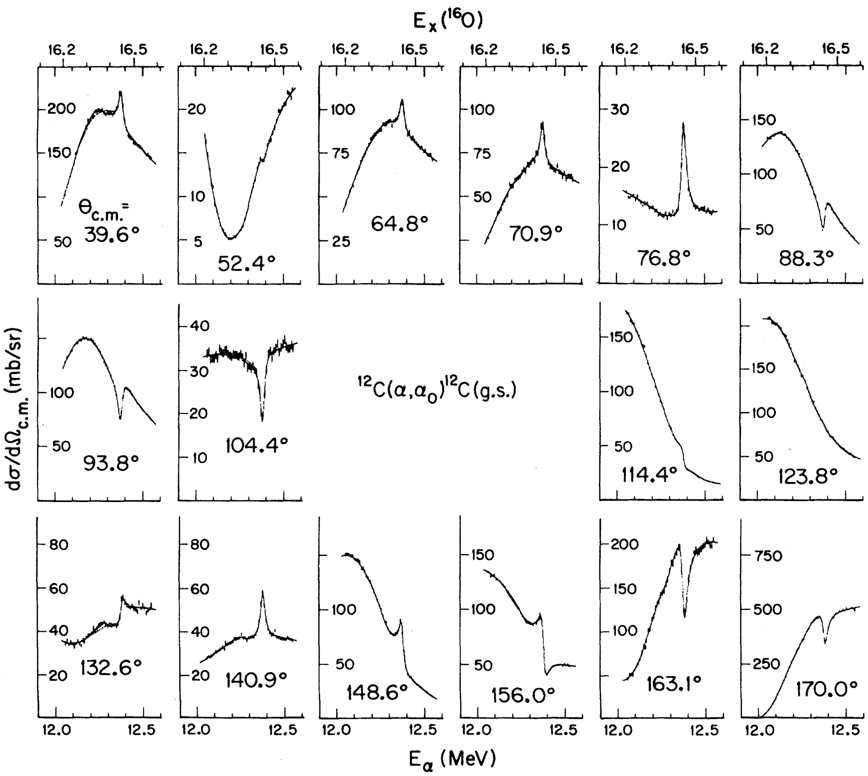

FIG. 14. Like Fig. 12 except for $16.2 \leq E_x \leq 16.6$ MeV. The solid line fit, $\chi^2=0.43$, uses the tail of Fig. 13's 3^- state, a very strong 6^+ resonance at $E_x=16.274$ MeV, a very weak 1^- at $E_x=16.361$ MeV, and a sharp 2^+ at $E_x=16.442$ MeV. Replacing the very weak 1^- by a 0^+ gives an equivalent fit, $\chi^2=0.45$. Main evidence for the 1^- or 0^+ state comes from (α,p_0) data (Fig. 15). Omission of the very weak state still gives a good $\chi^2=0.57$ and corresponds to the barely different dotted line fit shown at $\theta=39.6°$ and $\theta=132.6°$.

MeV to have 40% (4p-4h) components. Also Abgrall *et al.*[34] interpret the 2^+, 4^+, 6^+ ^{16}O levels seen by Chevallier *et al.*[35] via $^{12}C(\alpha,{}^8Be)^8Be$ as members of a rotational band generated by an axially symmetric 8p-8h state whose 0^+ band head would be $E_x \approx 16.75$ MeV. In fact in Chevallier *et al.*'s data there are cross section variations near $E_x=16.5$ which might arise from such a state. In the α_2 data, Fig. 4, there is a suggestion also of a state around $E_x=16.4$ MeV. In summary, the present data are consistent with a weak 0^+ level at $E_x \approx 16.4$ MeV but cannot fix its isospin nor exclude $J^\pi=1^-$.

The region $16.5 \leq E_x \leq 17.5$ MeV. Ajzenberg-Selove[2] lists three or four broad natural parity levels (chiefly from Ref. 1) for the lower half of the region. To make the program more sensitive to broad levels PSA used only every third datum point to broaden the fitting region. However, there was no evidence for any of these broad levels except a 4^+ state at $E_x=16.843$ MeV. Figure 16 shows a fit with and without such a resonance; a SUMDIF curve also supported the 4^+ assignment. While the α_0 channel had no evidence for the 2^+ level reported[35] at $E_x=16.94$ ($\Gamma=280$ keV) via $^{12}C(\alpha,{}^8Be)^8Be$, the α_2 channel did show a resonance of the same width and energy (see Fig. 4).

The only prominent level in the upper half of the region is the 107 ± 14 keV wide state at $E_x=17.129$ MeV which the fit unambiguously requires to be 2^+. Marvin and Singh[4] did not see the state and Ref. 1 only limited J to ≤ 2. The α_1 and p_0 data show it, and Black *et al.*[8] see it in the neutron channel. The 2^+ level reported[28] via $^{12}C(\alpha,{}^8Be)^8Be$ is sufficiently wider ($\Gamma \approx 200$ keV) and of enough higher energy ($E_x=17.17$ MeV) that it must be a different state. Indeed the α_2 data of Fig. 4 do have a slight anomaly at $E_x=17.17$ MeV with $\Gamma \approx 150$ keV which may come from the same level seen in the ^8Be channel.

In the $^{15}N(p,\gamma)^{16}O$ and $^{15}N(p,n)^{16}O$ reactions[2] and in $^{16}O(e,e')^{16}O$ scattering[26] a narrow (36 keV) 1^- state occurs at $E_x=17.14 \pm 0.02$ MeV which should be $T=1$, and hence, forbidden to the $T=0$

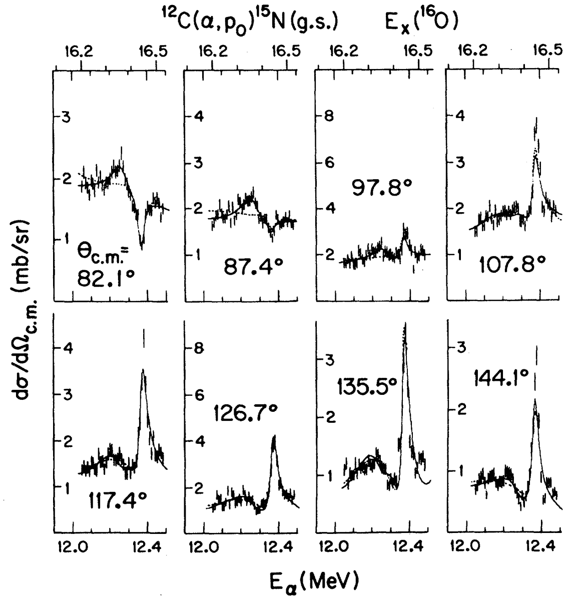

FIG. 15. A phenomenal PSA fit (see text) to ^{12}C$(\alpha,p_0)^{15}$N data over $16.2 \le E_x \le 16.6$ MeV. The dotted curve ($\chi^2=2.68$) involves the single sharp 2^+ state ($E_x=16.441$ MeV) and assumed exit channel $l=1$. If one adds either a $J=0^+$ or 1^- state at $E_x=16.353$ MeV, $\Gamma=76$ keV, the solid curve fit results and χ^2 drops to 2.21.

entrance channel of ^{12}C$+\alpha$. However, a weak unfitted anomaly of the proper width does appear in the α_0 and α_1 data at $E_x=17.15$ MeV and therefore suggests a small $T=0$ impurity in the state.

Ajzenberg-Selove[2] lists another 1^- resonance ($E_x=17.29$ MeV, $\Gamma=90\pm10$ keV) which appears strongly in reactions permitting $T=1$ states: ^{15}N$(p,\gamma)^{16}$O (Barnett and Tanner[36]); ^{15}N$(p,n)^{15}$O (Barnett[30]). However, Black *et al.*[8] claim to see a very weak ^{12}C(α,n) and ^{12}C(α,p) resonance of the proper width at this E_x. In the present α_0 data only a few angles show anything outside of statistics so the $T=1$ assignment appears likely.

The region $17.5 \le E_x \le 18.3$ *MeV*. The lower part of this region (Fig. 17) was impossible to fit with the levels cited in the literature. Instead, the first state PSA required was a 1^- at $E_x=17.510$ MeV which energy is within 200 keV of that expected from the well-known single particle 1^- state at $E_x=9.632$ MeV but with the ^{12}C core excited to the 0^+ state at 7.655 MeV (see below). To achieve the still high χ^2 of 1.37 required also: a weak 6^+ at $E_x=17.555$ MeV; a possible 0^+ or 1^- assignment to the lower member ($E_x=17.617$ MeV) of

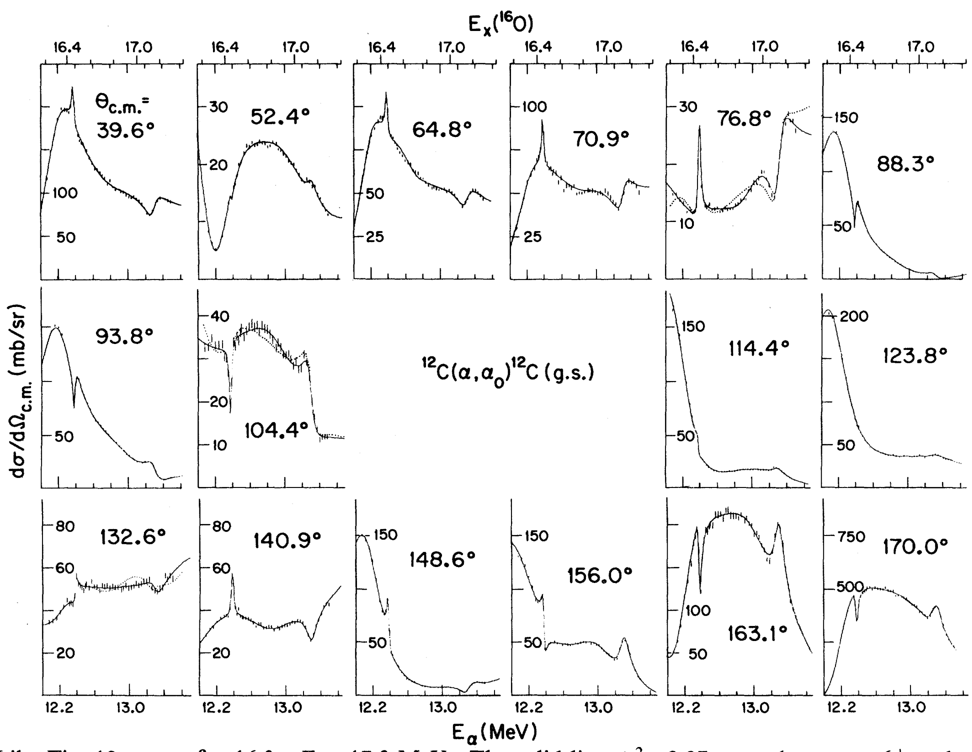

FIG. 16. Like Fig. 12 except for $16.3 \le E_x \le 17.3$ MeV. The solid line, $\chi^2=0.87$, uses the strong 6^+ and narrow 2^+ states of Fig. 14's fit plus a broad 4^+ resonance at $E_x=16.843$ MeV and a 2^+ at $E_x=17.129$ MeV. Omission of the 4^+ (dotted line fit) raises χ^2 to 2.69. Not plotted is a $\chi^2=0.78$ fit resulting from adding the broad but weak 5^- state suggested by Ref. 1.

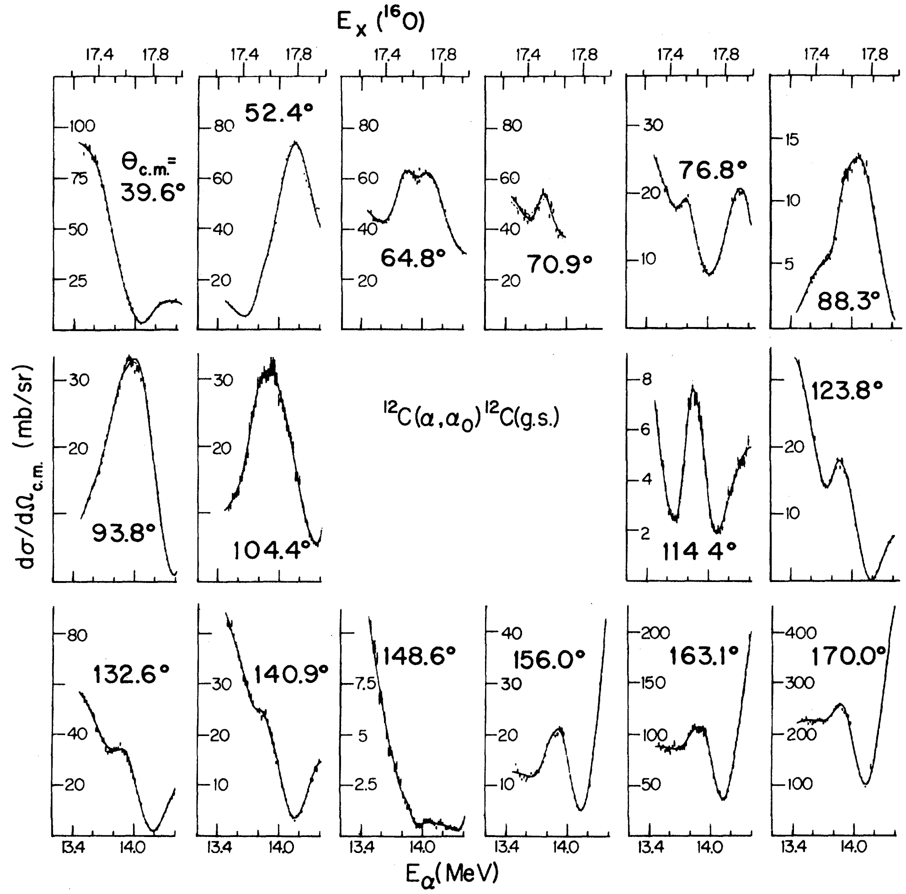

FIG. 17. Like Fig. 12 except for $17.3 \le E_x \le 17.9$ MeV. The solid line fit, $\chi^2=1.37$, uses five levels: a 1^- at $E_x=17.510$ MeV, a very weak (doubtful) 6^+ at $E_x=17.555$ MeV, a doubtful 0^+ at 17.617 MeV, a broad 4^+ at $E_x=17.784$, and the (unneeded) tail of a possible higher energy 2^+ level. Replacing the 0^+ with another 1^- gave an almost indistinguishable fit (dotted lines) and raises χ^2 only 7%.

Bernstein *et al.*'s[37] alleged isospin mixed doublet; and a strong and broad ($\Gamma=396$ keV) 4^+ state at $E_x=17.784$ MeV. The possible (0^+,1^-) assignment is very doubtful even though Fig. 18 shows a surprisingly good PSA fit of the α,p_0 channel for that assumption. Not only is the α,p_0 data limited in range and angle, but the conditions appropriate for using PSA with a reaction involving a spin 1 channel are not well satisfied (see preceding text). The extracted $E_x=17.608\pm0.011$ MeV and $\Gamma=100\pm25$ keV are probably reliable and in fact support the α,α_0 results, $E_x=17.617\pm0.020$ MeV and $\Gamma=175\pm55$ keV.

There is no support for the tentative level at $E_x=17.7$ MeV (0^+,2^+) reported[35] in the ^{8}Be channel unless one associates fluctuations in the (α,p_0) data (Fig. 18) at the back angles with such a state.

The strong broad 4^+ state needed at $E_x=17.784$ MeV probably corresponds to the unassigned $\Gamma\approx0.3$ MeV state (Mitchell *et al.*[16]) reported at $E_x=17.86$ MeV in the α_1 channel and to the tentative 4^+ state claimed by Ref. 35 for the ^{8}Be channel. For the neutron channel Black *et al.*[8] report a level of the proper energy but of undetermined width (because it appears as a low energy shoulder of the strong $E_x=18.10$ MeV state).

Except for the well known narrow ($\Gamma=14$ keV) 4^+ state at $E_x=18.016$ MeV, the α_0 data in the upper part of this region (Fig. 19) mainly reflect the effects of the previous 4^+ level and the tail of a stronger and even broader 5^- state which lies just outside this fitting region. Consequently, the χ^2 is relatively insensitive to other weaker levels. For example, the upper member of Bernstein *et al.*'s[37] alleged isospin mixed doublet at $E_x=18.089$ MeV, if 0^+, gives $\chi^2=1.85$; if 1^-, the result is 1.95; but a 3^- gives 1.58 if a higher weak 2^+ also is changed to 0^+ (mainly because of a

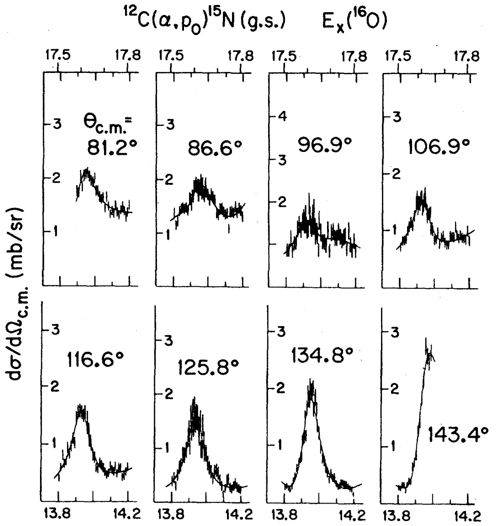

FIG. 18. Like Fig. 15 except for $17.5 \le E_x \le 17.8$ MeV. The solid line fit, $\chi^2 = 1.02$, involves a single 0^+ or 1^- state at $E_x = 17.617$ MeV.

small higher energy bump at $\theta = 148.6°$). An additional problem with the 0^+ assignment to the upper member ($E_x = 18.08$ MeV) of Bernstein's T mixed doublet[37] is that Black *et al.*'s (α,n) cross sections[8] (their Fig. 3) seem to exceed the maximum possible for an $l = 0$ resonance, $\sigma_{max} = \pi \lambda\!\!\!^{-2} \approx 15$ mb. Möbius and Gruhle[18] interpret their (α,p_0) angular distributions around $E_x = 18.1$ MeV as indicating a $J^\pi = 1^-$, 3^-, or 5^- state with 3^- preferred. So the J^π assignment for Bernstein's T-mixed doublet is still not clear.

The narrow 4^+ at $E_x = 18.016$ MeV merits further comment. Its energy is within 8 keV of the sum of the narrow ($\Gamma = 27 \pm 4$ keV) 4^+ state at $E_x = 10.353$ MeV and the energy of the 0^+ second excited state of ^{12}C (7.655 MeV). Hence, one can view this state as an excited core state (see Table II). This interpretation removes the problem Chevallier *et al.*[35] had in ascribing it to a rotational band where the other members had large widths.

Missing is a second close by and narrow level

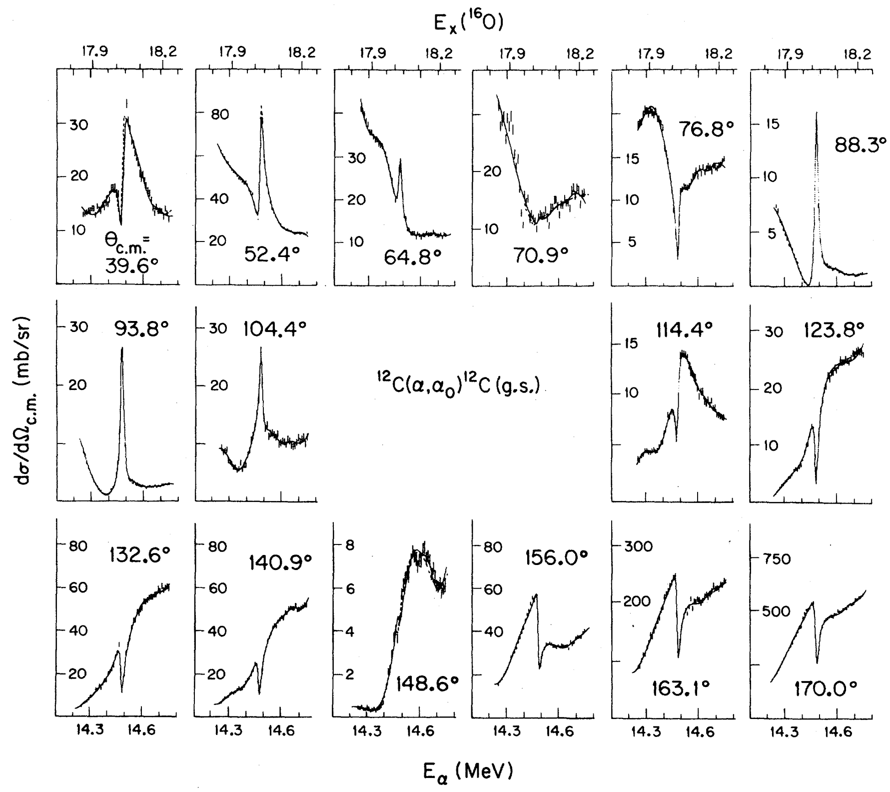

FIG. 19. Like Fig. 12 except for $17.9 \le E_x \le 18.2$ MeV. The solid line fit with a poor $\chi^2 = 1.85$ involves five levels: the tail of the 4^+ from Fig. 17, a sharp 4^+ at $E_x = 18.016$ MeV, a 0^+ at $E_x = 18.089$, a weak 2^+ at $E_x = 18.25$, and the tail of a 5^- from Fig. 20. The 0^+ and 2^+ are not well established; in fact an improved $\chi^2 = 1.58$ (dotted line) results from replacing them by a 3^- and 0^+.

TABLE II. Possible natural parity excited-core levels.[a]

$\alpha+{}^{12}C$(g.s.): Parent level[b]	1st excited 2^+ 4.439 MeV	2nd excited 0^+ 7.655 MeV	3rd excited 3^- 9.641 MeV
0^+ 6.049	2^+ 9.847	0^+ 14.043	3^- 15.407[c]
2^+ 6.917	4^+ 11.096		
	2^+ 11.521		
	0^+ 12.053		
1^- 9.632	1^- 12.442	1^- 17.510[d]	2^+ 19.257[d]
	3^- 13.130		
4^+ 10.353	6^+ 14.805[e]	4^+ 18.016[d]	5^- 20.540[d]
	2^+ 14.917[f]		
3^- 11.60	3^- 15.828[d]		6^+ 21.051[d]
			(4^+) 21.098[d]
5^- 14.67	(5^-) 19.0[d]		
6^+ 16.274[c]	20.50[d]	6^+ 23.879[e]	
7^- 20.856[c]			

[a]Except as noted, parameters and associations are from Ref. 53.
[b]Members of "rotational" bands.
[c]Present parameters, association by Ref. 53.
[d]Present parameters and associations.
[e]Parameters from Ref. 2, my association.
[f]Parameters from Ref. 2 and 22, my association.

which Ajzenberg-Selove[2] tentatively lists as 4^+. Possibly she misattributed the assignment of Ref. 1 to an unrelated level (see my thesis[9]).

Snover *et al.*[23] see a 370 keV wide 2^+ state at $E_x=18.3$ MeV via ${}^{12}C(\alpha,\gamma){}^{16}O$. The PSA fits do not require such a state, but again they are especially insensitive to low J *weak* broad states which can be lumped in the background terms. There are hints of such a level at some angles especially in the α_1 and p_0 channels; but since these data were not fit, the parameters in Table I are only rough estimates.

The region $18.3 \le E_x \le 19$ MeV. The only strong structure in this region is slowly varying. Good PSA fits (Fig. 20) result by using only three broad resonances; a 5^- at $E_x=18.403$ MeV, a 1^- at 18.773 MeV, and a 4^+ at 18.785 MeV. The 5^- assignment, supported also by SUMDIF plots, confirms Carter *et al.*'s[1] assignment. The 1^- is possibly the same state Snover *et al.*[23] identify by the $E1$ transition in the (α,γ) reaction, but is is not as narrow as the 75 keV width claimed by Carter *et al.*[1]. The 4^+ state at $E_x=18.785$ MeV probably corresponds both to the tentative 4^+ assignment Chevallier *et al.*[35] made on the basis of the ${}^8Be$ exit channel and to the 220 keV wide state Black *et al.*[8] report in the (α,n) reaction.

Carter *et al.*[1] also suggested a 1^- or 5^- state at $E_x=18.55$ MeV in the α_0 channel with width ≈ 190 keV. The present α_0 data at the back angles are inconsistent with Ref. 1, and adding such a 5^- level to PSA gave only a small improvement in χ^2. But, at this energy there are possible anomalies in the α_1 and α_2 channels which may be significant.[9]

The ${}^8Be$ exit channel measurements[25] report a tentative 0^+ or 2^+ level at $E_x=18.6$ MeV which PSA does not need in (α,α_0) fitting. However, the α_2 data (Fig. 5) has structure in this region resembling the ${}^8Be$ data but at angles inconsistent with 2^+ and rather favoring a 4^+ assignment. Unfortunately there are data at insufficient angles for a definite J^π assignment.

The region $18.9 \le E_x \le 19.8$ MeV. The first 300 keV of the region has no sharp structure and PSA easily fit the α_0 data with only the tails of resonances previously assigned at higher and lower energies. Thus the fit is inconsistent with Ref. 1's reported $\Gamma=55$ keV, $E_x=19.10$ MeV $(2^+,4^+)$ state and needs none of the natural parity ${}^{16}O$ levels reported in inelastic scattering studies: 3^-, $E_x=19.00$ MeV, ${}^{16}O$ (α,α_1), Ref. 38; 1^-, $E_x=19.00$ MeV, ${}^{16}O(e,e')$, Ref. 39; and 2^+,

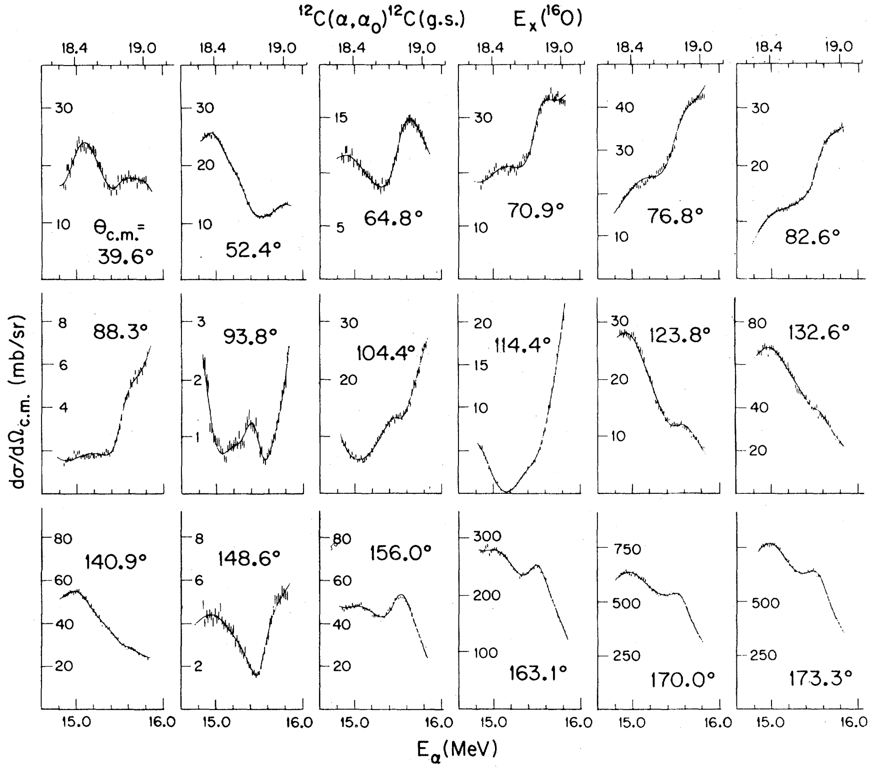

FIG. 20. Like Fig. 12 except for $18.3 \le E_x \le 19.0$ MeV. The solid line fit, $\chi^2=0.85$ involves only three broad states: a 5^- at $E_x=18.403$ MeV, a 1^- at $E_x=18.773$ MeV, and a 4^+ at $E_x=18.785$ MeV. By adding another weak 5^- at $E_x=18.55$ one obtains an equivalent fit with slightly lower $\chi^2=0.76$.

$E_x=19.09$, ^{16}O(^{3}He,^{3}He′), Ref. 40.

The rest of the region was more difficult, and PSA never achieved fits with χ^2 close to one. Detector malfunctioning at certain angles was part of the problem, but probably more levels are needed. The fit (Fig. 21) gives $\chi^2=1.84$ and involves the maximum five levels which PSA could handle. The narrow ($\Gamma=23$ keV) 4^+ state at $E_x=19.374$ MeV is the most prominent feature and appears in all reaction channels. The narrow width suggests $T=1$, but the possible analogs in ^{16}N or ^{16}F have no assignments. The α_0 fit includes a weak ($\Gamma_{\alpha_0}/\Gamma=0.07$) narrow 6^+ state at $E_x=19.319$ MeV which would be a tentative assignment except for the fact that the α_2 data are complete enough (barely) to permit a PSA fit. The result (Fig. 22) requires both the 4^+ and the 6^+ states. [The poor $\chi^2=2.69$ may result in part from the rapid change of θ (for fixed θ_{lab}) over the energy region fitted.] The ^{8}Be channel (Ref. 35) gives the only other evidence for the 6^+ level.

The PSA fits used three 2^+ levels of moderate widths and strengths in this energy region. Only the middle one at $E_x=19.526$ MeV seems to correspond to any previously reported state. Mitchell *et al.*[16] saw the middle resonance in the α_1 channel but made no J^π assignment. Harakeh *et al.*[41] via ^{16}O(α,α') report a 19.5 MeV state and their poorly fit α' angular distribution suggests 2^+ or 3^-. The two new 2^+ states at $E_x=19.257$ and 19.753 MeV are sufficiently strong and occur in enough channels that their absence in the literature is surprising. The close clustering of several such strong 2^+ levels (here and in the next energy region) may relate to fragmentation[41] of the giant quadrupole resonance.

Table I lists tentatively a very weak ($\Gamma_{\alpha_0}/\Gamma=0.04$) and narrow 5^- state at $E_x=19.252$ MeV because over a small portion of this region PSA did give a significantly better fit including this level and SUMDIF plots gave a surprisingly strong $l=5$ indication; but the parameters are certainly not well determined. There are only statistical fluctuations at $E_x=19.68$ MeV, where Carter

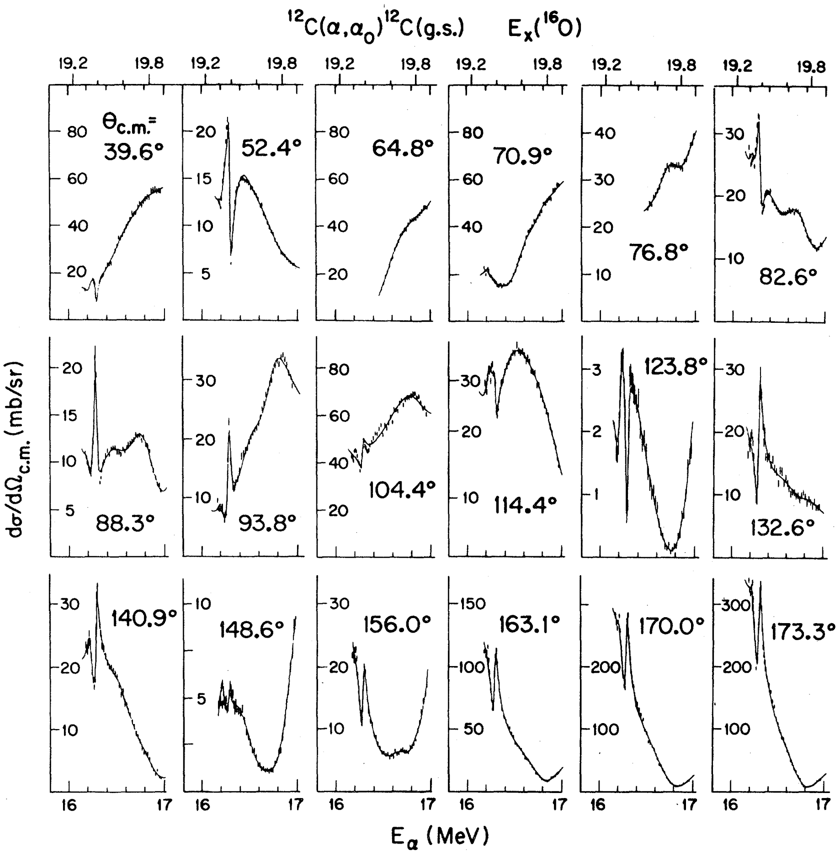

FIG. 21. Like Fig. 12 except for $19.2 \leq E_x \leq 19.8$ MeV. The solid line fit, $\chi^2=1.84$, employs five levels: a weak sharp 6^+ at $E_x=19.319$ MeV, a very narrow 4^+ at $E_x=19.374$ MeV, two broad 2^+ at $E_x=19.526$ MeV and $E_x=19.753$, a broad 4^+ near the high energy end. A somewhat better fit ($\chi^2=1.72$) results from adding a 2^+ at $E_x=19.257$ MeV and relegating the broad 4^+ to background. The last 2^+ state was also needed for other fits (not shown) of the overlapping region between this and the previous figure.

et al.[1] claim an even parity narrow level whose alleged width, 22 keV, is less than their quoted energy resolution.

The region $19.6 \leq E_x \leq 20.8$ MeV. For the lower part of the region PSA used only every other energy point to cover a wider energy range and be more sensitive to broad structure. The fit (Fig. 23) required, in addition to the tail of a higher energy 4^+ resonance, only two reasonably broad 2^+ resonances: the previously discussed one at $E_x=19.753$ MeV and a 432 keV wide one at $E_x=20.055$ MeV [probably Snover *et al.*'s[23] state $E_x=20.0$ MeV ($\Gamma=0.4$ MeV) seen by $^{12}C(\alpha,\gamma)$ and Harakeh *et al.*'s[41] state at $E_x=20.15$ MeV ($\Gamma\approx350$ keV) seen by $^{16}O(\alpha,\alpha')$]. There are several more much narrower but quite weak levels (e.g., $E_x\approx19.94$ and 20.11 MeV at $\theta=70.9°$ and 140.9°, Fig. 23) which if included should improve the fit. The 140.9° data where $P_3\approx0$ excludes a 3^- assignment for them. Carter *et al.*'s[1] tentative assignment of a $\Gamma\approx1100$ keV, 4^+ state at $E_x=19.9$ MeV is inconsistent with the α_0 data at $\theta=70.4°$ and 109.5° where $P_4\approx0$.

The upper energy range, though dominated by the tails of next section's strong resonances, also shows (Fig. 24) a new very narrow ($\Gamma=11\pm2$ keV) 5^- state at $E_x=20.540$ MeV. The parameters quoted for the narrow 5^- state come from a fit to remeasured data taken in finer steps at lower gas pressure and with a modified first pumping impedance to reduce beam straggling to the center of the target. The small width of the 5^- state suggests $T=1$, but the analog regions in ^{16}N or ^{16}F have not been well studied. An alternative possibility is a $T=0$ excited core state (see Table II).

Two other narrow anomalies in this region at

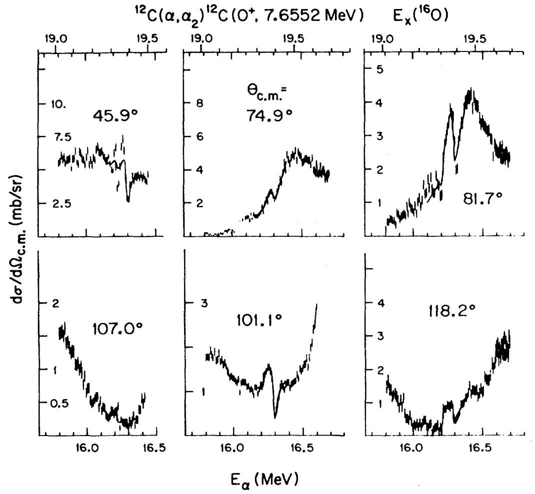

FIG. 22. A PSA fit of the ^{12}C$(\alpha,\alpha_2)^{12}$C(7.655 MeV) data for $E_x \approx 19.35$ MeV. Because θ varies so rapidly with incident energy, the fitting region was limited to 230 keV at a time and the χ^2's were high. Nevertheless, both of the narrow 6^+ and 4^+ states of Fig. 21 were needed for the fit shown ($\chi^2=2.69$). All other combinations gave $\chi^2>3$. The strengths $[(\Gamma_{\alpha_0}\Gamma_{\alpha_2})^{1/2}/\Gamma]$ for the 6^+ and 4^+ were 0.06 and 0.11, respectively.

$E_x=20.560$ and 20.614 MeV are too weak for a PSA fit. Their interference effects at $\theta\approx 88.3°$ do, however, imply even parity.

Table I also lists a 4^+, $\Gamma=150$ keV, state at $E_x=20.40$ MeV which is so weak in the α_0 channel that it is almost buried under the next strong broad level. But PSA gives better fits with it, and the α_2 channel shows it. The wider peak ($\Gamma\approx 300$ keV at $E_x=20.50$ MeV) in the α_1 channel is probably a different state.

The region $20.8 \le E_x \le 21.4$ *MeV*. The gross structure (Fig. 25) arises from just two strong resonances; a very broad ($\Gamma=904$ keV) 7^- state at $E_x=20.856$ MeV with $\Gamma_{\alpha_0}/\Gamma=0.6$ and a 205 keV wide 6^+ state at $E_x=21.051$ MeV with $\Gamma_{\alpha_0}/\Gamma=0.5$. In fact, $\chi^2=1.45$ resulted from using only these two states plus the tail of the lower 4^+ state. To further reduce χ^2 to 0.96 PSA required a number of other weak levels with rather poorly determined parameters.

The strong 7^- level is apparent from inspection of the excitation curves if one recalls the angles for which $P_7(\cos\theta)=0$; SUMDIF confirms the assignment; and PSA fixes the resonant parameters. The

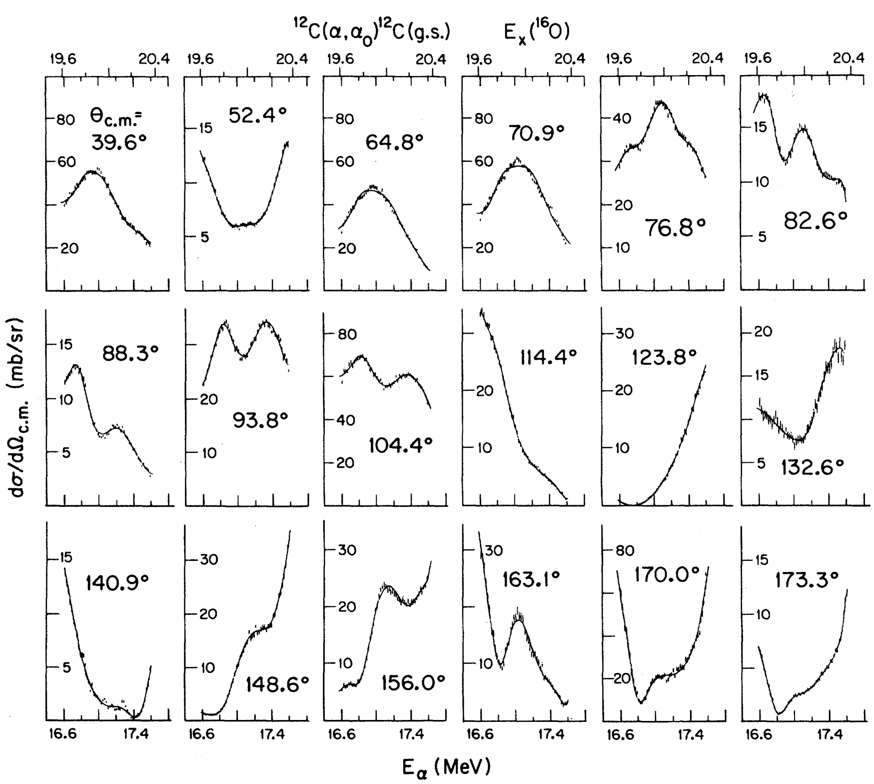

FIG. 23. Like Fig. 12 except for $19.6 \le E_x \le 20.3$ MeV. The solid line fit ($\chi^2=1.26$) needed only three resonances; two broad 2^+ levels (at $E_x=19.753$ and $E_x=20.055$ MeV) plus the tail of a 4^+ from Fig. 24.

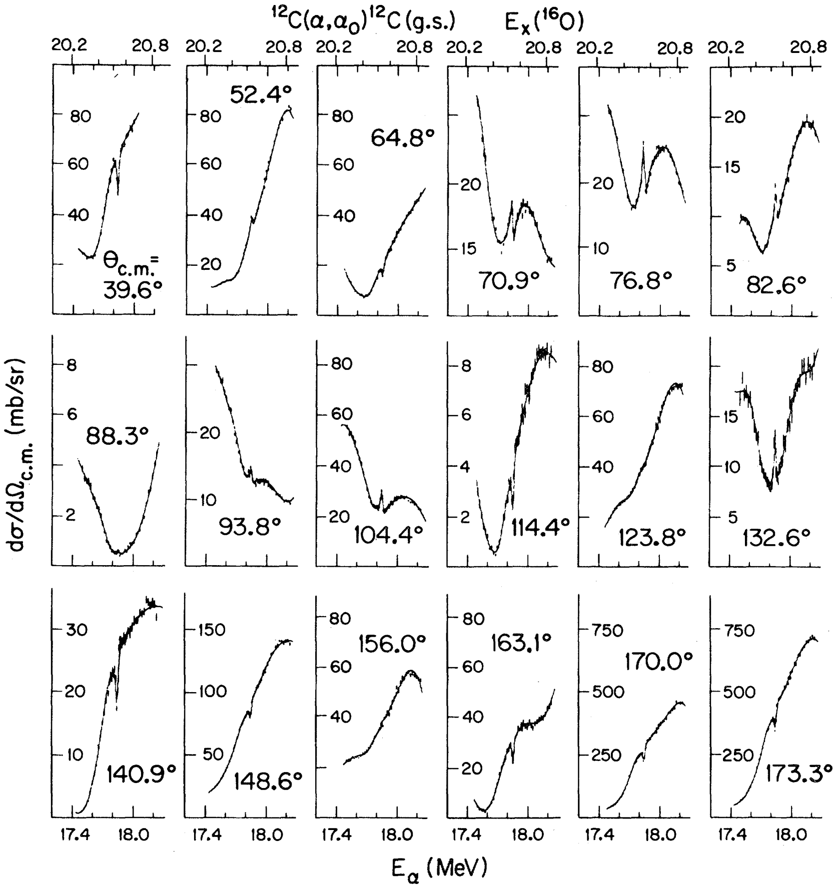

FIG. 24. Like Fig. 12 except for $20.3 \leq E_x \leq 20.8$ MeV. The solid line fit ($\chi^2=0.88$) used five levels: the tail of a 2^+ from Fig. 23, a 4^+ at $E_x=20.469$ MeV, a very sharp 5^- at $E_x=20.540$ MeV, a broad 7^- at $E_x=20.856$ MeV, and the tail of a higher very dubious broad 5^- whose effects are indistinguishable from background. Since the 4^+ level was weak in the α_0 channel, the parameters in Table I are from the α_2 data.

$^{12}C(^6Li,d)^{16}O$ studies[20,25,42] also report this level but systematically favor a $\Gamma_{\alpha_0}/\Gamma \approx 1$ and a narrower Γ. Such a systematic difference could suggest that the alpha-scattering 7^- data include several overlapping levels which the α transfer reaction does not populate. However, if one looks critically at the original alpha transfer spectra, there is much latitude in judging the half-width, and some of the authors may have been unduly influenced by the 750 keV $\Gamma_{c.m.}$ erroneously listed in the compilations[2] and attributed to alpha scattering. (The α scattering data[1] in fact gave $\Gamma_{c.m.} \approx 1000$ keV). A more serious difference is the α transfer result, $\Gamma_{\alpha_0}/\Gamma \approx 1$. In defense of the smaller ratio, note that in Fig. 2(a) lower energy ($E_x=16.274$ MeV) 6^+ resonance dwarfs the 7^- cross sections (at $E_x \approx 20.856$ MeV) whereas, because of the $[k^{-1}(2l+1)P_l(\cos\theta)]^2$ factor, the 6^+ should be only 28% larger than a 7^- if $\Gamma_{\alpha_0}/\Gamma=1$.

The higher energy ($E_x=21.051$ MeV) 6^+ state was tentatively suggested by Carter *et al.*[1] many years ago. Inspection of the present excitation curves where $P_6(\cos\theta)=0$ and of the SUMDIF curves supports $l=6$. The PSA fits are unambiguous but give resonant parameters considerably different from Ref. 1. Carter *et al.*[1] also suggested a broad 5^- at $E_x \approx 21.0$ MeV, but SUMDIF curves and PSA fits with and without the level give no support for such a state. Harakeh *et al.*[41] report a broad 2^+ level at $E_x=20.9$ MeV; SUMDIF plots suggest it may exist, but a PSA fit was not tried because of the dominating high spin states.

Suffert and Feldman[43] see a strong E-1 capture resonance in the $^{12}C(\alpha,\gamma)$ reaction at $E_x=21.05$ MeV with $\Gamma \approx 240 \pm 80$ keV and $\Gamma_\gamma \Gamma_\alpha/\Gamma \approx 6$ eV. When PSA tried such a 1^- level, the fits slightly

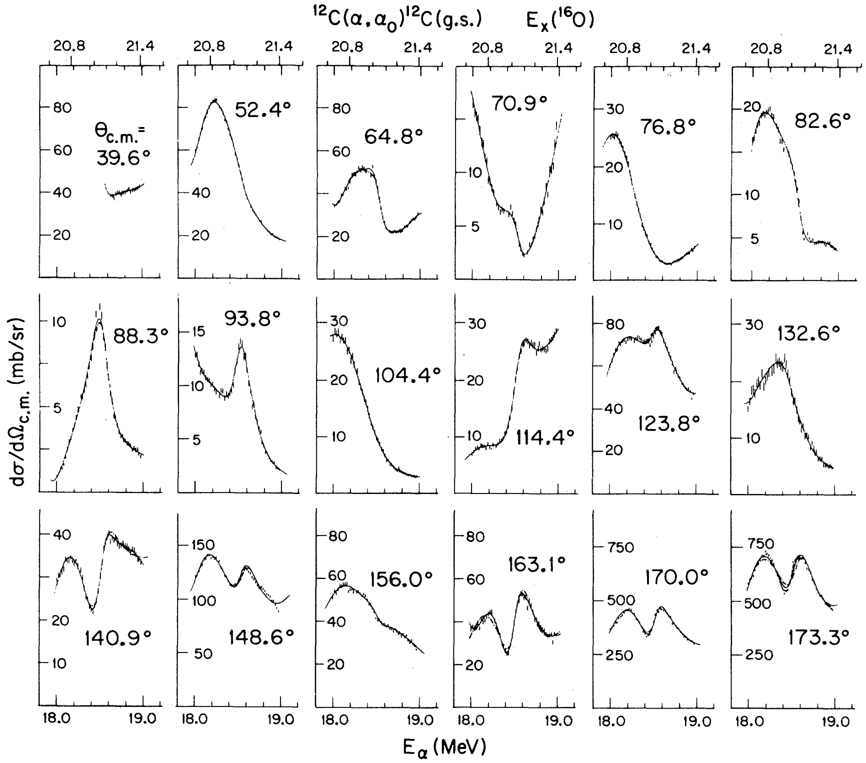

FIG. 25. Like Fig. 12 except for $20.7 \leq E_x \leq 21.4$. The solid line fit ($\chi^2 = 1.01$) uses four levels: the tail of the 4^+ from Fig. 24, a strong broad 7^- at $E_x = 20.856$ MeV, a strong 6^+ at $E_x = 21.051$ MeV, and a 4^+ at $E_x = 21.098$ MeV. Omitting the 4^+ (dot-dashed curve) raises the χ^2 to 1.45. Adding 1^- at $E_x = 21.027$ MeV reduces χ^2 to 0.96.

improved especially at the back angle. The resultant level parameters are not well determined since the $(2l+1)^2$ factors of the strong 7^- and 6^+ resonances dominate, but Table I includes them (for what they are worth).

For the best $\chi^2 = 0.96$, PSA required also a 4^+ state. The final parameters (Table I) were essentially the same as the initial guess. Such a state has never been reported, and is not apparent in the raw data. However, SUMDIF plots indicate $l = 4$. The 7^- and 6^- states so dominate the region that the 1^- and 4^+ parameters are not well determined.

The region above $E_x = 21.4$ MeV. The most prominent feature here is the strong 6^+ at $E_x = 21.647$ MeV ($\Gamma = 115$ keV). The assignment is obvious from its absence where $P_6(\cos\theta) = 0$; SUMDIF curves confirm the 6^+ and PSA unambiguously determines the parameters. This level has never been reported before in the α_0 channel though it is obvious in the data of Morgan and Hobbie.[7] Probably it corresponds to the 6^+ state seen in alpha transfer reactions [e.g., ^{12}C(^{6}Li,d)^{16}O] but reported[20,42,44–46] at 140 keV higher energy ($E_x = 21.8$ MeV). However, Cunselo *et al.*'s actual spectra[44] would seem to support Table I's $E_x = 21.647$ MeV rather than their quoted $E_x = 21.8$ MeV.

At angles where $P_6(\cos\theta) = 0$ (e.g., $\theta \approx 104°$ and 133°), there is in Fig. 26 a very weak narrow bump which SUMDIF and PSA want as a 7^- state ($E_x = 21.623$ MeV, $\Gamma = 61 \pm 32$ keV). This state may correspond to a $\Gamma = 55$ keV wide state Black *et al.*[8] see via (α,n) and (α,p) reactions but report as $E_x = 21.69$ MeV. Dracoulis and Legge[47] claim a narrow ($\Gamma < 40$ keV) state at $E_x = 21.66$ MeV in the ^{15}N+p reaction which resonates in the α_0 exit channel as well as in the p_0, p_1, and p_6 channels. Since the p_1 and p_6 groups leave ^{15}N in fairly high spin states, these results appear consistent with a 7^- assignment.

The last state which PSA needed in fitting this region is a weak ($\Gamma_{\alpha_0}/\Gamma = 0.07$), narrow ($\Gamma = 43$ keV), 3^- state at $E_x = 21.776$ MeV. At this excitation energy in the (α,n) and (α,p) reactions, Black *et al.*[8] report a $\Gamma = 55$ keV level which could be the same state. The ^{15}N+p data of Dracoulis and Legge[47] also show possible anomalies at this energy.

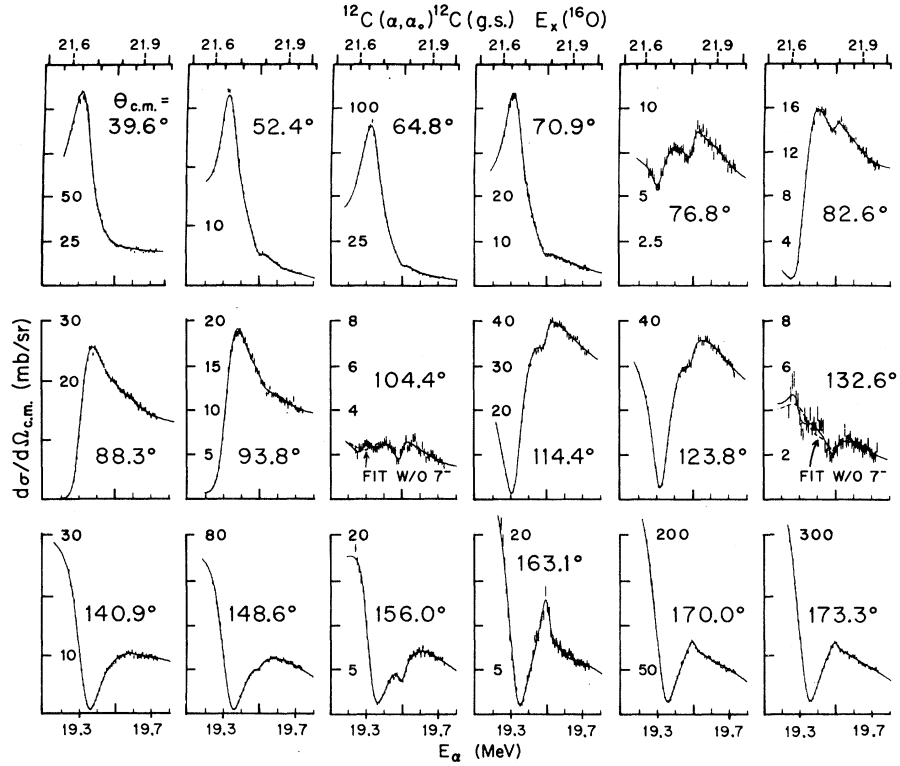

FIG. 26. Like Fig. 12 except for $21.6 \leq E_x \leq 22$ MeV. The solid line fit ($\chi^2=0.87$) used four levels: a weak dubious 7^- at $E_x=21.623$ MeV, a strong 6^+ at $E_x=21.647$ MeV, a 3^- at $E_x=21.776$, and a very weak, unlisted 4^+ (subsequently found possible to include in background). The dotted line shows an equivalent fit involving just the 6^+ and 3^- .

There were α_2 data at enough angles to try a PSA fit (Fig. 27) using only the 7^-, 6^+, and 3^- resonances discussed above. The parameters from the α_2 fit are consistent with those from the α_0 fitting. Reference 48 also reports the 7^- in the α_2 channel.

Excited core states. The $^{12}C+\alpha$ reaction is particularly sensitive to collective 4p-4h states (α clustering). Various authors[1,49–52] use different methods [oscillator and folded potentials, SU(3) model, tetrahedron of deformed α clusters] to describe these "rotational bands" or "threshold states." These states with $\Gamma_{\alpha_0}/\Gamma \approx 1$ (e.g., the 6^+ $E_x=16.274$ MeV state) can be viewed as an α particle plus a ^{12}C core and form a basis for families of other states corresponding to excited states of the core. The first three excited states of ^{12}C (2^+ at $E_x=4.439$, 0^+ at 7.655 and 3^- at 9.641 MeV) could contribute to the present energy region. To qualify as an excited core state, not only must the $E_x(^{16}O)$ approximate the $E_x(^{16}O$ parent) plus $E_x(^{12}C)$, but the J^π must correspond to the vector sum of the J^π of the parent state and the J^π of the ^{12}C excited state. One also expects the widths to correspond and that the alpha decay to the particular ^{12}C excited state be enhanced. Model calculations are needed to predict multiplet splittings and relative strengths.

Table II lists some possible core excited ^{16}O states. Many of the assignments are originally by Gol'dberg *et al.*[53] The most striking new example from the present data is the narrow 4^+ state at $E_x=18.016$ MeV whose energy is within 8 keV of the sum of the narrow parent 4^+ state at $E_x=10.353$ MeV and the 0^+ second excited state of ^{12}C at 7.655. My thesis[9] discusses each correspondence.

A discussion about 8^+ levels. In the usual description of ^{16}O states one assumes[54] that the first rotational band $(0^+,+2^+,\ 4^+,\ 6^+,\ldots)$ corresponds to the 0^+ state at $E_x=6.05$ MeV, 2^+ at 6.92, 4^+ at 10.35 and 6^+ at 16.27. Extrapolation predicts the 8^+ at $\sim$20 MeV, but many

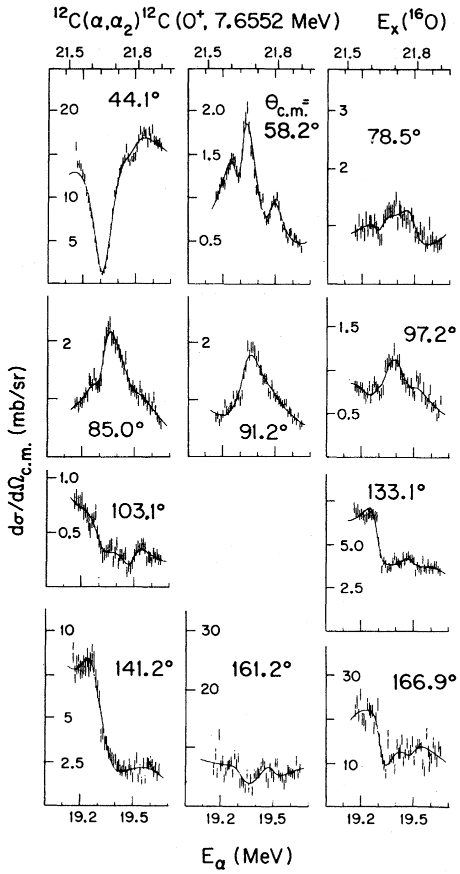

FIG. 27. Like Fig. 22 except for $21.5 \leq E_x \leq 21.9$ MeV. The change in θ as a function of incident energy is less rapid than in Fig. 22 and the fits are better. The solid line fit ($\chi^2 = 1.76$) uses the same 7^-, 6^+, and 3^- levels needed for the α_0 fits of Fig. 26.

searches (Refs. 7, 45, 48, 55, and 56) have failed to find any 8^+ levels in this region of ^{16}O.

I, too, looked carefully for an 8^+ level by checking each resonance at angles where $P_8(\cos\theta) = 0$. None was found. In addition all the ambiguous phase shift solutions provide corroboration: Experimental fits with L_{max} less than the l of a known resonance always gave terrible results, yet the programs fit all my data reasonably well with $L_{max} \leq 7$.

Carter[57] suggested that the 8^+ level might be very narrow and at a lower energy; PSA attempted fits to several unassigned narrow resonances assuming $J^\pi = 8^+$, all without success. None of the present data show any evidence for an 8^+ level.

The Yale group[21] make a tentative claim for an 8^+ at $E_x = 22.5$ MeV ($E_\alpha = 20.4$ MeV) but their ^{12}C(^{12}C,^{8}Be)^{16}O(α_0)^{12}C angular correlation data are not well fit so the 8^+ assignment is not convincing. The alleged level is ~ 0.5 MeV above the upper end of the present data; but if it were of the large reduced width characteristic of the $K^\pi = 0^+$ rotational band to which the Yale group assign it, the low energy tail would certainly have been noticeable in my phase shift fits and hence required $L_{max} = 8$ instead of the observed $L_{max} = 7$. Furthermore, the ^{12}C(α,α_0)^{12}C data of Morgan and Hobbie[7] preclude the possibility of any strong 8^+ alpha cluster state at this E_x. In particular, it should show strongly in Fig. 1 and 2 of Ref. 7 at some of the angles where $P_8 \neq 0$, namely $\theta = 94.8°$, $129.8°$, $152.5°$, $156.7°$.

Recently Robson[52] cites evidence that ^{16}O behaves like a tetrahedral rotor with level sequence 0^+, 3^-, 4^+, 6^+, 7^-, 8^+ corresponding to 0^+ (g.s.), 3^-(6.13), 4^+(10.35), and 6^+(16.27 MeV). When he includes higher order rotation-vibrations corrections, he predicts the 7^- and 8^+ at $E_x = 21.19$ and 29.18 MeV, respectively; one may identify the strong broad 7^- state at $E_x = 20.856$ MeV with the former. (Incidentally, this 7^- is the *only* strong broad 7^- state known in ^{16}O.) Thus to locate the 8^+, one needs much higher excitation data ($E_x \approx 29$ MeV). Two data sets are relevant: (1) The old ^{12}C(α,α_0) study by Morgan and Hobbie[7] whose 8 angles give only marginal coverage. However, at $\theta = 94.8°$ they show a broad (~ 1000 keV) rise centered at $E_\alpha \approx E_x = 29.5$ MeV that vanishes at $\theta = 141.9°$, $144.9°$, and $165.7°$ (near zeros of P_8). (2) The ^{12}C(α,^{8}Be)^{8}Be data of Brochard *et al.*[56] whose $l = 8$ partial wave cross section shows two broad peaks at $E_x = 27.5$ and $E_x = 30$ MeV. Also, their (α,α_0) monitor data at $\theta = 172°$ show two broad peaks at $E_x \approx 28.3$ and $E_x \approx 29$ MeV. The mystery of the missing 8^+ may be at an end.

ACKNOWLEDGMENTS

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