Resonances in the low-energy $^{13}C+^{13}C$ spectrum

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Complete angular distributions are presented ($\theta_{c.m.}=9°-90°$) for the reaction $^{13}C(^{13}C,\alpha)^{22}Ne$ in the energy range $E_{c.m.}=6.25-9.125$ MeV. The data exhibit significant nonstatistical behavior and have been fitted to a linear Legendre polynomial sum using a least-squares procedure. A second procedure makes a grid search to find a best fit to an amplitude squared equation. The correlations with structures in other C+C systems are discussed.

I. INTRODUCTION

The presence of nonstatistical resonances in the $^{12}C+^{12}C$ system has been well established for a number of years.[1] However, until recently little work has been done to probe the effect of valence nucleons on these phenomena. This inadequacy must be remedied as a number of theoretical interpretations depend on the α particle nature of the nuclei involved in these reactions to account for their systematic behavior.[2,3] One would naively expect that the large increase in the density of compound nuclear states in the intermediate nucleus, as more and more nucleons are added to the $^{12}C+^{12}C$ system, would drain away the strength of a given resonance.[4] Thus, no interesting structure would appear in the $^{12}C+^{13}C$ or $^{13}C+^{13}C$ systems. However, studies of the $^{13}C+^{12}C$ system (the one valence nucleon case) show clear signs of nonstatistical structure in the α channel and in fusion experiments, but the detailed systematics of the reaction mechanism remain unknown.[5,6] It has even been suggested that the $^{12}C+^{13}C$ system is not fundamentally different from the $^{12}C+^{12}C$ system.[6] Fusion studies of the $^{13}C+^{13}C$ system (a two valence neutron case) do not display the oscillatory behavior found in the $^{12}C+^{12}C$ system, but an extensive investigation of the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction that we performed shows significant nonstatistical behavior.[7,8] The seemingly contradictory conclusions of the fusion experiments and our reaction studies can be resolved by realizing that a resonance in this system must compete with many more alternative configurations than in the $^{12}C+^{12}C$ system (the density of states is about three orders of magnitude higher) so that a single resonance may be lost in a sea of compound states. In fusion experiments one is essentially summing over this multitude of alternative states, but a single exit channel could still exhibit that resonance as long as the strength of the background is reduced by the same amount as the resonant cross section. We have chosen the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction because its large, positive Q value (11.851 MeV) makes it readily distinguishable from other light-particle-producing reactions on ^{13}C and on a ^{12}C impurity and also tends toward matching incoming and outgoing angular momenta.

Other data on the $^{13}C+^{13}C$ system include elastic scattering and transfer experiments that provide evidence of nuclear orbital effects.[9] Reaction studies of the $^{12}C+^{14}C$ system (which passes through the same intermediate nucleus) collected data that are consistent with the statistical model,[10,11] but the data set is somewhat scanty, and inelastic scattering and transfer data are not in agreement with those conclusions.[12]

In this paper we present detailed angular distributions for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction in the range $E_{c.m.}=6.250-9.125$ MeV—an interval which corresponds to a broad peak in the angle-integrated cross section for the transition to the ^{22}Ne ground state and to a correlated peak in the summed deviation function for the transitions to the ^{22}Ne ground state and first two excited states.[7] The partial waves contributing to the reaction have been decomposed using two fitting techniques: a least-squares fit to a linear sum of Legendre polynomials and a grid-search method to fit the data to an amplitude-squared equation. Both methods are discussed in Ref. 8. The statistical analysis of Ref. 7 is discussed whenever it is relevant to the data in this energy range, and new calculations are presented. Finally, we compare the systematics of the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction with other C + C systems in this energy region.

II. EXPERIMENTAL DETAILS

Data for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction were collected using two position-sensitive slice detectors designed and built by Zurmühle and Csihas[13] and a ^{13}C beam from the University of Pennsylvania tandem Van de Graaff accelerator striking 20 $\mu g/cm^2$ self-supporting ^{13}C targets. Nickel foils in front of each slice detector stopped ions heavier than the α's, thus reducing the radiation damage to the detectors and lowering the rate of pileup events. The beam lost about 50 keV (in the center-of-mass system) in the target. Angular distributions ranging from $\theta_{c.m.}=9°-90°$ (and containing data at 141 angles) were each measured in six to eight hours. The angular resolution was about 0.6° in the center-of-mass system. Two solid-state detectors were placed at $\pm 10°$ to monitor the elastic scattering of the beam. Only the first few states in ^{22}Ne were resolvable, because at excitation energies greater than 4.65 MeV impurity peaks from the $^{12}C(^{13}C,\alpha)^{21}Ne$ reaction dominated the spectrum. Differential cross sections were extracted for the 0^+ ground, 2^+ (1.275 MeV), and 4^+ (3.357 MeV) states. The energy range covered was $E_{c.m.}=6.250-9.125$ MeV usually in 125 keV steps.

III. THEORY

Several features of the $^{13}C + ^{13}C$ system should be noted. The incoming channel consists of two spin one-half fermions which can couple to a symmetric ($s=1$) or an antisymmetric ($s=0$) part of the wave function. Thus, even though the two particles are identical, both even and odd l values will contribute to the interaction. It has been shown[9] that for the 0^+ final states only the $m=1,s=1$ and $m=0,s=0$ amplitudes are nonzero so that the differential cross section for decay to the ^{22}Ne ground state can be written as

$$\frac{d\sigma}{d\Omega}=\frac{\pi}{2k^2}\left[\left|\sum_l^{\text{even}}(2l+1)^{1/2}S_{l,l}^{0,l,0}Y_l^0(\theta,\phi)\right|^2+\left|\sum_l^{\text{odd}}(2l+1)^{1/2}S_{l,l}^{1,l,0}Y_l^1(\theta,\phi)\right|^2\right], \quad (1)$$

where $S_{l,l}^{S,J,S'}$ refers to the scattering matrix and all other quantities have their standard definitions. Equation (1) can be parametrized so that

$$\frac{d\sigma}{d\Omega}=\left|\sum_l^{\text{even}}c_lY_l^0(\theta,\phi)\right|^2+\left|\sum_l^{\text{odd}}c_lY_l^1(\theta,\phi)\right|^2 . \quad (2)$$

Equation (2) will be used in the grid-search technique discussed below. When integrated over all angles, the total cross section is

$$\sigma_{\text{total}}=\sum_l \sigma_l , \quad (3)$$

where

$$\sigma_l=|c_l|^2 . \quad (4)$$

Thus, a successful fit to Eq. (2) readily yields the partial cross sections for each of the l values involved in the reaction.

An important consideration in the business of heavy-ion resonances is separating the true resonances from a fluctuating background caused by particle emission from a thermally equilibrated (i.e., statistical) compound nucleus. The tests applied to the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction are discussed fully in Ref. 7 and clearly indicate that the majority (about 75%) of the cross section is the result of nonstatistical processes. Reference 7 also noted the existence of correlations among the excitation functions of different states in the residual nucleus. Such correlations are considered an important signature of entrance channel resonances.[14] Significant correlations were found in the summed deviation function of the angle-integrated cross section for the transition to the ground state and first two excited states in ^{22}Ne at center-of-mass energies of 8.0, 9.63, 11.38, and 11.75 MeV. The correlated peak at 8.0 MeV occurs at a maximum in the angle-integrated cross section for the transition to the ^{22}Ne ground state in the middle of the energy range examined in this work (a correlated peak in this work will refer to one of those structures in the summed deviation function in Ref. 7 that exceeded the 3% probability level).

The statistical model has been used to calculate the total cross section for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction and the partial cross sections for each of the l values contributing to the reaction using the computer code STATIS.[15] The total cross section, σ_{HF}, for the ground state and first two excited-state transitions are significantly underpredicted by the Hauser-Feshbach model (by a factor of about 4).[7] The calculated partial cross sections will be compared with those extracted from the data in Sec. IV. The details of the calculations (e.g., parameter sets, exit channels used, etc.) are given in Ref. 7.

IV. ANALYSIS AND RESULTS

The data were fitted first with a linear sum of Legendre polynomials:

$$\frac{d\sigma}{d\Omega}=\sum_{L=0}^{L_{\max}}a_LP_L(\cos\theta) , \quad (5)$$

where L refers to a term in Eq. (5) (not to the angular momentum quantum number, l) and $L_{\max}$ is the last term in the sum. Only even L's are needed as the target and projectile are identical. The largest L value needed to fit the data results in a reduced χ^2 of about unity and is twice the largest l value contributing to the reaction. Recalling that $\sigma_l=|c_l|^2$ and equating Eqs. (2) and (5), one can show that for $l=l_{\max}$ and l even:

$$|c_l|^2=a_{L_{\max}}\frac{4\pi}{2l+1}\frac{1}{(ll00|L_{\max}0)^2},\quad L_{\max}=2l , \quad (6)$$

and similarly for $l=l_{\max}$ and l odd:

$$|c_l|^2=-a_{L_{\max}}\frac{4\pi}{2l+1}\frac{1}{(ll1-1|L_{\max}0)(ll00|L_{\max}0)} ,\quad L_{\max}=2l . \quad (7)$$

The partial cross section for the largest l value contributing to the reaction can be extracted unambiguously from the linear fit coefficients. Unfortunately, the amplitudes and phases for the other l values contributing to the reaction cannot be so easily obtained since there are more unknowns than equations [compare Eqs. (2) and (5)].

Good fits were obtained at all energies using the linear Legendre polynomial fitting method ($\chi^2/\nu\approx1$, where ν is the number of degrees of freedom in the fitting procedure) and the magnitude of the amplitude of the largest l value involved in the reaction at each energy was extracted using Eqs. (6) and (7). The partial cross sections for $l_{\max}$ are displayed in Fig. 1. The value of $l_{\max}$ changes rapidly with energy and in no case does $\sigma_{l_{\max}}$ make up a significant fraction of σ_{total}. This unruliness is not surprising when one realizes that the Coulomb barrier is at $E_{c.m.}\approx6.4$ MeV, and $l_{\max}$ rises quickly from roughly zero at that energy to $l_{\text{grazing}}\approx7$ at 9.125 MeV.

The paucity of information on the behavior of the partial waves contributing to the reaction from the linear Legendre polynomial fits, strongly motivates the application of the amplitude-squared fitting technique. The problem is that while the physics is readily transparent, it

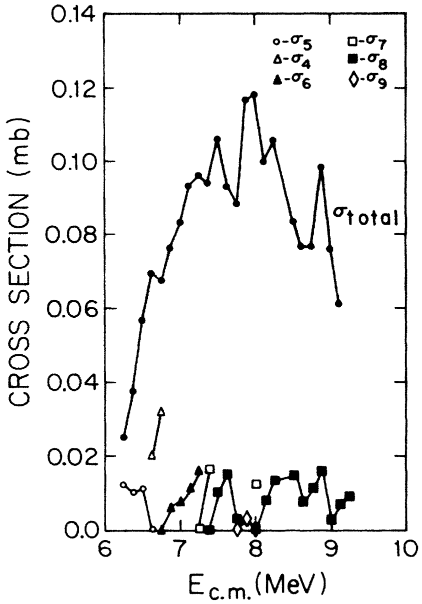

FIG. 1. Partial cross sections for l_{max} as a function of energy extracted from the linear Legendre polynomial fits.

is computationally laborious; and, more importantly, there exists ambiguities in the fit parameters—for a particular angular distribution there exists a unique set of a_L's [a solution to Eq. (5)], but there is more than one set of c_l's [a solution to Eq. (2)] that will give an equivalent fit. However, implicit in this statement is that all l values up to and including l_{max} participate in the reaction. If only a few l values contribute to the cross section then there is still hope that the differential cross section will yield enough information to support a unique solution to Eq. (2). That hope is well founded in some instances. The general nature of these reactions in other systems suggests

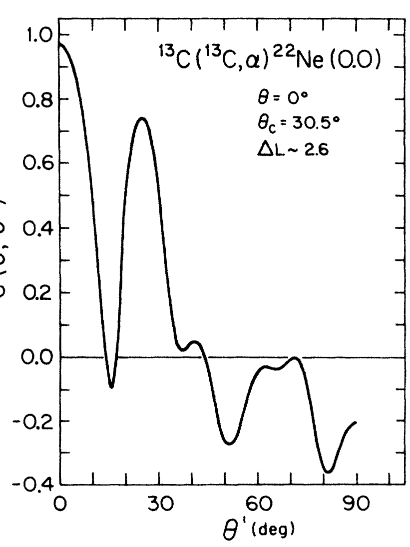

FIG. 2. Angular cross-correlation function for the ^{22}Ne 0^+ ground state.

the existence of an l window around the grazing l value such that only the angular momenta in the window contribute. If an l value is too high there is insufficient overlap between the ions for the reaction to proceed—if the l value is too low it is absorbed into the intermediate nucleus. If the latter possibility occurs the cross section will be close to the statistical-model prediction and will make up only a small fraction of σ_{total} (recall that $\sigma_{total}/\sigma_{HF} \approx 4$).

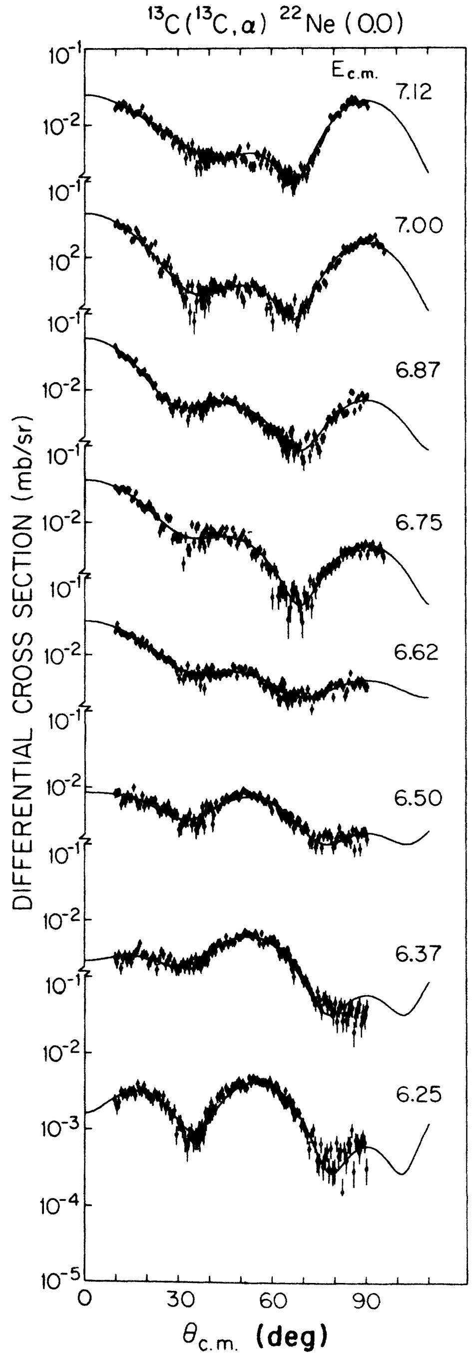

FIG. 3. Angular distributions for ^{13}C(^{13}C,α)^{22}Ne in the range $E_{c.m.} = 6.250$–7.125 MeV. The curves are best fits to Eq. (2) obtained using the grid search technique discussed in the text.

The width of the l value distribution can be measured by using the angular cross-correlation function defined by

$$C(\theta,\theta')=\frac{\langle\sigma(E,\theta)\sigma(E,\theta')\rangle}{\langle\sigma(E,\theta)\rangle\langle\sigma(E,\theta')\rangle}-1\ , \tag{8}$$

where $\sigma(E,\theta)$ is the differential cross section at an energy E and center-of-mass angle θ. The angular cross-correlation function for the transition to the ^{22}Ne ground state is shown in Fig. 2. The function $C(\theta,\theta')$ was calculated using the linear Legendre polynomial fits to the angular distributions. The coherence angle, θ_c, is that angle at which $C(\theta,\theta')$ drops to half its maximum value and does not rise to that level again. The coherence angle determines the separation needed to have statistically independent single-angle excitation functions. This quantity has traditionally been calculated using the "black nucleus" approximation in which the transmission coefficients are unity (complete absorption) until the grazing l value is reached ($l_{\text{grazing}}\approx kR$ where k is the wave number and R is the nuclear radius), above which they are zero. This as-

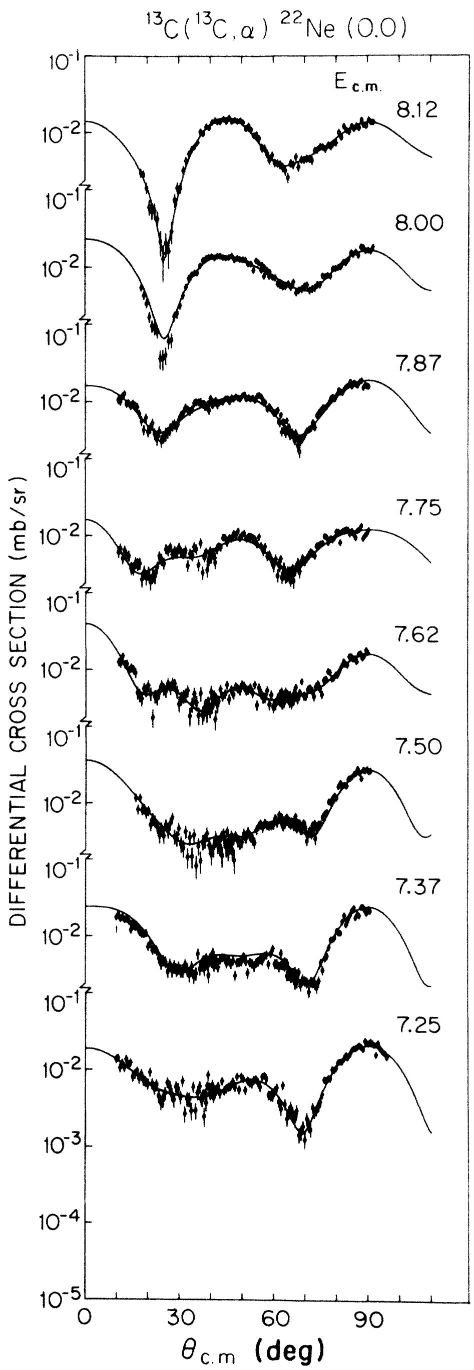

FIG. 4. Same as Fig. 3 for the range $E_{\text{c.m.}}=7.250-8.125$ MeV.

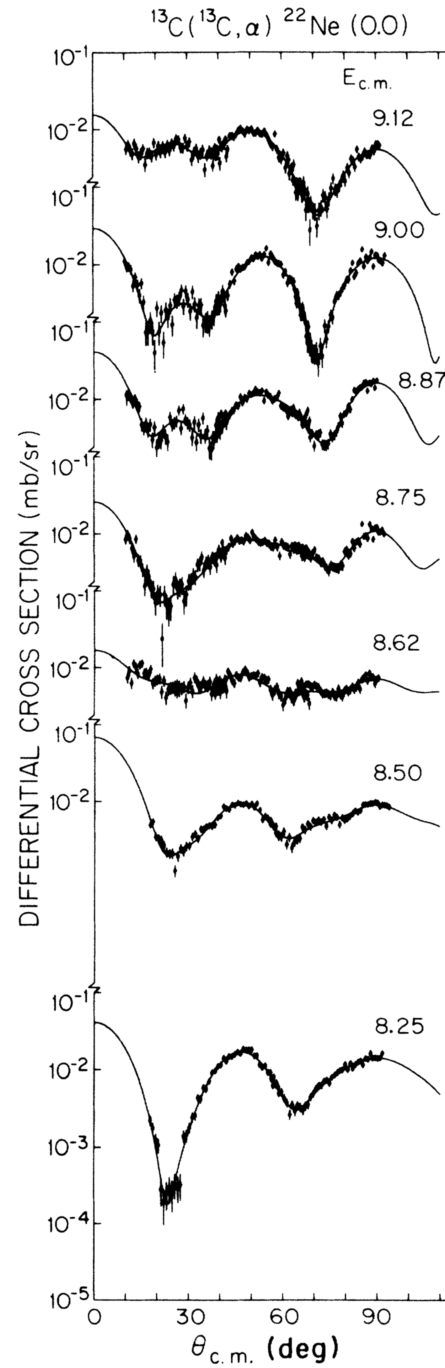

FIG. 5. Same as Fig. 3 for the range $E_{\text{c.m.}}=8.250-9.125$ MeV.

TABLE I. Fit parameters obtained by finding a best fit to Eq. (2) using the grid-search method described in the text.

l value	Amplitudes	Phases
	6.25 MeV $\chi^2/\nu=1.2$	
0	0.0853	180.0
1	0.0691	225.5
4	0.0733	0.0
5	0.109	0.0
	6.375 MeV $\chi^2/\nu=2.1$	
0	0.137	169.2
2	0.0206	81.5
4	0.0846	0.0
5	0.100	0.0
	6.500 MeV $\chi^2/\nu=1.4$	
0	0.145	185.0
2	0.107	80.0
4	0.114	0.0
5	0.105	0.0
	6.625 MeV $\chi^2/\nu=1.3$	
0	0.0879	183.0
2	0.205	85.0
4	0.141	0.0
	6.750 MeV $\chi^2/\nu=1.9$	
0	0.0437	116.2
2	0.177	92.1
4	0.178	0.0
	6.875 MeV $\chi^2/\nu=1.7$	
0	0.139	100.0
2	0.205	20.0
4	0.094	287.5
6	0.078	0.0
	7.000 MeV $\chi^2/\nu=1.9$	
0	0.068	72.5
2	0.250	340.0
4	0.092	214.5
6	0.0863	0.0
	7.125 MeV $\chi^2/\nu=1.7$	
0	0.0156	101.0
2	0.259	308.0
4	0.122	176.5
6	0.106	0.0
	7.250 MeV $\chi^2/\nu=1.8$	
0	0.041	22.0
2	0.238	312.5
4	0.148	159.5
6	0.126	0.0
	7.375 MeV $\chi^2/\nu=1.5$	
0	0.022	189.0
2	0.192	313.5
4	0.127	164.5
6	0.150	0.0
7	0.132	0.0
	7.500 MeV $\chi^2/\nu=2.0$	
0	0.0308	136.0
2	0.239	270.5
4	0.161	40.5
6	0.111	227.0
8	0.101	0.0
	7.625 MeV $\chi^2/\nu=1.$[illegible]	
0	0.0741	196.0
2	0.203	282.5
4	0.131	84.5
6	0.0922	271.0
8	0.123	0.0
	7.750 MeV $\chi^2/\nu=1.8$	
0	0.0853	52.0
2	0.225	298.5
4	0.141	156.5
6	0.0934	25.0
8	0.057	0.0
	7.875 MeV $\chi^2/\nu=1.9$	
0	0.150	23.0
2	0.215	305.6
4	0.200	121.5
6	0.0861	2.0
9	0.055	0.0
	8.000 MeV $\chi^2/\nu=1.8$	
0	0.109	357.0
2	0.155	256.0
4	0.253	92.0
6	0.0955	0.0
7	0.110	0.0
	8.125 MeV $\chi^2/\nu=1.1$	
0	0.0166	112.0
2	0.172	40.0
4	0.249	261.0
6	0.0473	155.0
8	0.090	0.0
	8.250 MeV $\chi^2/\nu=1.3$	
0	0.035	92.0
2	0.215	36.0
4	0.219	251.0
6	0.053	73.0
8	0.116	0.0
	8.500 MeV $\chi^2/\nu=1.3$	
0	0.0294	329.0
2	0.203	9.0
4	0.110	239.0
6	0.134	79.0
8	0.121	0.0
	8.625 MeV $\chi^2/\nu=1.6$	
0	0.0152	268.0
2	0.168	348.0
4	0.170	243.0

TABLE I. (*Continued*).

l value	Amplitudes	Phases	l value	Amplitudes	Phases
6	0.103	101.0			
8	0.0874	0.0			
	8.750 MeV $\chi^2/\nu=1.4$			9.000 MeV $\chi^2/\nu=1.7$	
0	0.0208	36.0	0	0.0295	336.0
2	0.147	20.0	2	0.083	16.0
4	0.153	259.0	4	0.194	199.0
6	0.147	105.0	6	0.177	335.0
8	0.106	0.0	8	0.049	0.0
	8.875 MeV $\chi^2/\nu=1.6$			9.125 MeV $\chi^2/\nu=1.4$	
0	0.0433	328.0	0	0.0326	56.0
2	0.113	12.0	2	0.019	352.0
4	0.191	259.0	4	0.167	171.0
6	0.177	89.0	6	0.154	285.0
8	0.127	0.0	8	0.0851	0.0

sumption fails miserably for heavy ions due to the l window which allows angular momenta below the grazing one to participate. It has been shown[16] that the large second maximum in Fig. 2 is indicative of a narrow l value distribution and the FWHM (Δl) of the distribution of partial cross sections for each l value is related to the coherence angle by

$$\Delta l \approx \frac{1.4}{\theta_c} . \quad (9)$$

The coherence angle for the transition to the ^{22}Ne ground state is 30.5°, implying $\Delta l = 2.6$. This narrow distribution indicates that only a few l values contribute to the cross section—supporting the use of only a few l values to fit the differential cross section.

To further ensure the uniqueness of the amplitude-squared fits, additional physical constraints can be invoked. The amplitude for the maximum l value at each energy is fixed at the value extracted from the linear Legendre polynomial fits. The partial cross sections are expected to have a "smooth" behavior from one energy to the next (the method of incorporating this constraint into the procedure is described below). Finally, several tests are applied to the fit parameters: (1) the quality of the fit must be very good, (2) the fit parameters must reproduce the experimentally determined angle-integrated cross section [see Eqs. (3) and (4)], and (3) any a_L's calculated from the c_l's must match the measured ones.

The grid-search technique is as follows: the amplitude for the largest l value is extracted from the linear Legendre polynomial fit and is fixed in the program which then searches over the appropriate amplitudes and phases of up to four other l values. Once a good fit is obtained for an angular distribution at one energy the fit parameters are varied slowly from one distribution to the next to ensure that the fits are consistent over a broad energy range (keeping the amplitude of the largest l value fixed at the value extracted from the linear Legendre polynomial fit). The combination of l values is changed only when it is clear that a particular l value no longer makes a significant contribution to the reaction and the poor fit quality indicates that a different l value is needed.

The fits to the differential cross sections are displayed in Figs. 3–5 along with the data. The quality of these fits is in general superb, with the reduced χ^2 at most energies close to that of the linear Legendre polynomial technique. The fit parameters satisfied the various criteria for a successful fit to the data mentioned above. The angle-integrated cross section calculated with the c_l's matches the data [see Fig. 6(f)] and the second-to-last coefficient of the linear Legendre polynomial fit is consistent with that calculated from the grid-search parameters (the calculation of lower-order terms in the linear Legendre polynomial fit is dominated by the uncertainties). The grid-search fit parameters are displayed in Table I.

The partial cross sections for each l value are plotted in Figs. 6 and 7. The uncertainty in each σ_l is twice the change in c_l that causes the reduced χ^2 to change by unity except where $l = l_{\max}$. If $l = l_{\max}$ then the uncertainty is the value associated with the linear Legendre polynomial fit. The $l=0$ contribution is small except near the Coulomb barrier, while most of the cross section appears in the $l=2$ and $l=4$ channels. The $l=2$ cross sections show a broad peak centered at about 7.5 MeV that is fragmented into narrower structures. The $l=4$ cross sections show a similar behavior, but there is a very strong peak at 8.0 MeV at which the angular distribution resembles a $|Y_4^0(\theta,\phi)|^2$, but the positions of the minima are distorted by the presence of other l values. This energy corresponds to a peak in the angle-integrated cross section for the transition to the ^{22}Ne ground state and a maximum in the summed deviation function that is correlated with peaks in the angle-integrated excitation functions of the 1.275-MeV and 3.357-MeV states in ^{22}Ne. The cross sections for $l=6$ and $l=8$ do not show any strong resonant character and do not dominate σ_{total} as do the $l=4$ and $l=2$ partial cross sections.

The results for the odd l values are shown in Fig. 7.

Surprisingly, there is little strength in any of these l values. In fact, the average cross sections for the odd l values are comparable in size to those predicted by the Hauser-Feshbach calculations discussed in Sec. III. Note also that the "background" is not constant as the standard view of these interactions would lead one to suspect—it varies considerably. The angular distributions at the minima of the angle-integrated excitation functions for the transition to the ^{22}Ne ground state change significantly from one minimum to the next. The cross section is made up of many overlapping l values, none of whose amplitudes are constant over any sizable energy range.

The relative phases of the various l values used in the fits are also listed in Table I. A resonance is a pole in the S matrix for a given l value and in the case of an isolated resonance sitting atop a constant or slowly varying background the phase has a well understood behavior. When the energy region consists of many overlapping levels (as it is here) the situation becomes chaotic. Since amplitudes for most of the l values are varying, the relative phases show no consistent behavior and it is difficult to extract any useful information. All of the features of this data set (the lack of strength in the odd l values, the rapidly varying background, and the erratic behavior of the relative phases) are consistent with the systematics of this reaction at higher energies.[8]

As discussed in the Introduction, the prime motivating factor in examining the $^{13}C + {}^{13}C$ system is the presence

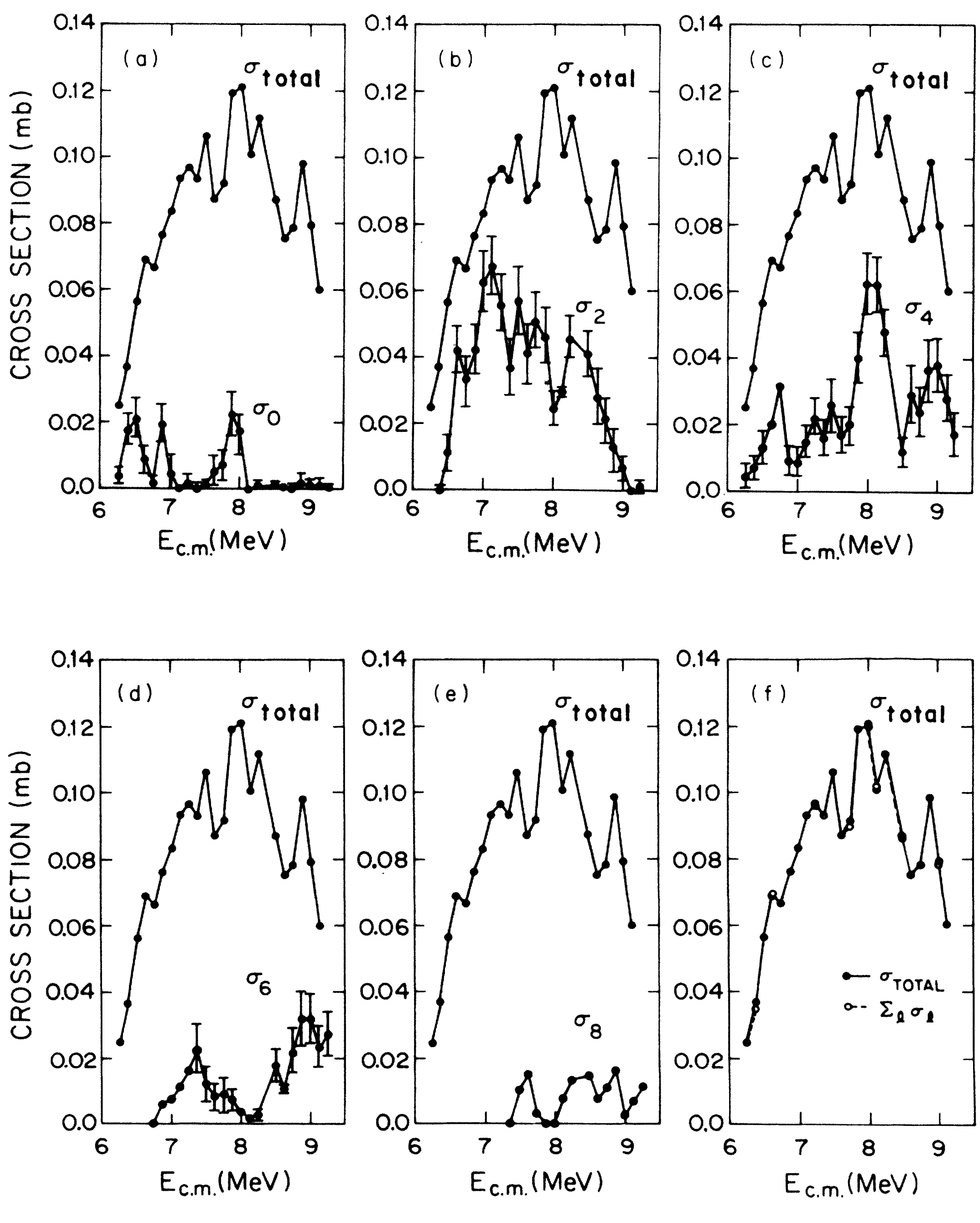

FIG. 6. Partial cross sections for the even l values extracted with the grid search technique. The calculation of the uncertainties in the σ_l's is described in the text. (f) compares the measured total cross section for the transition to the ^{22}Ne ground state with the total cross section calculated from the amplitude-squared fit results.

of resonant structure in the $^{12}C+{}^{12}C$ and $^{12}C+{}^{13}C$ systems. A detailed comparison will now be made between all of the prominent levels in ^{26}Mg identified in this work and resonances identified in other C + C systems. The evidence for or against the identification of these prominent peaks in the partial cross section excitation functions as resonances will also be summarized.

At 8.0 MeV an $l=4$ resonance exists that coincides with a maximum in the angle-integrated cross section for the transition to the ^{22}Ne ground state and a correlated maximum in the summed deviation function for this state and the first two excited states. In a strikingly similar fashion a well-known quasimolecular resonance was identified by Erb *et al.* at $E_{c.m.}=7.71$ MeV in the $^{12}C(^{12}C,\alpha)^{22}Ne$ reaction.[17] The $^{12}C+{}^{12}C$ state corresponds to a maximum in the angle-integrated ground-state cross section and is correlated with peaks in the excited-state excitation functions. In addition, these workers found that the total cross section at the resonant energy exceeded the statistical-model prediction by a factor of 28 (they assumed that all the cross section came from the $l=4$ resonance). In the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction at 8.00 MeV the partial cross section for $l=4$ exceeds the Hauser-Feshbach prediction by a factor of 23. The state in $^{13}C+{}^{13}C$ is wider than in the $^{12}C+{}^{12}C$ system (420 keV vs 250 keV), but a difference is not unexpected since the greater number of states in the $^{13}C+{}^{13}C$ system could readily increase the width. The real surprise is that the system is resonating so strongly and only weakly coupling to the hundreds of compound nucleus states open to it. In

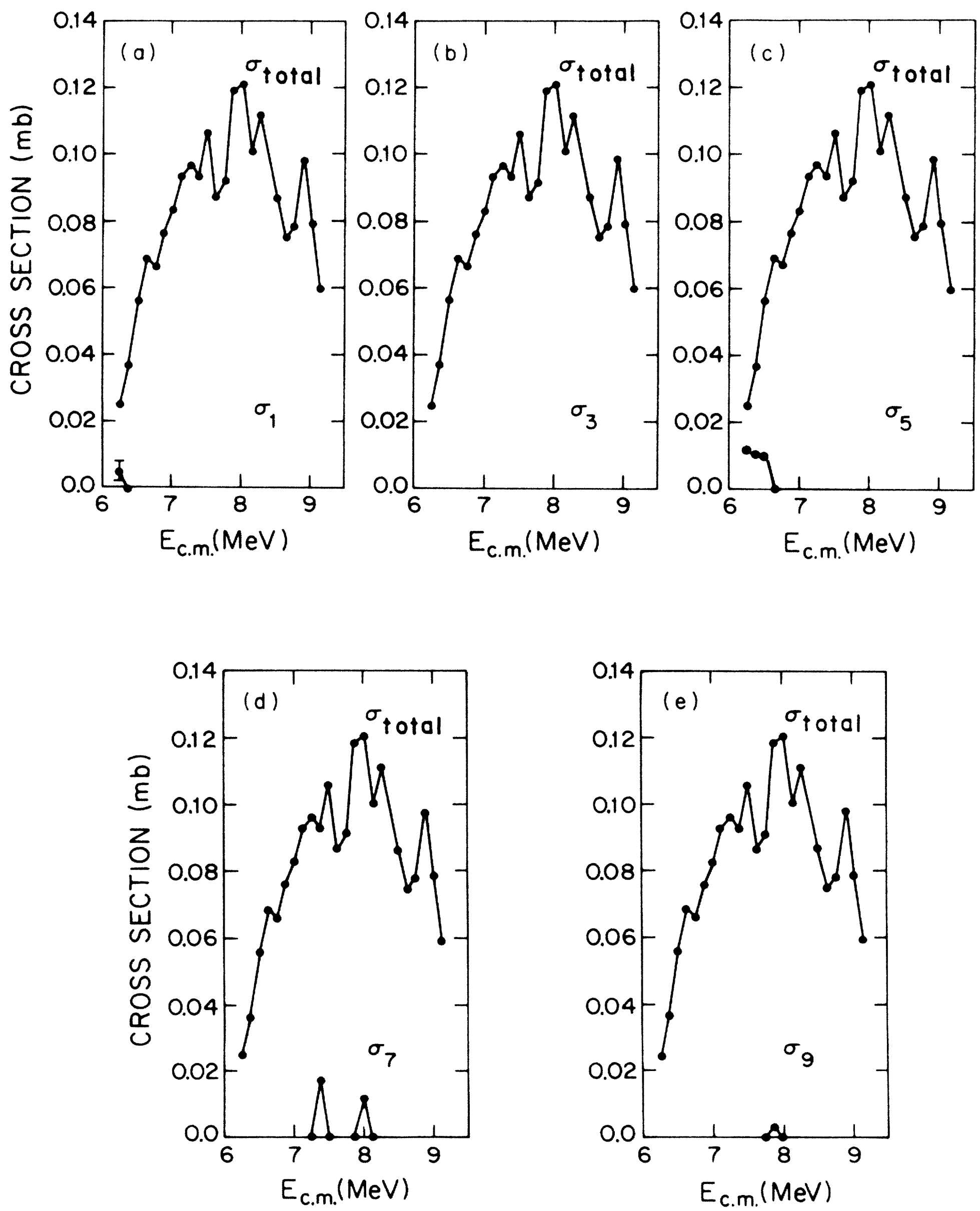

FIG. 7. Partial cross sections for the odd l values extracted with the grid search technique. The calculation of the uncertainties in the σ_l's is described in the text.

the $^{12}C(^{13}C,\alpha)^{21}Ne$ reaction at $E_{c.m.}=7.8$ MeV there exists a distinct peak in the excitation function for all states whose excitation energy is less than 5 MeV.[5] No l value was assigned to this structure, but it is tempting to believe that it could be an $l=4$ resonance of parentage similar to that of the structures observed in the other two systems. Correlated structures are seen in $^{12}C(^{14}C,\alpha)^{22}Ne$ at nearby energies (7.2 and 8.3 MeV), but no l values were assigned and these workers collected data at only a few angles.[10] The 8.0-MeV resonance seen in σ_4 in the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction is the strongest candidate for a quasimolecular state in this energy range.

In addition to the 4^+ resonance at 8.0 MeV there are a number of other notable enhancements. Large partial cross sections exist for $l=2$ at 7.125 and 8.375 MeV (not correlated peaks in the summed deviation function). These peaks do, however, exceed the Hauser-Feshbach calculations by factors of 39 and 33, respectively. The $^{12}C(^{12}C,\alpha)^{22}Ne$ reaction shows no strong peak in the 7.125 MeV region in the ground-state angle-integrated excitation function, but there is a correlated structure at about 8.3 MeV.[17] The differential cross section here is clearly dominated by only a few l values (it is highly oscillatory) and does resemble the angular distributions of the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction. Both have the same number of minima, namely two. This number is consistent with an $l=2$ resonance since the deep minimum of a $Y_2^0(\theta,\phi)$ occurs around 45° where even a small contribution from the other l values will fill in this minimum. The angular distribution thus does not resemble a pure $l=2$, which is probably why Erb *et al.* did not consider this structure significant. There are peaks in the $^{12}C(^{13}C,\alpha)^{22}Ne$ reaction at 7.2 and 8.3 MeV, but again no l values were assigned.

V. CONCLUSION

The $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction has been extensively studied in the energy range $E_{c.m.}=6.25$—9.25 MeV and found to have a rich nonstatistical spectrum consistent with previous work in other systems. The system consists of several prominent states among many broad, overlapping levels in ^{26}Mg with the 4^+ resonance at 8.0 MeV being the strongest. The $l=2$ partial wave also displays resonant character at 7.125 and 8.375 MeV. The average partial cross sections for the odd l values agree with the statistical model expectation, while the average partial cross section for the even l values is considerably larger than the prediction of that model. The correlation with structures in other C + C systems is striking—especially the 8.0-MeV 4^+ resonance. The 8.375-MeV 2^+ enhancement is also correlated with a structure seen in $^{12}C(^{12}C,\alpha)^{22}Ne$. The lack of l value assignments in similar systems, such as $^{12}C+^{14}C$ and $^{12}C+^{13}C$, points to the need for more thorough investigations of systems with valence nucleons to understand their influence on this heavy-ion phenomenon.

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