Resonances in the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction for $E_{c.m.}=10.3-13.4$ MeV

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Complete angular distributions ($\theta_{c.m.}=9°-90°$) have been measured for the reaction $^{13}C(^{13}C,\alpha)^{22}Ne$ in the energy range $E_{c.m.}=10.38-13.38$ MeV. The data exhibit significant nonstatistical behavior and have been fitted to a linear sum of Legendre polynomials using a least-squares procedure. An 11^- resonance is identified at $E_x(^{26}Mg)=34.21$ MeV and a possible 10^+ at $E_x(^{26}Mg)=33.71$ MeV.

I. INTRODUCTION

The discovery of resonances in light heavy-ion (HI) systems led to a considerable effort, both experimental and theoretical, into the study of these phenomena.[1-4] One naively expects that under the conditions of temperature and density nuclei are subjected to in heavy-ion reactions, the many-body features of the compound nucleus would dominate the interaction, and produce relatively unstructured spectra. Instead a rich array of oscillations in the excitation functions for a number of reactions is seen by researchers. Typically, these oscillations are of two kinds: broad, gross structure peaks with widths in the several MeV range and intermediate structures with widths of the order of hundreds of keV. A classic example of this phenomenon is the $^{12}C+^{12}C$ system which exhibits a number of resonances that have been identified as quasimolecular states in ^{24}Mg (the compound nucleus formed in the entrance channel).[1]

The gross structure associated with light heavy-ion systems can be related to the nature of the optical-model potentials that are used to fit the elastic scattering. For most light, HI systems, the potentials are surface transparent. The deep interior of the nucleus is black and any particle penetrating to this region forms a thermally equilibrated compound nucleus. Near the periphery of each fragment, though, the ions can interact without fusing (the density of high-spin states that couple to the incoming channel at these excitations energies is low). This surface transparency is responsible for the presence of an l window, a region of low absorption lying between the yrast line and an area of strong absorption at higher excitation energy in the compound nucleus. Most of the resonances experimenters have found lie in this l window.

The narrow intermediate width structures are not so amenable to our understanding. A variety of schemes have been proposed by theorists to explain various sets of data, but no single prescription has been successful in describing a significant fraction of the data. The common starting point for most of these theories is the doorway state mechanism.[5] A simple eigenstate of some angular momentum J is fragmented by a weak residual interaction that spreads the incoming flux over a set of more complex states. The choice of these more complex configurations that couple to the doorway state is a critical component of such theories. Some of the most spectacular resonances exist in systems in which the ions consist of an integral number of α particles. Michaud and Vogt attributed the intermediate structure in the $^{12}C+^{12}C$ system to special configurations of ^{24}Mg consisting of a ^{12}C core and three α particles.[6] Others have classified systems of α nuclei from $^{12}C+^{12}C$ to $^{16}O+^{28}Si$ in an attempt to explain the features of heavy-ion reactions in these systems as excitations of α particles.[7]

If the residual interaction does couple the incoming channel to α particle excitations of the ions, then one expects the addition of valence nucleons would disrupt this pattern as the α-particle substructure disappears. However, a rich spectrum of resonance phenomena has been observed in C+C systems which have one or more valence neutrons added to the $^{12}C+^{12}C$ system. The $^{12}C(^{13}C,\alpha)^{21}Ne$ reaction (the one valence neutron case) displayed some evidence of intermediate resonant structure at a number of energies,[8] and a fusion study of this system found it to be fundamentally similar to the $^{12}C+^{12}C$ system.[9] Investigations of the $^{12}C+^{14}C$ system (a two valence neutron case) have produced contradictory results,[10-12] but a study by Konnerth *et al.*[13] found strong evidence of intermediate structure. The gross structure of the elastic and inelastic scattering of the $^{13}C+^{13}C$ system (a two valence nucleon system and with no α nuclei) is consistent with the two carbon nuclear orbiting around one another,[14] and a global study of the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction by us uncovered extensive intermediate structure.[15-17] Fusion studies did not reveal resonant structure, but nevertheless the data were fitted with a surface transparent optical potential similar to that of other resonant systems.[18] The $^{14}C+^{14}C$ elastic, inelastic, and transfer channels were also measured by Konnerth *et al.*, who observed gross structure similar to that in $^{16}O+^{16}O$ (a resonating system) in the 90° elastic scattering excitation function.[13] The weight of evidence is tilting against the α-particle degrees of freedom as the dominant source of intermediate structure. Further evidence from the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction will be presented in the following which supports that conclusion.

We have chosen to study the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction for several reasons. The density of states in the $^{13}C+^{13}C$

system is about three orders of magnitude greater than in the $^{12}C+^{12}C$ system, so one might expect any interesting structure to be smeared out over many compound nuclear states. However, if one examines a single exit channel, namely the α channel, as long as the strength of the background amplitude is drained away by these other states, as much as the strength of the resonant states, one can still observe the resonances. In addition, this exit channel has a large, positive Q value (11.851 MeV), making 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.

In this paper we extend the range of our previous measurements and present detailed angular distributions for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction in the range $E_{c.m.}=10.38-13.38$ MeV. These data cover the angular range $\theta_{c.m.}=9°-90°$. The missing forward-angle data do not contribute significantly to the total cross section. A comparison between the angle-integrated differential cross section and the total cross section extracted from the linear Legendre polynomial fit (see the following) showed no significant differences.

A statistical analysis of the data has been performed[15] over the energy range $E_{c.m.}=6.25-13.38$ MeV, and the results of that work relevant to the present discussion will be summarized. Some of the partial waves contributing to the reaction have been extracted by fitting the differential cross section of the transition to the ^{22}Ne ground state with a linear sum of Legendre polynomials. The positions of resonances in the maximum l value are then used to calculate the moment of inertia of the parent compound nucleus giving rise to these states. Finally, a calculation is made of the l window in the ^{26}Mg intermediate nucleus and compared with our results.

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[19] and a ^{13}C beam from the University of Pennsylvania tandem Van der 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 $E_{c.m.}=10.38-13.38$ MeV, usually in 125 keV steps.

II. ANALYSIS AND RESULTS

The identification of heavy-ion resonances is hindered by Ericson fluctuations arising from the formation of a thermally equilibrated compound nucleus. A number of criteria exist that can be used for this task. We have performed a statistical analysis of the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction over a broad range (from $E_{c.m.}=6.25$ to 13.38 MeV) for the transitions to the ground and first two excited states in ^{22}Ne, and have presented that work elsewhere.[15] In the following we will quote the results relevant to the identification of resonant states in this energy region.

The simplest test for resonances is to locate peaks in the angle-integrated excitation function for the transition to a particular state. It is worth noting that single-angle excitation functions are inadequate for this purpose, since interference of the resonant amplitudes with a nonresonant background can cause rapid fluctuations in the excitation function that do not exist in the angle-integrated cross section. Gay *et al.*[20] calculated synthetic excitation functions using the statistical model that were qualitatively similar to resonant data. Figure 1 displays the angle-integrated excitation functions for transitions to the ground state and first two excited states in ^{22}Ne. Each transition shows several peaks that are possible resonance candidates, but peaks alone do not establish resonant character. Statistical tests can establish with varying degrees of precision the nonstatistical component of a given data set. The autocorrelation function and the distribution of cross sections about their average are means to this end. Our previous results imply that a large ($\approx 90\%$) fraction of the cross section to the ground state is from a nonstatistical mechanism.[15] The same calculations for the excited-state transitions are consistent

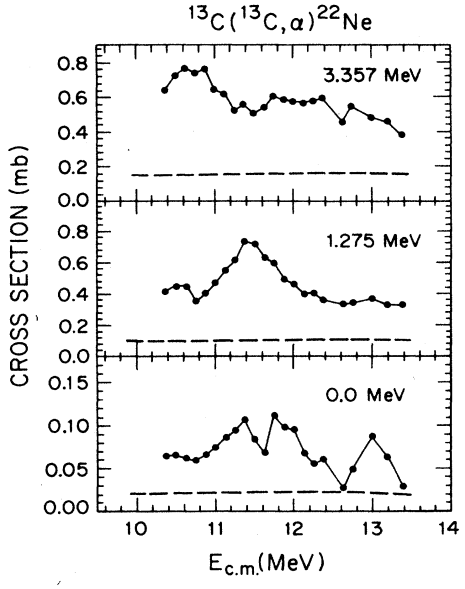

FIG. 1. Excitation functions of the angle-integrated cross sections for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction leading to the ground state and first two excited states. The dashed curves are Hauser-Feshbach calculations for each transition.

with this conclusion, but they suffer from a large ambiguity in calculating the resonant component. The correlation of peaks in the excitation functions for the transitions to a number of different final states is an important signature of the existence of resonances. The summed deviation function can pinpoint the energies in the excitations for several final states that are candidates for the correlated peaks, indicative of quasimolecular resonances. There are two peaks in the summed deviation function at 11.38 MeV and 11.75 MeV (consisting of three energies out of the total of twenty-two being discussed here) whose value exceeds a 3% probability level.[15] These peaks are possible resonances and will be referred to as correlated peaks in the following.

The cross-correlation function provides information about the distribution of l values that are contributing to the reaction over a broad energy range.[21] Our previous results indicate that, on average, only ≈ 2.5 values of l contribute to the cross section at any particular energy.[15] In addition, the maximum angular momentum involved in the reaction, $l_{\max}$, was found using a linear Legendre polynomial fit to the differential cross section (see the following). The value ranges from $l_{\max}=8$ to $l_{\max}=12$ in this energy range. Only a few of the possible angular momenta are contributing to the reaction—consistent with the existence of a region of surface transparency and an l window.

Hauser-Feshbach (HF) calculations were performed to predict the energy-averaged strength of a particular transition. An enhancement in the data above the calculation can be evidence of the formation of resonances. The computer code STATIS was used to calculate the energy-averaged, angle-integrated cross sections for the transitions to the ground and first two excited states in ^{22}Ne.[22] The details of the calculation are described in Ref. 15. The dashed curve under each excitation function in Fig. 1 represents the statistical-model prediction for that state. The average cross section in this range exceeds the HF prediction by a factor of 3.6 for the transition to the ^{22}Ne ground state, and by factors of 4.2 and 3.7 for the transitions to the first and second excited states, respectively. Thus, most of the cross section arises from a nonstatistical process.

The partial wave decomposition was done by fitting the differential cross section at each energy with a linear sum of Legendre polynomials,

$$\frac{d\sigma}{d\Omega}=\sum_{L=0}^{L_{\max}} a_L P_L(\cos\theta)\ , \tag{1}$$

where L refers to a term in Eq. (1) (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 (χ/ν, where ν is the number of degrees of freedom in the fitting procedure) of about unity and is twice the largest l value contributing to the reaction. The angular distributions and their associated fits are shown in Figs. 2–4 for the transition to the ^{22}Ne ground state. The ground-state distribution more clearly represents the angular momentum of the parent ^{26}Mg because the intrinsic final spins of the α and the ^{22}Ne are both $J=0$, while the excited-state spins of the ^{22}Ne are $J=2$ and $J=4$. The excited states have many magnetic substates that can contribute to the differential cross section and produce relatively unstructured distributions.

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[14] that for the 0^+ final states only the $m=1$, $s=1$ and the $m=0$, $s=0$ amplitudes are nonzero, so the differential cross section for the decay to the ^{22}Ne ground state (or any $s=0$ final state) can be written as

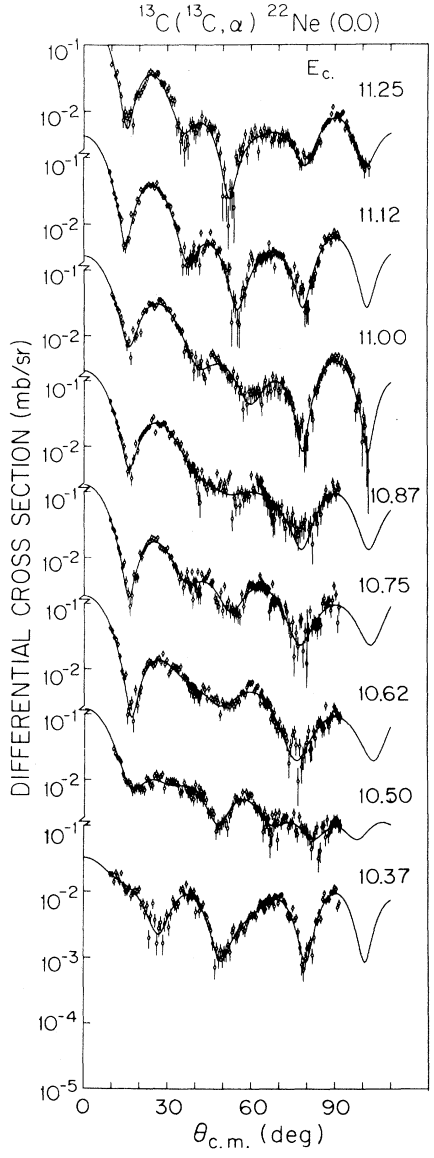

FIG. 2. Angular distribution for ^{13}C(^{13}C,α)^{22}Ne(0.0) in the range $E_{c.m.}=10.37$–11.25 MeV. The curves are linear Legendre polynomial fits to the data.

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

where $S_{l,l}^{S,J,S'}$ refers to the reaction matrix, and all other quantities have their standard definitions. Equation (2) can be parametrized as

$$\frac{d\sigma}{d\Omega}=\left|\sum_{l}^{\text{even}}c_l Y_l^0(\theta,\phi)\right|^2+\left|\sum_{l}^{\text{odd}}c_l Y_l^1(\theta,\phi)\right|^2, \quad (3)$$

where the c_l's are complex. When integrated over all angles, the total cross section is

$$\sigma_{\text{total}}=\sum_l \sigma_l , \quad (4)$$

where

$$\sigma_l=|c_l|^2 . \quad (5)$$

Equating Eqs. (1) and (3), one can show 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

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

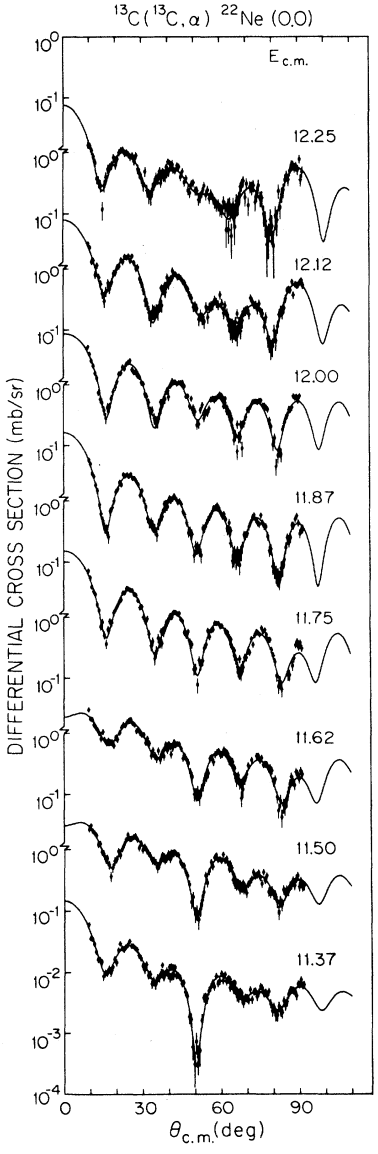

FIG. 3. Same as Fig. 2 for the range $E_{c.m.}=11.37-12.25$ MeV.

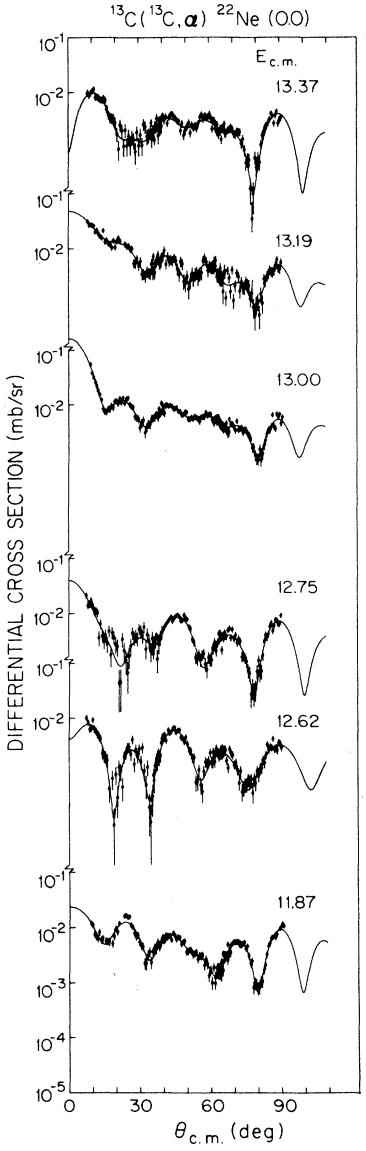

FIG. 4. Same as Fig. 2 for the range $E_{c.m.}=11.87-13.37$ MeV.

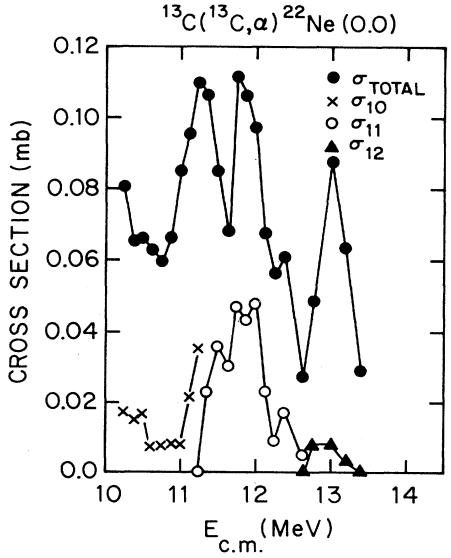

FIG. 5. Partial cross sections for l_{max} as a function of energy extracted from the linear Legendre polynomial fits. The filled circles are the angle-integrated cross sections for the transition to the ^{22}Ne ground state.

The partial cross section for the largest l value contributing to the reaction can thus be extracted unambiguously from the linear fit coefficients. Unfortunately, the amplitudes and phases for the other angular momenta contributing to the reaction cannot be so easily obtained since there are more unknowns than equations [compare Eqs. (1) and (3)].

Good fits were obtained at all energies using the linear Legendre polynomial fitting method ($\chi^2/\nu \approx 1$) 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. 5. The filled circles represent the angle-integrated cross section for the transition to the ^{22}Ne ground state and the other symbols represent the cross section for the different maximum l values for the same transition. The partial cross section for $l=10$ begins a dramatic rise at 11.12 MeV and constitutes about one-third of the total cross section when the maximum l value shifts to $l=11$. The cross section for $l=10$ is rising significantly at an energy near a correlated maximum in the summed deviation function at 11.38 MeV. The enhancement in σ_{11} is even greater. It makes up about one-half of the total cross section at its peak and is located at an energy that is a maximum in the angle-integrated cross section for the transition to the ^{22}Ne ground state and a correlated peak in the summed deviation function at 11.75 MeV. It exceeds the Hauser-Feshbach prediction by a factor of 12. The σ_{11} excitation function then tails off to a small value as does σ_{total}. The shape of the excitation function for σ_{11}, its large cross section, and its correlation with one other transition argue for its identification as an 11^- state at a ^{26}Mg excitation energy of 34.21 MeV. The differential cross section at $E_{c.m.}=11.75$ MeV is displayed in Fig. 6 with the curve

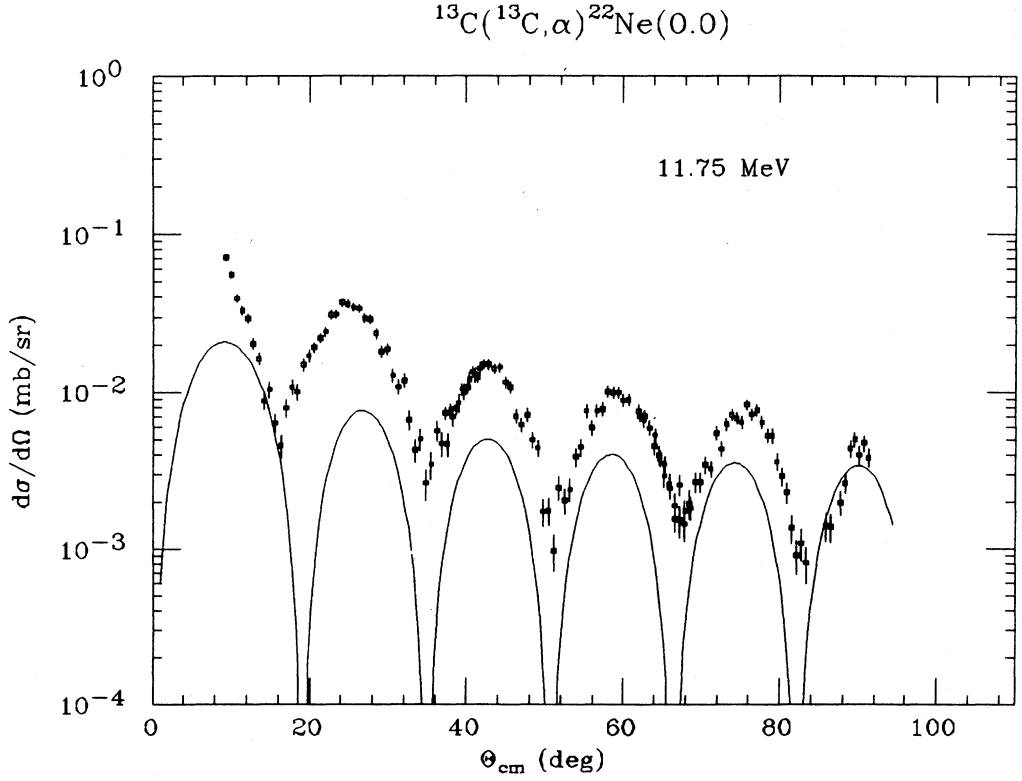

FIG. 6. The angular distributions for the transition to the ^{22}Ne ground state at $E_{c.m.}=11.75$ MeV. The solid curve is the shape of the angular distribution one expects from a pure $|Y^1_{11}(\theta,\phi)|^2$.

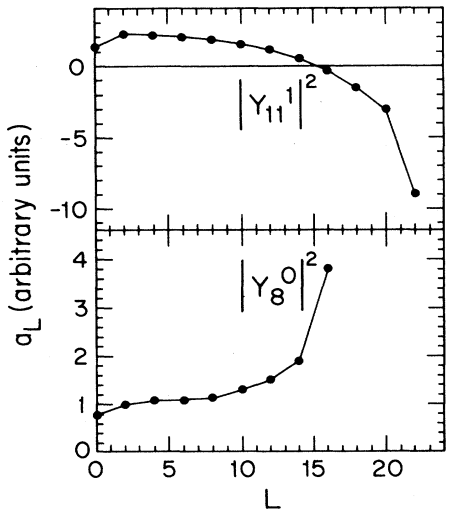

FIG. 7. Linear Legendre polynomial coefficients (a_L's) for a pure $|Y_{11}^1|^2$ angular distribution (upper panel) and a pure $|Y_8^0|^2$ angular distribution (lower panel).

one expects for a transition to the ground state arising from a pure $|Y_{11}^1(\theta,\phi)|^2$. The shape of the angular distribution is consistent with a predominance of $l=11$ strength. At 12.75 MeV l_{max} becomes 12, but this partial cross section never becomes a significant fraction of the total. The final maximum in σ_{total} is not correlated with peaks in the excitation functions of the transitions to the ^{22}Ne excited states and is not a good candidate for a resonance.

Except for the fit coefficient for the largest L value in the linear Legendre polynomial sum, each of the other a_L's is a complicated mix of the phases and amplitudes contributing to it. However, one can still glean some information from the behavior of the a_L's by examining their energy dependence and their composition at a particular energy. It is worth noting the behavior of the Legendre polynomial fit coefficients for angular distributions made up of a single l value. Figure 7 displays the a_L's for a pure $|Y_8^0(\theta,\phi)|^2$ and a pure $|Y_{11}^1(\theta,\phi)|^2$ angular distribution. For the even l value the coefficients are all positive and increase to a peak at $L=2l$ (in this case $L=16$). The coefficients for the odd l value start out positive also, but at large L they go strongly negative and reach a minimum at $L=2l$ ($L=22$ here). This behavior can be modified in a real angular distribution because of interference with other amplitudes.

Figure 8 displays the coefficients of the fits to the angular distributions for the transition to the ^{22}Ne ground state for $E_{c.m.}=10.38-13.38$ MeV. The points of most interest are those in the correlated peaks in the summed deviation function at 11.38 MeV and 11.75 MeV.[15] If an angular distribution is dominated by a single, even l value one expects that all the fit coefficients below $2l$ will exhibit resonance behavior. The coefficients from a_{20} and below in Fig. 8 are all at a local maximum at 11.25 MeV. This implies a possible $l=10$ resonance, but it does not rule out the presence of other l values resonating below the maximum one. This energy is on the shoulder, but

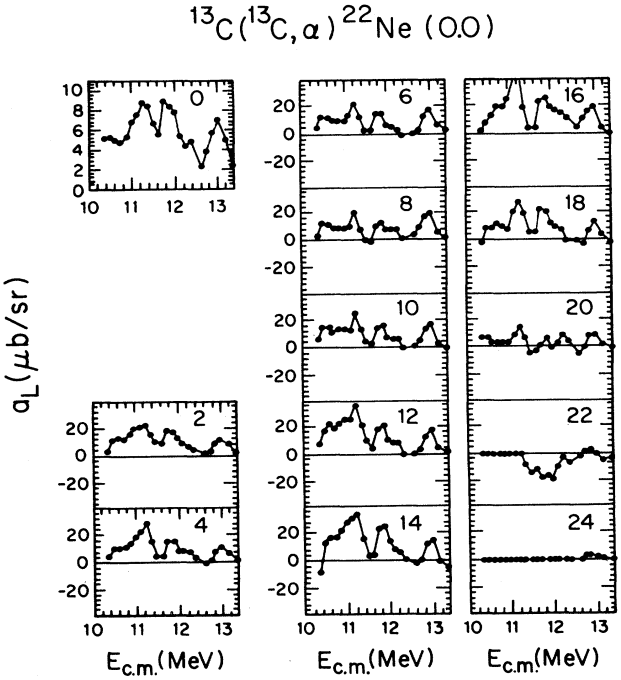

FIG. 8. Excitation functions of the coefficients of the linear Legendre polynomial fits [the a_L's in Eq. (1)] for the transition to the ^{22}Ne ground state.

not at the maximum of the correlated peak at 11.38 MeV. We make a tentative assignment of 10^+ for this state at a ^{26}Mg excitation energy of 33.71 MeV.

At 11.75 MeV (the second correlated peak observed in the summed deviation function) the partial cross section for $l=11$ is a maximum. The fit coefficient a_{20} is small while the other a_L's exhibit maxima at this energy. The contribution of the 11^- to the fit coefficients can still be negative for $L>11$. The coefficients a_{16} and a_{18} are at local maxima here while a_{20} is small. This behavior is consistent with the presence of a significant additional contribution from either $l=8$ or $l=10$. The coefficient a_{20} could remain small even if σ_{10} were large due to the negative contribution from the 11^- resonance. However, half of the total cross section on resonance is in the 11^- channel and argues against an 8^+ or 10^+ spin assignment.

In the $^{12}C+^{12}C$ system there exists a rotational band of resonances whose energies are described by

$$E_x(^{24}\mathrm{Mg})=\frac{\hbar^2}{2I}l(l+1)+E_0\ , \tag{8}$$

where E_x is the excitation energy of the intermediate nucleus, $I=2MR^2$ is the moment of inertia of that nucleus (M and R are the mass and radius of the ions), l is the angular momentum of the resonance, and E_0 is the zero point energy.[1] The value of the rotational parameter, $\alpha=\hbar^2/2I$, is 76 keV. This value is consistent with that of two ^{12}C spheres just touching one another and provides strong motivation to view the system as a nuclear "molecule". A value of $\alpha=76$ keV gives an interion separation of 6.78 fm and a radius parameter r_0 of 1.48 fm ($R=r_0A^{1/3}$). The radius R is half the interion distance

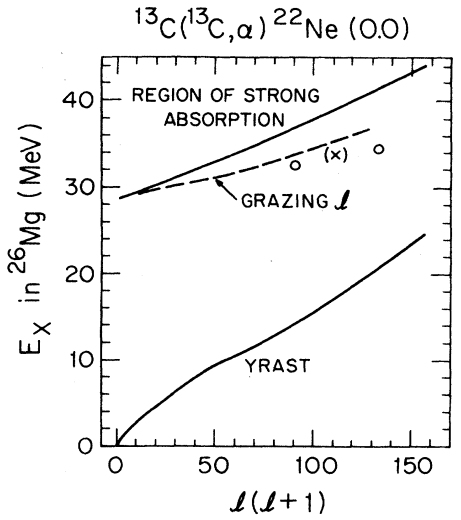

FIG. 9. The angular momentum window in ^{26}Mg. The squares represent the 11^- identified in this work and the 9^- reported earlier (Ref. 16). The cross represents the tentative 10^+ assignment to the peak at $E_{c.m.}=11.25$ MeV. The area above the upper solid curve represents the region of strong absorption, the lower solid line is the yrast line, and the dashed curve is the grazing partial wave. The calculations are described in the text.

in the case of identical particles. Using this value of r_0 one calculates for the $^{13}C+^{13}C$ system a rotational parameter of 66 keV corresponding to an interion separation of 6.96 fm. Korotky *et al.* performed an optical-model analysis of the elastic scattering and found $r_0=1.35$ fm ($R=6.24$ fm).[14] If the particles were to orbit one another at the fusion radius of 7.90 fm, then α is 52 keV.[18]

We have located an $l=11$ resonance at $E_{c.m.}=11.75$ MeV in this work and there exists a 9^- resonance at $E_{c.m.}=9.87$ MeV.[16] That level was identified in a manner similar to the method already discussed. The energies of these two odd l value resonances implies a rotational parameter of 56 keV and a band-head energy [E_0 in Eq. (8)] of 28.30 MeV. The interion distance is 7.59 fm—close to the value of two ^{13}C interacting at the fusion radius. This radius is larger than one expects from the results of the $^{12}C+^{12}C$ system, but it is consistent with the formation of a dinuclear complex consisting of two ^{13}C nuclei orbiting one another at the fusion radius. The attraction between the tails of the nuclear mass distribution give rise to the nuclear "molecule."

Figure 9 displays the l window alluded to in the Introduction. The yrast line is calculated from known states in ^{26}Mg and from the work of Wildenthal,[23] who used the shell model to calculate the energies of positive-parity states in ^{26}Mg. The strong absorption region is where the real part of the entrance-channel S matrix for a given l value is smaller than 0.1. The calculations were done using DWUCK and potential parameters from the literature.[18,24] The curve representing the grazing angular momentum was generated by defining a particular l value to be the grazing one when its transmission coefficient (calculated with DWUCK) was one-half. In the strong absorption region any resonances formed will presumably couple to many compound nuclear states and their strength will dissolve away. The observed levels fall within the molecular window created by the surface transparency of the ^{13}C nuclei. Both levels observed here lie 1–2 units of angular momentum outside the grazing l value. The interaction between the fragments is a peripheral one formed by the interaction of the long tails of the nuclear mass distributions.

IV. CONCLUSIONS

We have measured angular distributions for the $^{13}C(^{13}C,\alpha)^{22}Ne$ reaction for the transitions to the ^{22}Ne ground state and first two excited states. Our previous statistical analysis has established that the reaction proceeds by a predominately nonstatistical mechanism, and in this work we have unambiguously identified an 11^- level in ^{26}Mg at an excitation energy of 34.21 MeV in the compound nucleus. The peak in the partial cross section for the transition to the ^{22}Ne ground state occurs at an energy that is correlated with the excitation functions for the two excited states, and exceeds the Hauser-Feshback prediction by a large margin. The moment of inertia calculated from the position of this level and the position of a 9^- at $E_x=32.33$ MeV, implies a dinuclear complex is formed with the ^{13}C cores orbiting at a distance of 7.59 fm, just inside the fusion radius. The ambiguity of the linear Legendre polynomial fitting procedure clouds the interpretation of the results for the l values that are less than the maximum one, and an attempt to unravel those coefficients is incomplete. We, nonetheless, make a tentative spin assignment of 10^+ to the peak observed at $E_x=33.71$ MeV in ^{26}Mg. Finally, the positions of the resonances lie within the transparent window between the yrast line and a strong absorptive region, and their positions outside the grazing partial wave points to the peripheral nature of the reaction.

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