Resonant structures in the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction, $E_{c.m.}$ = 9 to 20 MeV

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(Received 2 October 1975)

Coincident detection of α particles is used to measure the differential cross section of the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction for $\theta_{c.m.} \simeq 12°$ to 68° and for each 100 keV interval from $E_{c.m.}$ = 9 to 20 MeV. A large number of resonant enhancements is observed in the cross section and the J^{π} values of these are unambiguously determined. The energies and widths of some of these resonant structures agree with resonances reported in other exit channels, in particular those which have been interpreted as a quasimolecular collective band in ^{24}Mg. Well defined gross structure with J = 8, 10, and 12 is observed at $E_{c.m.} \sim 12$, 14.5, and 19 MeV.

[NUCLEAR REACTIONS Measured $d\sigma/d\Omega$ for $^{12}C(^{12}C,^{8}Be)$ at $\theta_{c.m.} \simeq 12°$ to 68° and $E_{c.m.}$ = 9 to 20 MeV in 100 keV steps. Determined energy width and dominant J^{π} value of resonant enhancements.]

I. INTRODUCTION

The discovery of sub-Coulomb resonances in heavy-ion collisions[1] nearly 15 years ago has led to a continuing variety of experiments designed to determine the energy and mass domains of heavy-ion resonances and to probe their intrinsic structures. Almost simultaneous with the first experiments, simple models were developed to describe these structures as quasimolecular.[2] More sophisticated theoretical descriptions now exist although no completely satisfactory explanation has been found for heavy-ion resonant structures above the Coulomb barrier. The subject of heavy-ion collisions and resonances has recently been reviewed by a number of authors.[3]

Recent studies[4-6] of the $^{12}C + ^{12}C$ interaction by observation of a number of exit channels have firmly established a resonance near $E_{c.m.}$ = 19.3 MeV. A series of three strong resonances in the $^{12}C(^{12}C, p)^{23}Na^*$ reaction, which are most beautifully displayed in the channel proceeding to the 9.81 MeV excited state of ^{23}Na, has been interpreted as part of a $^{12}C + ^{12}C$ quasimolecular rotational band in the compound system ^{24}Mg by Cosman *et al.*[5] Correlated, although less distinctive, resonances in the $^{12}C(^{12}C, \alpha_0)^{20}Ne$ reaction led Cosman to assign J^{π} values of 8^+ and 10^+ to the first two of these three resonances at $E_{c.m.} \simeq 11.4$ and 14.3 MeV. Less direct evidence[5] was used to support $J^{\pi} = 12^+$ for the third resonance at $E_{c.m.} \simeq 19.3$ MeV. It was suggested that the enhancement of the $^{12}C + ^{12}C$ collective band in the $^{23}Na^* + p$ channel is due to a structural or shape similarity between the band and the exit channel.[5] These results are very encouraging for further heavy-ion resonance work even though a recent report[7] rejects the $\frac{17}{2}^+$ assignment for $^{23}Na^*$ (9.81 MeV) which was inferred by Cosman *et al.*[5] as an important ingredient for their arguments.

The present work reports on measurements of over a hundred angular distributions of the $^{8}Be + ^{16}O$ exit channel for $^{12}C + ^{12}C$ center of mass energies from 9 to 20 MeV. A large number of enhancements in cross section is observed including fairly weak resonant structures at $E_{c.m.}$ = 11.43, 14.3, and 19.45 MeV which are in approximate agreement with the energies of the collective band proposed by Cosman *et al.* The J^{π} values of these anomalies are unambiguously determined as 8^+, 10^+, and 12^+, respectively. The correlation between the many anomalies observed and those from other reaction channels is discussed.

II. DETECTION OF ^{8}Be AND ENERGY SPECTRA

An α-particle coincidence method in conjunction with an array of eight Si(Li) detectors in a system previously described[8] has been used to measure the energy spectra of ^{8}Be particles from the interaction of $^{12}C + ^{12}C$. Energy spectra at seven reaction angles and at 5° intervals are gathered simultaneously. An on-line two dimensional (E_{α_1} vs E_{α_2}) sorting procedure is used to record ground state ^{8}Be events, while excited ^{8}Be events and all single α particles are discarded in order to simplify data accumulation and storage. The absence of recorded noncoincident α-particle energy spectra and a simpler coincidence method is the principal difference between the present method and an earlier description.[9] Although events involving the first excited state of ^{8}Be at 2.9 MeV are of potential interest and are often apparent in the two dimensional spectrum, no systematic procedure has

been developed for extracting the ^{8}Be* yield and the detection efficiency is inherently uncertain because of the width (~1.4 MeV) of that state. The two dimensional gating procedure provides much lower background than obtained in earlier work[10] where the α-particle energies were simply summed. It should also be pointed out that the two dimensional gating procedure not only reduces the number of accidental α-α coincidences but it also eliminates from the ^{8}Be energy spectra most of the three body final state events which could be present in the earlier work.

An energy spectrum of ground state ^{8}Be particles from the reaction ^{12}C(^{12}C,^{8}Be)^{16}O measured at a bombarding energy of 36.6 MeV and observed at 10° is shown in Fig. 1. Strongly excited are the 0^+, 2^+, and 4^+ members of the $K^\pi = 0^+$, 4p-4h rotational band as well as the 0p-0h ground state of ^{16}O. The states 6.06 MeV, 0^+ and 6.92 MeV, 2^+ are of course not resolved from the 6.13 MeV, 3^- and 7.12 MeV, 1^-, 1p-1h states. Also excited, though more weakly, are the 8.87 MeV, 2^- state, the 11.10 MeV, 4^+ state, and 9.60 MeV, 1^- and 11.63 MeV, 3^- members of the $K^\pi = 0^-$, 3p-3h band. The excitation of the 3p-3h band and the 2^- state at 8.87 MeV indicates that more compound nucleus formation is present at this lower bombarding energy than at $E_l \sim 46$ MeV, where Artz, Greenfield, and Fletcher[10] found primarily population of the ground state and the 4p-4h band—levels which can be populated by direct transfer of an α particle. The observation of extra states in the present work is also aided by the reduced background associated with the two dimensional gating procedure used.

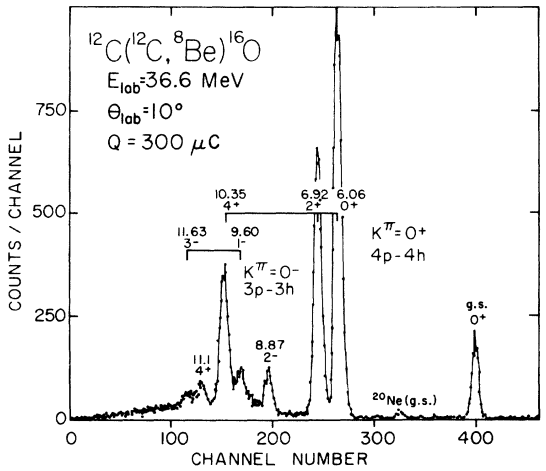

FIG. 1. Energy spectrum of ^{8}Be events following ^{12}C bombardment at 36.6 MeV of a ^{12}C target. Prominent groups are labeled by ^{16}O excitation energy in MeV and by J^π values. The states labeled 6.06 and 6.92 MeV are unresolved doublets. The yield to ^{20}Ne(g.s.) is not due to single α-particle events but is from oxygen impurity in the target and the ^{16}O(^{12}C, ^{8}Be) ^{20}Ne reaction.

Only the results of ^{12}C(^{12}C, ^{8}Be)^{16}O(g.s.) cross section measurements are reported here. Although final states other than ^{16}O(g.s.) were observed in many of the individual energy spectra, the data could not be extracted at all angles and all bombarding energies. This situation arose because aluminum foil thick enough to stop elastically scattered ^{12}C ions was placed over the detectors. In order to avoid changing the foils often, a foil thickness sufficient for a wide range of bombarding energy was used at the expense of energy resolution and energy range in the ^{8}Be energy spectra. The spectrum of Fig. 1 is typical of the forward angle data in the present experiment with an energy resolution of ~400 keV. At the largest angles measured, $\theta_L \leq 40°$, the energy resolution degraded by a factor of 2.

Angular distributions of the reaction ^{12}C(^{12}C, ^{8}Be)-^{16}O(g.s.) were measured at 14 angles between $\theta_{c.m.} = 12°$ and 68° and at each 200 keV interval in bombarding energy from $E_{lab} = 18$ to 40 MeV. The energy loss of the beam particles traversing the target thickness was between 100 and 200 keV. The resulting corrections to resonance energies and widths have been made in values quoted. Statistical uncertainty as large as 15% is encountered for the smallest cross sections measured, but usually the relative error is much less than that. The cumulative uncertainty in the absolute cross section determination is no more than 15%.

III. EXPERIMENTAL RESULTS

The angular distributions of a reaction in which all nuclei involved have zero spin, such as the ^{12}C(^{12}C, ^{8}Be)^{16}O(g.s.) reaction, may be expressed as

$$\sigma(\theta, E) = \left| \sum_L A_L(E) e^{i\delta_L(E)} P_L(\cos\theta) \right|^2 . \qquad (1)$$

In the present case the values of L in the summation are restricted to even integers because of the presence of identical bosons in the entrance channel. When, as a function of energy, the compound system goes through a resonant state with $J^\pi = L^+$, the appropriate coefficient, $A_L(E)$, reflects this by passing through a maximum value. When a particular L-value contribution dominates the cross section, the angular distribution can be expected to exhibit an angular dependence similar to the function $|P_L(\cos\theta)|^2$. To simplify comparisons with the data the functions $|P_L(\cos\theta)|^2$ for a number of even integer values of L are shown in Fig. 2. The angular range displayed corresponds to

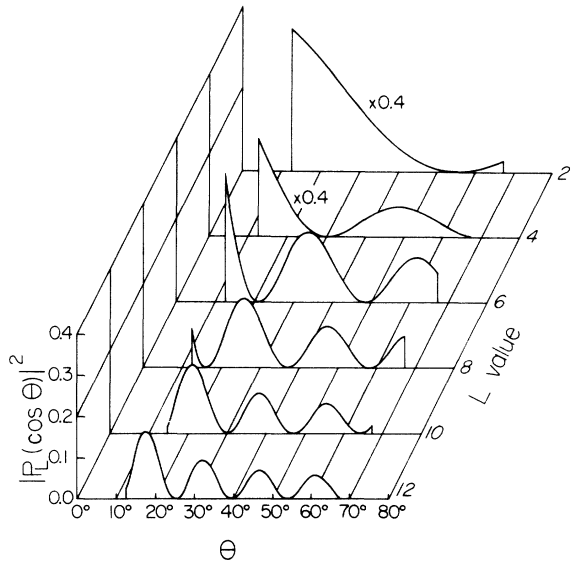

FIG. 2. The squares of even Legendre polynomials plotted over the angular range of the present experiment.

that of the present experiment. A reaction yield measured at angles where a particular function P_L is maximum is expected to resonate when a compound resonance is formed with $J = L$.

Five of the fourteen yield curves measured are shown in Fig. 3. The data in the upper portion of the figure show resonant structures characteristic of $L = 8$ at five center of mass energies between 11.4 and 12.9 MeV, all of which are strongly correlated at two reaction angles which are near maxima in the function $|P_8(\cos\theta)|^2$. The lower three energies which also indicate additional enhancements are not identified as $L = 8$ because of the ratios of the cross sections at $\theta_1 = 15°$ and 27.5° and because of a lack of similarity to the function $|P_8(\cos\theta)|^2$ at other angles measured. Above $E_{c.m.} = 13$ MeV there does not appear to be any dominant $L = 8$ structure present. In addition to showing $L = 8$ structure the solid curve depicts data at an angle where the $L = 10$ Legendre function has appreciable relative strength and the dashed curve is near an angle which would show $L = 12$ structures, as can be seen from Fig. 2.

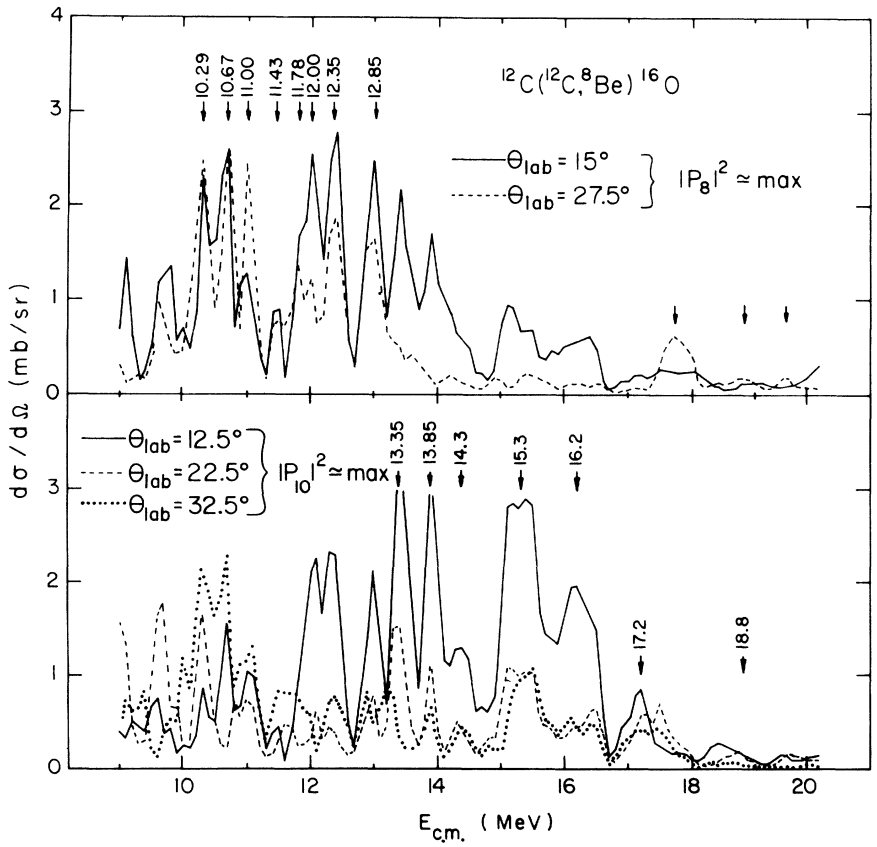

FIG. 3. Yield curves of the $^{12}C(^{12}C, ^{8}Be)^{16}O$ reaction measured at angles selected to illustrate the effects of $L = 8$ and 10 contributions from $E_{c.m.} = 9$ to 20 MeV.

The lower portion of Fig. 3 illustrates enhancements of the reaction yield characteristic of $L=10$ at a number of center of mass energies between 13.2 and 17.4 MeV. The enhancements are well correlated at all three angles (see Fig. 2) which correspond to near maxima in the function $|P_{10}(\cos\theta)|^2$. The structure at 15.3 and 16.2 MeV may be complex. A center of mass energy resolution in that region of about 100 keV is the largest value encountered throughout the experiment.

A more detailed angular distribution measurement shown in Fig. 4 was obtained at $E_{c.m.}=17.2$ MeV for the ground state of ^{16}O and for the two excited doublets near 6.1 and 6.9 MeV. The cross sections to the different final states are comparable at this center of mass energy whereas usually these excited doublets are much stronger than the ground state, such as in Fig. 1. If the transition strength to the 0^+ state at 6.06 MeV is appreciably greater than that to the 3^- state at 6.13 MeV, then the reaction mechanisms for the two 0^+ states are very different. There are, however, far too many uncertainties to pursue a mechanism interpretation by performing a finite range distorted wave Born approximation calculation.

The resonant enhancement of the ground state transition shown in Fig. 4 is clearly dominated by $L=10$. This point is emphasized because it appears so close in energy to very definite $L=12$ structures shown in the yield curves of Fig. 5. The resonant structures at $E_{c.m.}=17.75$ and 19.45 MeV are well defined in position and width at each of the three angles at which the function $|P_{12}(\cos\theta)|^2$ is a maximum. The structure spanning the energy range 18.3 to 19.0 MeV is, however, not attributed to a definite value of L. The combined evidence of these yield curves and angular distributions measured at each 100 keV interval indicates the presence of overlapping $L=12$ and $L=10$ structures with the $L=12$ structure having a greater strength and width. This greater width of the $L=12$ structure may account for the report of a "pure" $L=12$ structure at an energy of 18.5 MeV.[11]

There exists some slight enhancement in the yields shown in Fig. 5 at $E_{c.m.}=18.4$ MeV. The maxima in the measured angular distributions near $\theta_{c.m.}=30°$ and 50° determined at this energy correspond more closely to those of the function $|P_{12}(\cos\theta)|^2$ than do the maxima observed at 18.5 MeV by ~1.0° and ~1.5°, respectively. We, there-

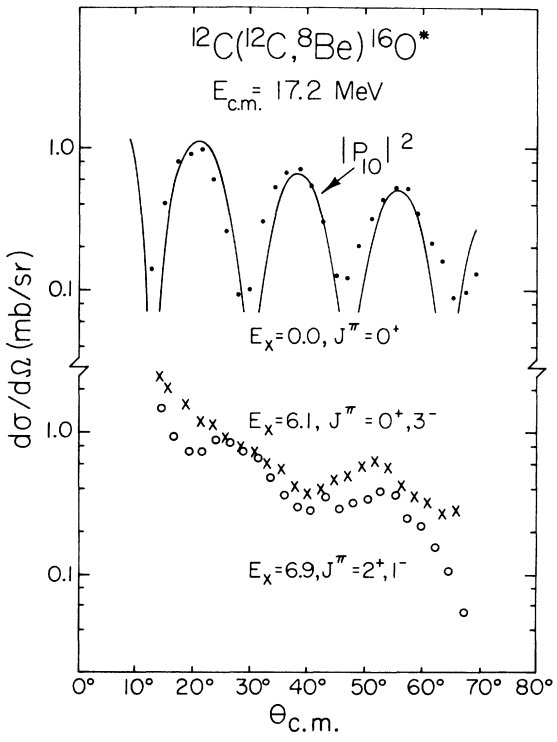

FIG. 4. Angular distributions measured near the $J^\pi=10^+$ enhancement at $E_{c.m.}=17.15$ MeV. The solid curve is a $|P_{10}(\cos\theta)|^2$ distribution. Statistical errors at the smallest cross sections observed do not exceed 15%.

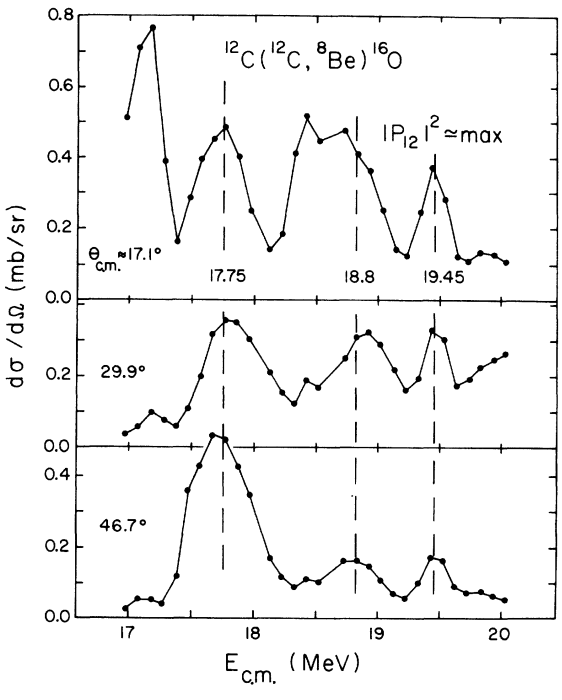

FIG. 5. Yield curves of the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction measured at angles selected to illustrate the effects of $L=12$ contributions from $E_{c.m.}=17$ to 20 MeV. In addition to the $L=12$ structures indicated there is the $L=10$ enhancement at 17.15 MeV and a weak $L=12$ at 18.4 MeV. At $\theta_{c.m.}\approx 30°$ and 47° the contribution from P_{10}^2 is zero (see Fig. 2).

fore, place a weak resonant structure at 18.4 MeV in agreement with the $^{12}C(^{12}C, \alpha)^{20}Ne$ results[12] rather than the higher value of 18.5 MeV.[11]

The angles $\theta_{c.m.} = 29.9°$ and 46.7°, for which yield curves are shown in Fig. 5, are not only near maxima for $|P_{12}(\cos\theta)|^2$, but also they are at minima for $|P_{10}(\cos\theta)|^2$. These yield curves, therefore, indicate an additional $L = 12$ structure at $E_{c.m.} \approx 18.8$ MeV. The angular distributions of Fig. 6 show that this structure is clearly not pure $L = 12$ but includes $L = 10$ strength, as a yield curve plotted at $\theta_{c.m.} \approx 40°$ would clearly show.

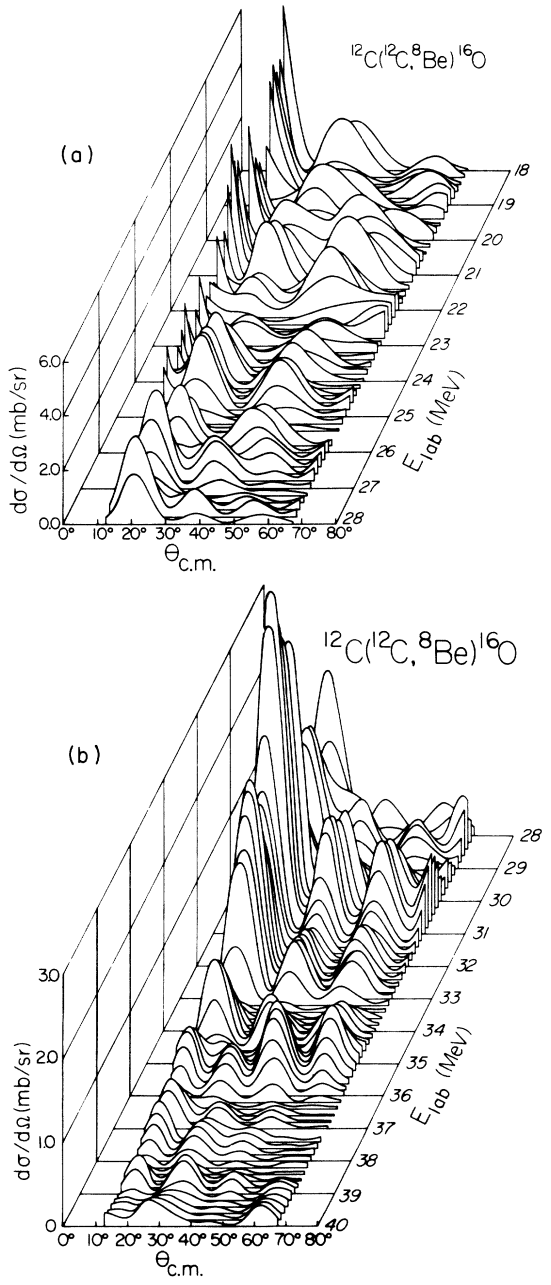

FIG. 6. Angular distributions vs bombarding energy from $E_l = 18$ to 40 MeV ($E_{c.m.} = 9$ to 20 MeV). Only curves drawn through each 14 point angular distribution are shown. The regions of $L = 8$, 10, and 12 gross structure are clearly shown. Note the scale change between parts (a) and (b).

TABLE I. Anomalies in $^{12}C + ^{12}C$ reactions.

Exit channel	$E_{c.m.}$ (MeV)	$\Gamma_{c.m.}$ (keV)	J^π
$^{8}Be + ^{16}O$	11.43	200	8^+
(Present work)	(11.78)	•••	(8^+)
	12.0	200	8^+
	12.35	300	8^+
	12.86	350	8^+
	13.35	350	10^+
	13.85	260	10^+
	14.3	280	10^+
	15.3	600 [a]	10^+
	16.2	800 [a]	10^+
	17.15	350	10^+
	17.75	500	12^+
	(18.4)	•••	12^+
	18.8	400	12^+
	18.8	<400	10^+
	19.45	250	12^+
$\alpha + ^{20}Ne^*$	17.9	340 ± 60	•••
(Ref. 12)	18.4	400 ± 30	•••
	18.6	375 ± 100	•••
	19.0	310 ± 60	•••
	19.4	320 ± 30	•••
$^{8}Be + ^{16}O^*$	18.5	•••	12^+ [b]
(Ref. 11)			
$p + ^{23}Na^*$	11.4	•••	8^+ [c]
(Ref. 5)	14.3	•••	10^+ [c]
	19.3	•••	12^+ [c]

[a] May be comprised of many overlapping structures.
[b] J^π determined from ground state channel.
[c] J^π values are inferred from other reactions.

Curves representing the entire angular distribution data vs bombarding energy are shown in Fig. 6. By comparison of these data with the curves of Fig. 2, the energy regions of $L = 8$, 10, and 12 enhancement are clearly identified as $E_l \approx 23$ to 27 MeV for $L = 8$, 27 to 35 MeV for $L = 10$, and greater than 35 MeV for $L = 12$. The energy region below 23 MeV shows no dominant L value. The energies indicated in Fig. 6 are not corrected for energy loss in the target or a recent accelerator analyzing magnet recalibration and therefore they may not correspond exactly with resonance positions shown in the yield curves of Figs. 3 and 5 or the numbers quoted in Table I which have been corrected. The values of $E_{c.m.}$ and $\Gamma_{c.m.}$ from the present work in Table I have estimated errors of ≤ 50 keV and 20%, respectively.

Of particular note in Fig. 6 is the abrupt change

from the well defined and nearly pure $L=10$ structure at $E_l=34.4$ MeV, characterized by three maxima in the angular distribution, to the $L=12$ structure at $E_l=35.5$ MeV, which is characterized by four maxima. The angular distributions in the region of the $L=12$ and $L=10$ overlapping structures ($E_l=36.8-38.0$ MeV, $E_{c.m.}=18.4-19.0$ MeV) clearly show the weaker $L=10$ contribution filling the central minimum of the $L=12$ angular distribution and the destructive effect in the fourth maximum at $\theta_{c.m.}\sim 60°$. These effects place this $L=10$ structure at about $E_{c.m.}=18.8$ MeV. The very sharp $L=12$ structure placed at $E_{c.m.}=19.45$ MeV from the yield curves is also clearly evident as $L=12$ from the angular distribution data.

IV. DISCUSSION

The resonance structure data extracted from the present work are summarized in Table I. The energies and widths are estimated to be accurate to within 50 keV. Greater uncertainties are indicated by parentheses or omissions unless footnoted. Similar information from other experiments[5,11,12] is also listed for comparison. The specific points of the comparison are as follows:

(1) Reported from the $^{12}C(^{12}C,\alpha)^{20}Ne^*$ work[12] is an anomaly at 17.9 MeV which is not observed in the present experiment. The resonance energies in the region 18.6 to 19.0 MeV do not correspond within experimental errors.

(2) The structure found at 18.4 MeV in the present work and by Fortune *et al.*,[12] may be the same as from the $^{12}C(^{12}C,{}^8Be)^{16}O^*$ (6.1 MeV) reaction[11] since it is not clear in this latter work if target thickness correction was made to the resonance position.

(3) The structures observed at $E_{c.m.}=11.43$, 14.3, and 19.45 MeV are among the narrowest and weakest of their respective J values observed in the entire energy range of 9 to 20 MeV. If these structures are indeed the resonances interpreted by Cosman *et al.*,[5] it can be argued that their weak excitation in the ^{8}Be channel is due to the large proton and deuteron decay probabilities.

(4) The assigned values of J^π are in general unambiguous in the present work. In particular the values for the anomalies at $E_{c.m.}=11.43$, 14.3, and 19.45 MeV are clearly identified as 8^+, 10^+, and 12^+, respectively, whereas these assignments were merely inferred for the resonances in the $^{12}C(^{12}C,p)^{23}Na^*$ reaction.[5]

(5) The structures near $E_{c.m.}=19.4$ MeV listed for different experiments in Table I show more energy variation than what one might expect if they are due to the same compound structure. In addition, Sperr *et al.*,[13] have observed a strong resonance in the $^{12}C(^{12}C,n)^{23}Mg$ reaction at $E_{c.m.}=19.35$ MeV, the elastic scattering shows a strong anomaly at 19.2 MeV,[6] and the resonance structure near this energy in the $^{12}C(^{12}C,d)^{22}Na^*$ reaction spans $E_{c.m.}=19.1$ to 19.6 MeV.[14] Such variations are difficult to explain as one resonance.

In support of a resonance interpretation of the cross section enhancements discussed are reports[10,11] of structures at similar energies in other (^{12}C, ^8Be) reaction channels. The data of Artz *et al.*[10] show the same anomalies ($E_{c.m.}\sim 17.2$, 17.8, 18.7, and 19.5 MeV) for the $^{12}C(^{12}C,{}^8Be)^{16}O$(g.s.) reaction. Their yield curves at a small angle could not resolve the confusion in the 18.5 to 19.0 MeV region as all L-value contributions maximize at small angles. Their anomalies at 18.7 MeV and other energies also appear in the $^{16}O^*$ exit channels, but again in this region of overlapping $L=10$ and 12 structures, the resonances cannot be separated since exit particles are not all spin zero.

An expression such as Eq. (1) has been used to describe the angular distribution data, and many of the anomalies listed in Table I are apparent from such an analysis. The number of ambiguous sets of parameters A_L and δ_L is, however, so large that no completely reliable energy dependence of these parameters has been obtained. A procedure for handling these ambiguities is being developed[15] so that in the near future the energy dependence of the measurements can be considered analytically rather than qualitatively as has been done in this report.

The gross structure for the $^{12}C+{}^{12}C$ scattering has been described by Fink, Scheid, and Greiner,[16] using a nonabsorptive potential interaction which they have justified because of the energy proximity of the $^{12}C+{}^{12}C$ molecular states to the ^{24}Mg yrast line. They find broad resonance structures with $L=6$, 8, and 10 at $E_{c.m.}\approx 9$, 12.5, and 17 MeV, respectively, with widths of approximately 1, 2, and 4 MeV. The positions and widths calculated are in good agreement with the gross structure for $L=8$ and 10 observed in the (^{12}C, ^8Be) reaction channel. To a large degree only one partial wave dominates the gross structure at a given energy, above $E_{c.m.}\sim 12$ MeV, although some overlay of $L=10$ and 12 has been cited. Such simplicity is not the case in the lower energy portion of our data.

This observed "giant resonance" like structure is fragmented into a number of substructures. There exists some variation in widths of the smaller resonant structures over the gross structure width; however, in only two cases do there exist resonant structures with widths comparable to the experimental resolution. From a statistical

point of view one might expect a greater variety of widths; however, the proximity of the high J-value structures to the yrast line may so restrict the number of compound states of that J value that statistical considerations may no longer be entirely valid. Similar widths of the substructures could result from population of similar compound states of fairly simple nuclear structure.

A partial separation of the effects of different L-value contributions has also been shown to arise from a Hauser-Feshbach calculation for the $^{12}C(^{12}C, \alpha)^{20}Ne$ reaction.[17] The similarity of that result and the presently observed gross structure would support an interpretation of the effects as due to entrance channel absorption of the surface angular momentum. The observation, in the present data, of weaker structures for $L = 12$ is then consistent with the increasing angular momentum mismatch as incident energy is increased. The mismatch in the $^{12}C(^{12}C, ^{8}Be)$ reaction increases from $1\hbar$ to $3\hbar$ over the energy range of the experiment.

It is entirely possible that the resonant structure observed results from a combination of the effects of statistical fluctuations and excitation of quasi-bound molecular states whether they be from coupled channels and the double resonance mechanism[18] or α-particle clustering,[19] either of which could generate an intermediate structure of precompound states. Recent analyses[20] of real and simulated data have concluded that such combined effects are not reliably separated in a statistical analysis. In fact, there may even be little difference between statistical and precompound effects if the high J level density is indeed small. Because of these uncertainties a preferred approach to understanding the $^{12}C + ^{12}C$ interaction is to investigate all possible reaction channels and search for cross correlated resonances. Due to the presence of overlapping structures of different J value, the reactions with zero final state channel spin, such as in the present work, should prove to be the most valuable for separating the resonant structures.

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