Resonances in $^{12}C+^{12}C$ inelastic scattering to the 0^+_2, 3^-_1, and 4^+_1 states

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Excitation functions for $^{12}C+^{12}C$ inelastic scattering to the 0^+_2, 3^-_1, and 4^+_1 levels have been measured over the energy range of the gross structure resonances seen in the single and mutual 2^+_1 inelastic scattering channels. Resonant structure is observed which is similar to, but more fragmented than, that in the low lying channels. The general features of the results are in agreement with the band crossing model of the $^{12}C+^{12}C$ interaction, but detailed comparison indicates some serious discrepancies. Particularly, a strong resonance in the 0^+_2 channel violates the band crossing hypothesis.

[NUCLEAR REACTIONS $^{12}C(^{12}C, ^{12}C)^{12}C^*$; $E_{lab}=44$ to 80 MeV; $\theta_{lab}=15°$ to 25°; Measured $\sigma(\theta,E)$ for 0^+_2, 3^-_1, and 4^+_1; Deduced energies and widths of intermediate structures in ^{24}Mg.]

I. INTRODUCTION

Since their first observation,[1] considerable effort has been devoted to the investigation of resonantlike structures in $^{12}C+^{12}C$ reactions. Study of this large body of data indicates that resonances of the same spin are clustered into groups of a few MeV width[2] and the centroids of these gross structure resonances appear to follow a $J(J+1)$ rule[2,3] with a moment of inertia comparable to that of two touching ^{12}C spheres and a bandhead at $E_x \simeq 18-19$ MeV, which is comparable to the Q value plus Coulomb barrier for $^{12}C+^{12}C\rightarrow{}^{24}Mg$. These features have been interpreted as evidence for[2] a quasimolecular band of doorway states (of width $\Gamma\sim2-3$ MeV) which are fragmented into individual states with $\Gamma\sim100-800$ keV by weak coupling to the excited states of the system.

More recently, extensive studies at energies well above the Coulomb barrier have revealed a prominent series of intermediate width structures (i.e., narrower than potential resonances but significantly broader than structures expected from purely statistical fluctuations) in the total cross sections for single and mutual excitation of the 2^+_1 (4.44 MeV) first excited state in ^{12}C.[4] The energy centroids of these structures appear to lie on the quasimolecular rotational band and are suggested to be an extension to the (12^+), (14^+), (16^+), and (18^+) members, although no direct spin assignments are available. The large yield of these excitations suggests a strong coupling between the elastic and 2^+_1 channels in this energy region, and a partial width analysis[4] qualitatively indicates the importance of the inelastic channels in the wave function of the molecular states. Hence, at the higher energies, other components would appear to be important in the resonant state wave function beyond pure $^{12}C+^{12}C$ molecular shape resonances.

Based on the above considerations, successful fits to the intermediate structure resonances in the 2^+_1 and mutual 2^+_1 inelastic channels have been obtained by Kondo *et al.*[5] with the band crossing model (BCM). These coupled channel calculations assume the existence of molecular rotational bands in the $^{12}C+^{12}C$ interaction potential, the spin aligned members of which, for the excited ^{12}C states, cross the ground state band in differing regions of excitation. Figure 1 shows the relevant molecular bands in ^{24}Mg, calculated as in Ref. 5, according to

$$E_J(I_c)=\frac{\hbar^2}{2\mathscr{I}_0}L_c(L_c+1)+E_0+\epsilon_c,$$

where I_c is the exit channel spin, L_c the exit channel orbital angular momentum, and J is the total resonance spin ($\vec{J}=\vec{I}_c+\vec{L}_c$). E_0 and $\mathscr{I}_0$ are the bandhead energy and moment of inertia in the elastic channel and ϵ_c is the channel excitation energy. At each J several L_c are allowed; in general $L_c=J+I_c,\ldots, J-I_c$, but only the aligned case $L_c=J-I_c$ is shown in Fig. 1, since detailed calculations reveal that this coupling is dominant. Based on the experimental centroids of $J^\pi\leq10^+$ resonances, Fig. 1 has been prepared with $\hbar^2/2\mathscr{I}_0=100$ keV and $E_0=18.3$ MeV.

The full coupled channels calculations of Ref. 5 verify, as expected, that strong configuration mixing occurs in the resonance wave function at energies corresponding to band crossings. In the present paper we compare the predictions of this band crossing picture with new inelastic scattering measurements for the 0^+_2 (7.6 MeV), 3^-_1 (9.6 MeV), and 4^+_1 (14.08 MeV) states. Several

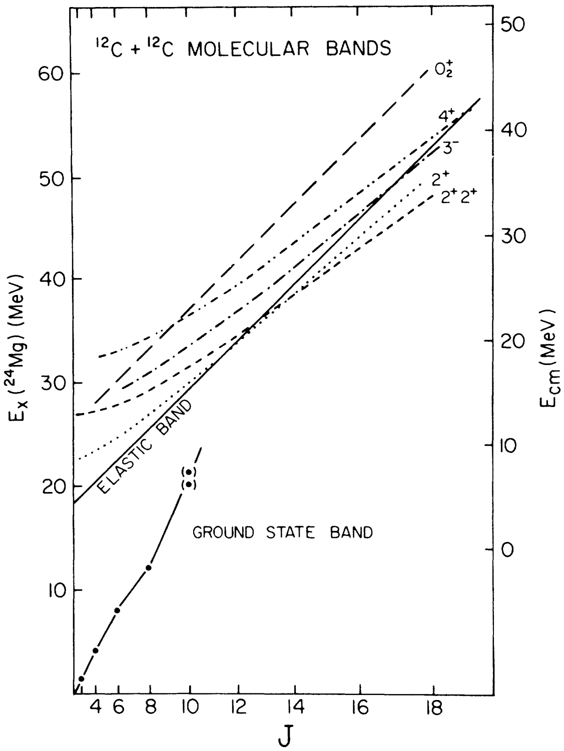

FIG. 1. Schematic band crossing diagram for the $^{12}C + ^{12}C$ molecular resonances in the elastic $(2_1^+ 0_1^+)$, $(2_1^+ 2_1^+)$, $(0_2^+ 0_1^+)$, $(3_1^- 0_1^+)$, and $(4_1^+ 0_1^+)$ channels. The resonance band parameters are discussed in the text.

features are observed in these data which question, at least in part, the completeness of this model.

II. EXPERIMENTAL METHOD

Excitation functions for inelastic scattering to various states in $^{12}C + ^{12}C$ have been measured over the laboratory energy range 44 to 80 MeV at 1 MeV intervals ($\Delta E_{c.m.} = 500$ keV). The data were obtained using beams from the University of Rochester MP tandem Van de Graaff accelerator, and the reaction products were momentum analyzed in the Rochester heavy ion counter[6] at the focal plane of an Enge split pole spectrograph. The angle measuring properties of this detector made possible the use of a 9-slit aperture at the spectrograph entrance, greatly increasing the data taking rate. The angular separation of these slits was 1.174°, each with an in plane angular acceptance of 0.39° and a solid angle acceptance of 0.245 msr. Carbon buildup on the target (40 μg/cm^2 self-supporting natural carbon foil) was reduced to a minimum by mounting a large liquid nitrogen cooled surface in close proximity to the target, and repeated overlap runs enabled the remaining small variation to be removed.

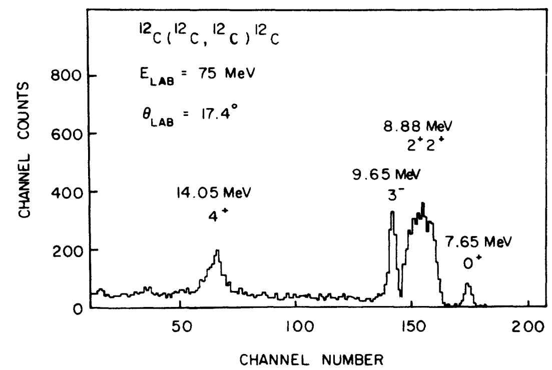

FIG 2. A typical inelastic scattering spectrum obtained in the $^{12}C + ^{12}C$ interaction.

Energy averaging of the data due to the finite target thickness ranges from $\Delta E_{lab} \pm 20$ keV to ±30 keV at the lowest energies and the average energy loss is not corrected for in the figures. The absolute cross section normalization was obtained from a comparison of the 2_1^+ inelastic scattering differential cross section, measured under the same experimental conditions, with previous results.[7] The absolute cross sections are uncertain to ±10% due largely to target thickness uncertainties and uncertainties in the energy dependence of charge state fraction corrections. At several selected energies, total cross sections were determined by measuring complete angular distributions, extending in some cases down to $\theta_{lab} = 3°$.

Figure 2 shows an example of the inelastic scattering energy spectrum, with clearly visible excitations of the 0_2^+ (7.65 MeV), 3_1^- (9,64 MeV), and 4_1^+ (14.08 MeV) states in ^{12}C, along with the Doppler broadened peak from the mutual 2_1^+ (4.44 MeV) excitation. The rising continuum background under the 4_1^+ peak is due to the 3α reaction, which opens in the region of the 2_1^+ mutual excitation. No other states are strongly excited in the region up to 15 MeV of excitation.

III. RESULTS AND DISCUSSION

A. Results

Excitation functions for the $2_1^+ 2_1^+$, 0_2^+, 3_1^-, and 4_1^+ channels were obtained at nine angles simultaneously spanning the range $\theta_{lab} = 15°$ to 25° ($\theta_{c.m.} \simeq 33°$ to 55° for the 3$^-$ state). This angular range is large enough to contain all of the significant structure contained in the total cross section. This has been verified by (1) comparing the energy dependence of the 2_1^+ mutual excitation yield integrated from $\theta_{lab} = 15°$ to 25° with that of the total cross section for mutual 2_1^+ inelastic

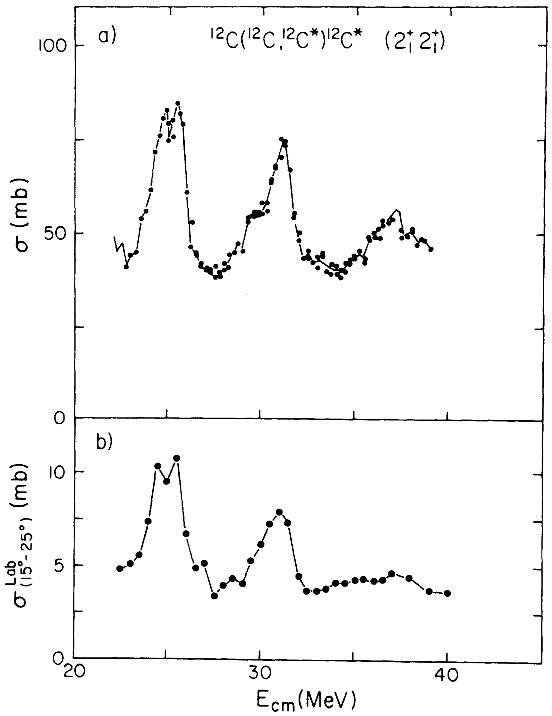

FIG. 3. Comparison of the mutual 2_1^+ channel angle integrated cross section ($\theta_{lab}=15°-25°$) excitation function with the total cross section for this channel (Ref. 4).

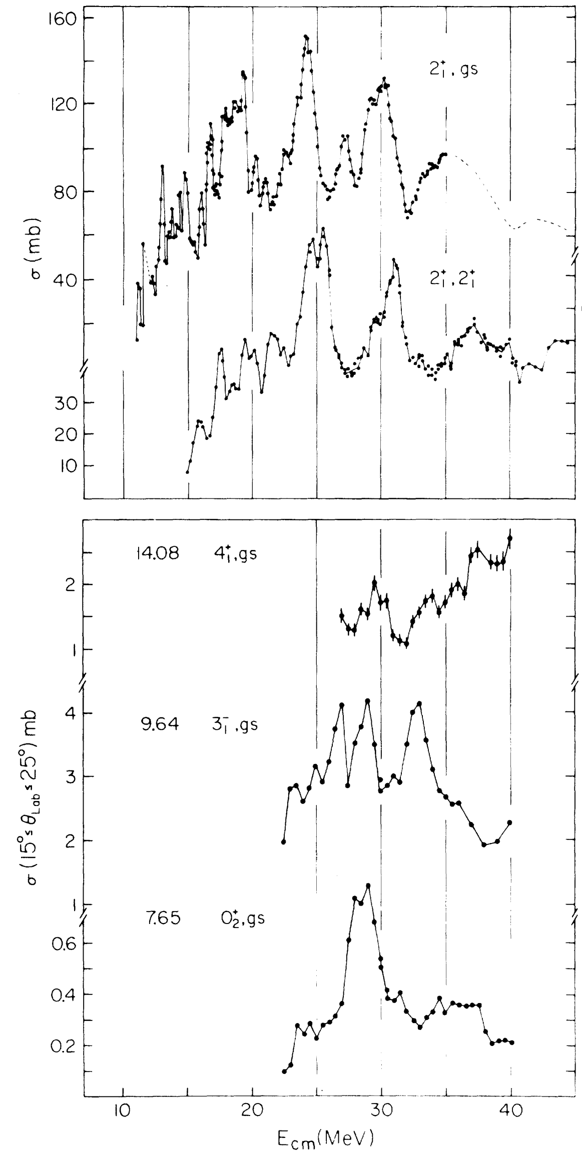

FIG. 4. Angle integrated cross sections ($\theta_{lab}=15°-25°$) for the 0_2^+, 3_1^-, and 4_1^+ levels. The total cross section measurements of the single and mutual 2_1^+ channels are from Ref. 4.

scattering observed in a previous experiment[4] (Fig. 3) and (2) comparing the energy dependence of the partial cross sections (in the range $\theta_{lab} = 15°$ to $25°$) for several inelastic transitions with the energy dependence of their total cross sections as deduced from measurements of complete angular distributions in the present experiment.

Excitation functions for the 0_2^+, 3_1^-, and 4_1^+ levels, integrated in the angular range $\theta_{lab} = 15°$ to $25°$, are shown in Fig. 4 along with the total cross section excitation functions for single and mutual 2_1^+ inelastic scattering from a previous experiment.[4] In Ref. 4 a normalization error of almost a factor of 2 occurs in the 2_1^+ channel data, over the $E_{c.m.} = 10$ to 15 MeV range. This has been corrected for in Fig. 4. The individual excitation functions for the 0_2^+ and 3_1^- levels are shown in Fig. 5 for each of the nine angles.

B. The 0_2^+, 3_1^-, and 4_1^+ channels

The strengths of the 3_1^- and 4_1^+ transitions are substantial. For example, the total cross sections at $E_{c.m.} = 28.5$ MeV for the 3_1^- and 4_1^+ levels are 27 and 13 mb respectively. These are to be compared with average cross sections in this energy range of 100 and 50 mb for the single and mutual 2_1^+ channels respectively. As a further comparison, note that $2\pi(2l+1)\lambda\!\!\!^-{}^2 \simeq 7.64\ (2l+1)$ mb in this energy range. The experimental fusion cross section,[8,9] as well as detailed optical model studies,[10] point unambiguously to $l = 16$ as the grazing partial wave near $E_{c.m.} \simeq 30$ MeV. For $l = 16$ the unitarity limit is thus 252 mb. Clearly the total inelastic scattering cross section to these few discrete levels accounts for essentially all of the flux associated with the 16th partial wave.

The cross section for inelastic excitation of the

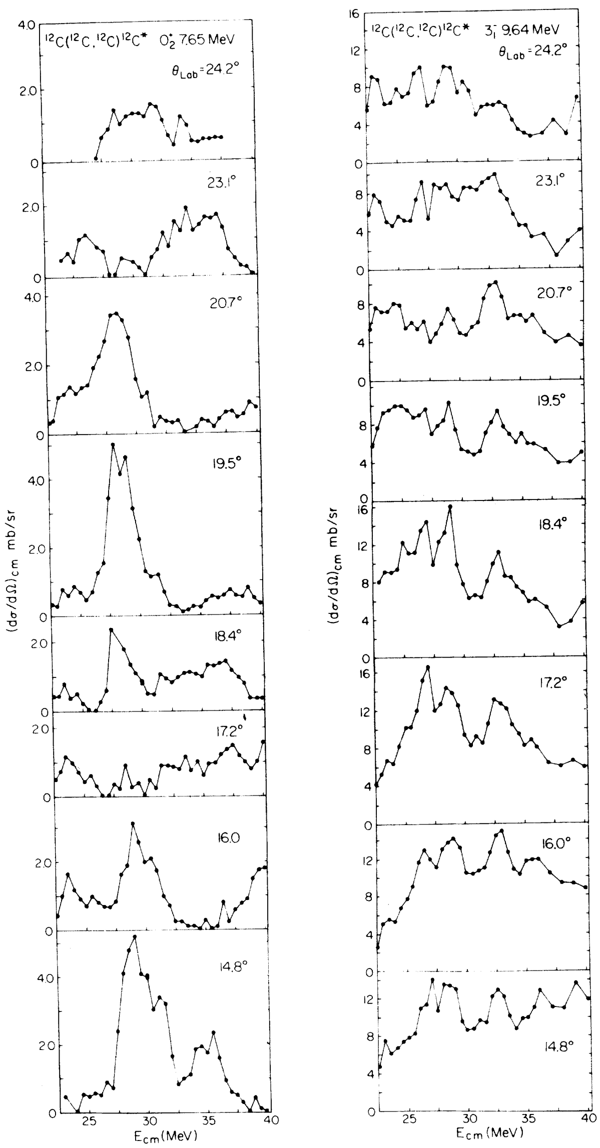

FIG. 5. Individual angle excitation functions for the 0_2^+ and 3_1^- levels.

0_2^+ level is an order of magnitude weaker than the 3_1^-. We note, however, that the Coulomb penetrability ratio[11] of the 0_2^+ channel relative to that of the 2_1^+ channel is $P(2_1^+)/P(0_2^+) \simeq 38$. Thus the small relative cross section of the 0_2^+ level may be adequately explained purely on the basis of its energy and angular momentum mismatch, without relying on the enhanced collectivity of the 2_1^+ level. This situation is similar to that observed by Malmin *et al.*[12] in $^{16}O + ^{12}C$ inelastic scattering to the 6.05 MeV, 0_2^+ level of ^{16}O, where it was noted that the 0_2^+, 4p4h level might assume significant collectivity by mixing with the 1p1h giant resonance.

TABLE I. Resonances in 0_2^+, 3_1^-, and 4_1^+ $^{12}C + ^{12}C$ inelastic scattering.

Channel	Resonance energy $E_{c.m.}$ (MeV)	E_x (MeV)	Γ (MeV)	σ_{Res} [a] (mb)
0_2^+	28.5	42.4	2.6 ± 0.2	3.4 ± 0.3
	36.0	49.9	4.3 ± 0.3	
3_1^-	27.0	40.9	1.4 ± 0.1	
	28.75	42.65	1.8 ± 0.1	13.0 ± 1.5
	32.75	46.65	1.9 ± 0.2	
4_1^+	29.5	43.4	2.4 ± 0.2	

[a]The on resonance total cross section minus an estimated nonresonant background.

The structure seen in the 0_2^+, 3_1^-, and 4_1^+ excitation functions is similar to structures seen in the 2_1^+ and mutual 2_1^+ channels. The prominent features to be noted are summarized in Table I.

For some of the peaks seen in the 0_2^+, 3_1^-, and 4_1^+ excitation functions, it is possible to find correlations with peaks in the 2_1^+ and/or mutual 2_1^+ channels. For example, the $E_{c.m.} = 27.0$ MeV peak in the 3_1^- channel correlates well with a corresponding isolated peak in the 2_1^+ channel, but no corresponding resonance is observed in the mutual 2_1^+ channel. The structure at $E_{c.m.} = 29.5$ MeV in the 4_1^+ channel correlates with the lower member of the apparent doublet at $E_{c.m.} = 29.5$ in *both* the 2_1^+ and mutual 2_1^+ channels. Finally, the strong 0_2^+ resonance at $E_{c.m.} = 28.5$ MeV correlates reasonably well with a corresponding structure at $E_{c.m.} = 28.75$ MeV in the 3_1^- channel, but *no* obvious correlation with either the 2_1^+ or mutual 2_1^+ channel appears to exist.

C. Comparison to the BCM

A comparison of the present data with the band crossing calculations of Kondo *et al.* is presented in Fig. 6. This figure is similar to Fig. 3 of Ref. 5 except that (1) the normalization of the 2_1^+ data from $E_{c.m.} = 10$ to 15 MeV has been corrected and (2) the 3_1^- calculation is now compared with 3_1^- data, whereas in Ref. 5 the comparison was inadvertently made with a single angle excitation function from Ref. 13, which is a mixture of unresolved 3_1^-, $2_1^+2_1^+$, and 0_2^+ levels. It may be observed that the calculations are in reasonable agreement with the relative strengths of the 2_1^+, $2_1^+2_1^+$, and 3_1^- channels. However, the peak to background ratios are as much as three times those of the data, although this could presumably be rectified within the parameter space of the model. A more serious failing occurs in the 3_1^- channel, where the widths are systematically overpredicted

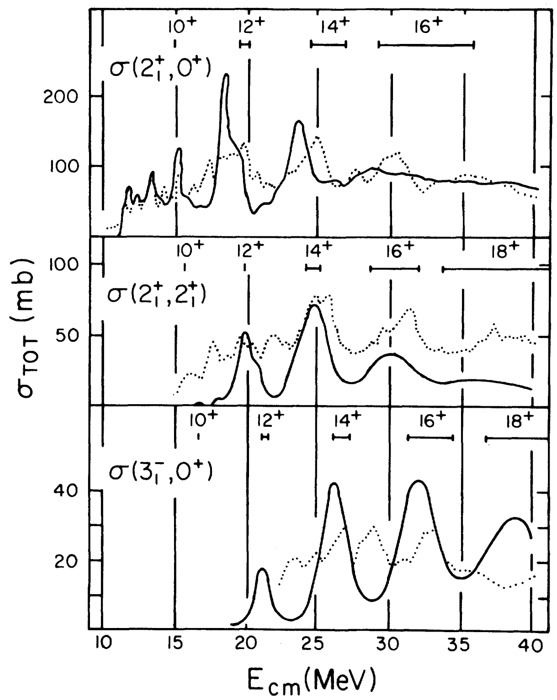

FIG. 6. Comparison of the band crossing model predictions (solid lines) with the excitation functions for the single and mutual 2_1^+ channels (Ref. 4) and the 3_1^- channel (this work). The 3_1^+ data have been normalized to total cross section measurements taken around the $E_{c.m.} = 29$ MeV peak.

by a factor of ~2 and where the existence of the resonance at $E_{c.m.} = 28.75$ MeV is not predicted at all. This is apparently the same resonance observed in the 0_2^+ channel. We note, as Fig. 1 illustrates, that resonances in the 0_2^+ channel are not allowed in the band crossing picture since all 0^+ molecular bands are parallel. This statement is true even if sequential excitation $0_1^+ \rightarrow 2_1^+ \rightarrow 0_2^+$ is included.

IV. CONCLUSIONS

Resonances in the 0_2^+, 3_1^-, and 4_1^+ $^{12}C + ^{12}C$ inelastic channels have been observed which are similar to those seen in previous 2_1^+ and mutual 2_1^+ inelastic data. The net inelastic cross section associated with the discrete excitations of $^{12}C + ^{12}C$ is sufficient to exhaust almost the entire strength of the $l = 16$ grazing partial wave near $E_{c.m.} \simeq 30$ MeV.

A comparison of the quantitative as well as qualitative predictions of the band crossing model suggests that while the model is in reasonable overall agreement with many features of the data, it seems to be incomplete. In particular, the calculations consistently underpredict the amount of fragmentation of the gross structure resonances, as for example in the 12^+ resonance region ($E_{c.m.} \sim 19$ MeV) of the 2_1^+ excitation function. The number of resonances in the 3_1^- channel is underpredicted and their widths are overpredicted by a factor of ~2. This latter feature will be extremely difficult to reconcile with any reasonable model for the potential in the 3_1^- channel. Finally, a strong resonance has been observed in the 0_2^+ channel which seems to violate the band crossing hypothesis.

Each of these features suggests that the band crossing model does not yet incorporate all the relevant degrees of freedom. The observation of pronounced resonant strength in the 0_2^+ channel may be taken as indirect, though hardly compelling, evidence for the importance of α-particle degrees of freedom. Resolution of this possibility will require a difficult quantitative analysis because, as noted in the discussion, the magnitude of the 0_2^+ cross section is dominated by an energy and angular momentum mismatch and is not at first sight inconsistent with the cross sections to other levels.

Going beyond the present data, it has recently been noted[14] that, in the $E_{c.m.} = 30$ MeV region, nucleon rearrangement channels such as $^{10}B + ^{14}N$ carry a substantial fraction of the resonant strength when compared for example to the mutual 2_1^+ channel. These data may suggest that even individual nucleon degrees of freedom may be essential to an understanding of the positions, fragmentation, and total widths of the $^{12}C + ^{12}C$ resonances.

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[1]E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 4, 515 (1960).
[2]H. Feshbach, J. Phys. (Paris) Colloq. 37, C5, 177 (1976).
[3]E. R. Cosman, T. M. Cormier, K. Van Bibber, A. Sperduto, G. Young, J. Erskine, L. R. Greenwood, and O. Hansen, Phys. Rev. Lett. 35, 265 (1975); D. R. James and N. R. Flecther, Phys. Rev. C 17, 2248 (1978).
[4]T. M. Cormier, C. M. Jachcinski, G. M. Berkowitz, P. Braun-Munzinger, P. M. Cormier, M. Gai, J. W. Harris, J. Barrette, and H. E. Wegner, Phys. Rev.

Lett. 40, 924 (1978).
[5]Y. Kondo, Y. Abe, and T. Matsuse, Phys. Rev. C 19, 1356 (1979).
[6]D. Shapira, R. M. DeVries, H. W. Fulbright, J. Tōke, and M. R. Clover, Nucl. Instrum. Methods 129, 123 (1975).
[7]T. M. Cormier *et al.* (unpublished).
[8]P. Sperr, T. H. Braid, Y. Eisen, D. G. Kovar, F. W. Prosser, J. P. Schiffer, S. L. Tabor, and S. Vigdor, Phys. Rev. Lett. 37, 321 (1976).
[9]Y. Abe, T. Matsuse, and Y. Kondo, Phys. Rev. C 19, 1365 (1979).
[10]A. Gobbi, Heavy Ion Scattering, Proceedings of the Symposium, Argonne National Laboratory 1971, Report No. ANL 7837, National Technical Information Service, Springfield, Virginia.
[11]J. M. Blatt and V. F. Weisskopf, in *Theoretical Nuclear Physics* (Wiley, New York, 1963), p. 333. The penetrability ratio was evaluated for a $J^{\pi}=16^{+}$ resonance in the stretched spin coupling configuration. Although the value of the channel radius is uncertain, the results are not very sensitive to the exact value of this parameter. The quoted figure is for a channel radius of 5.5 fm.
[12]R. E. Malmim, Fide Kahn, and P. Paul, Phys. Rev. C 17, 2097 (1978).
[13]W. Reilly, R. Wieland, A. Gobbi, M. W. Sachs, J. Maher, R. H. Siemssen, D. Mingay, and D. A. Bromley, Nuovo Cimento 13A, 913 (1973).
[14]M. R. Clover, T. M. Cormier, B. R. Fulton, and B. J. Herman, Phys. Rev. Lett. 43, 256 (1979).