Molecular Resonances in $^{12}C + ^{12}C$ Inelastic Scattering*

T. M. Cormier, J. Applegate, G. M. Berkowitz, P. Braun-Munzinger, P. M. Cormier, J. W. Harris, C. M. Jachcinski, and L. L. Lee, Jr.
Department of Physics, State University of New York, Stony Brook, New York 11794

and

J. Barrette and H. E. Wegner
Brookhaven National Laboratory, Upton, New York 11793
(Received 18 February 1977)

The energy dependence of the total cross section for the mutual inelastic scattering reaction $^{12}C + ^{12}C \rightarrow ^{12}C(2_1^+) + ^{12}C(2_1^+)$ has been measured from $E_{c.m.}(^{12}C) = 15$ to 45 MeV. A rotationlike sequence of resonances is observed with strengths up to 17% of the unitarity limit and widths approaching the $^{12}C + ^{12}C$ single-particle width.

The present Letter reports the observation of a striking series of previously unobserved resonances in the angle-integrated cross section of the reaction $^{12}C(^{12}C, ^{12}C(2^+))^{12}C(2^+)$ which shed new light on the nature of the intermediate-structure resonances in the $^{12}C + ^{12}C$ system.

The initial studies[1] of the light-particle decay channels of the $^{12}C + ^{12}C$ system by Almqvist, Bromley, and Kuehner revealed resonances in the total reaction cross section near and below the Coulomb barrier ($E_{c.m.} = 5$ to 7 MeV). Subsequent research[2] showed that these unusual compound-nucleus states have a partial width for decay back into the entrance channel which approaches the Wigner limit. These measurements constituted the first examples of nuclear molecular phenomena.

In recent years the search for nuclear molecular phenomena in $^{12}C + ^{12}C$ has been extended to energies well above the Coulomb barrier. Detailed excitation functions of the p, d, n, α, ^8Be, ^{12}C, and $^{12}C^*$ channels as well as the total "fusion" cross section have been measured.[3-13] The light-particle decay channels are dominated by statistical evaporation processes and Ericson fluctuations. Detailed statistical analyses and searches for cross-channel correlations have revealed, however, discrete intermediate structures with $150 \leq \Gamma_{tot} \leq 700$ keV. One such study,[3] which focused on the $p + ^{23}Na$ channel, identified a rotational sequence of resonances with $J^\pi = 8^+$ to 12^+.

Feshbach[14] has recently summarized the existing information on resonances in the light-particle channels and demonstrated that resonances of the same spin are generally clustered within 2 to 3 MeV. In this light, the broad structures[13] observed in the total fusion cross section may be understood as a superposition of all of the individual sharp resonances seen in the light-particle decay channels. This suggests[14] that the individual sharp resonances are examples of isolated doorway states which are excited within energy windows defined by molecular shape resonances in the elastic channel. Two experimental questions are posed by this interpretation: (1) Do the molecular shape resonances exist, and if so, what are their energies, spins, widths, and strengths? (2) What are the dynamics involved in the generation of the doorway state?

The present Letter reports new experimental data on the energy dependence of the total cross section for the mutual inelastic scattering reaction $^{12}C + ^{12}C \rightarrow ^{12}C(2_1^+) + ^{12}C(2_1^+)$ as well as the inclusive cross section for producing either one or two carbon nuclei in their 2_1^+ state. These measurements furnish direct experimental information on both of the questions posed above.

The experiments consisted of detecting γ rays from the ^{12}C $2_1^+ \rightarrow 0^+$ transition ($E_\gamma = 4.44$ MeV) in singles and coincidence using two 10-in.$\times$10-in. NaI crystals positioned in plane in a highly efficient geometry. An inset in Fig. 1 shows a typical γ spectrum obtained at $E_{lab} = 71$ MeV. ^{12}C beams from the State University of New York at Stony Brook FN tandem accelerator and the Brookhaven National Laboratory three-stage MP tandem facility were used to cover the bombarding energy range of $E_{c.m.} = 15$ to 45 MeV in steps of $\Delta E_{c.m.} \leq 250$ keV. Self-supporting natural carbon foils of 20 $\mu g/cm^2$ thickness mounted close to a liquid-nitrogen-cooled surface were used for all measurements, and carbon buildup on the target was negligible.

The resulting excitation functions for inclusive $2_1^+ \rightarrow 0^+$ transitions and mutual inelastic scatter-

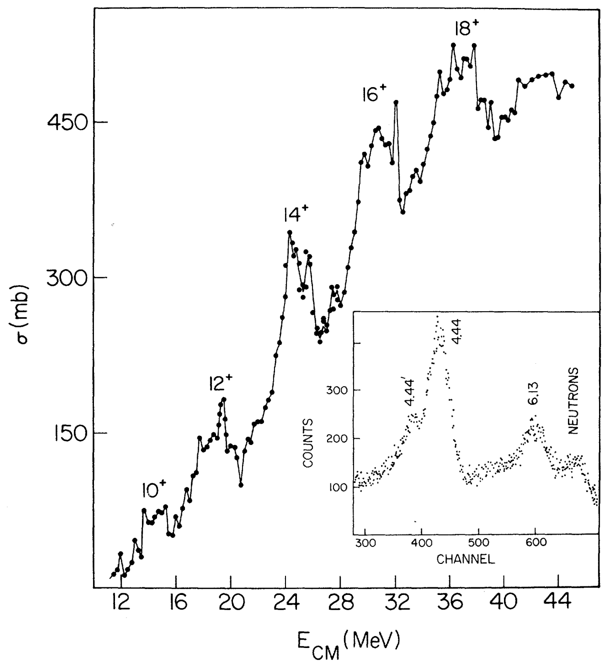

FIG. 1. Energy dependence of the total cross section for ^{12}C $2_1^+ \to 0^+$ γ-ray transitions observed in $^{12}C + ^{12}C$ collisions. Spin assignments of the resonances are discussed in the text. The inset shows a typical singles γ spectrum obtained at $E_{lab}(^{12}C) = 71$ MeV.

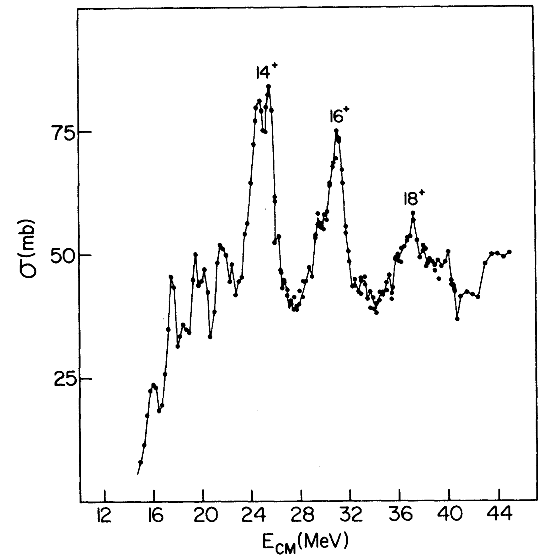

FIG. 2. Energy dependence of the total cross section for the reaction $^{12}C(^{12}C, ^{12}C(2^+))^{12}C(2^+)$. Spin assignments of the resonances are discussed in the text.

ing are shown in Figs. 1 and 2, respectively. The scale of the absolute total cross section for the mutual-inelastic-scattering data was established in a charged-particle experiment in which the corresponding angular distribution was measured from $\theta_{lab} = 5°$ to $45°$ at $E_{c.m.} = 22$ and 24.5 MeV. This procedure is accurate to ± 20%. The absolute cross-section scale for the inclusive $2_1^+ \to 0^+$ data was established (to ± 40%) using a measured solid angle, calculated total efficiency, and estimated line shapes for the 4.44-MeV γ rays in the NaI detectors. Further experimental details are given by Cormier *et al.*[15]

The excitation functions are dominated by a series of broad resonances which, in the case of mutual inelastic scattering, have peak-to-background ratios of up to 2:1. Although the present experiment does not allow a direct measurement of the spins of the resonances it is instructive to compare the positions of the measured resonances with previously observed sharp resonances in light-particle decay channels for which spin assignments could be made. Thus one notes, e.g. (see Table I of Ref. 14), that states with spins 12^+ are generally clustered in the range $18 < E_{c.m.} < 20$ MeV, which is around the position of the strong structure observed at $E_{c.m.} \simeq 19$ MeV in our data. Similar statements apply for the bumps around $E_{c.m.} = 14$ and 25 MeV where 10^+ and 14^+ strength seems to be concentrated. It should, however, be mentioned that the above correlation is not completely unique since two $J^\pi = 10^+$ states have been identified at $E_{c.m.} = 18.8$ MeV[5] and $E_{c.m.} = 19.0$ MeV[12] indicating that states with the same spin may be spread out over several MeV.

The correlation between our resonances and high-spin states identified in light-particle decay channels is even more suggestive if one plots the energy centroids of the structures observed in the singles excitation function (Fig. 1) versus the dominant $J(J+1)$ values. Assuming spins 10^+ and 12^+ for the resonances at $E_{c.m.} \approx 14$ and 19 MeV immediately suggests the identification of the higher-energy resonances as members of a common (molecular) rotational band with spins 14^+, 16^+, and 18^+ at energies $E_{c.m.} = 25$, 30.5, and 37.1 MeV, respectively, as shown by the straight line in Fig. 3.

Figure 3 also displays the results of an optical-model calculation of the $^{12}C + ^{12}C$, $n = 0$ single-particle states obtained using the Yale potential[16] and an energy-dependent potential of the type discussed by Malmin.[17] In both cases the absorption is taken to be zero.[18] These states, which, in the molecular model, correspond to the lowest lying $K^\pi = 0^+$ molecular rotational band in ^{24}Mg, are in remarkable agreement with our experimen-

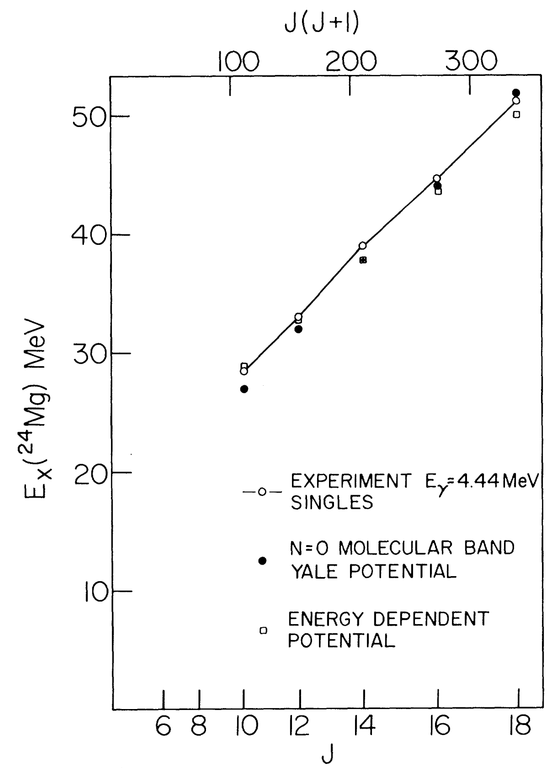

FIG. 3. Experimentally observed resonant energy centroids vs $J(J+1)$ for the spin assignments given in Table I. The energies of the $n=0$ molecular rotational band are shown for comparison using two different prescriptions for the real potential as discussed in the text.

tal energy centroids.[19] Table I compares the total widths observed in the singles excitation function with these calculated single-particle, molecular widths. The comparison suggests that the observed resonances are reasonably pure single-particle states. In fact, it is observed that the experimental widths of the 10^+ and 12^+ resonances exceed the single-particle width. In terms of the doorway-state interpretation, this suggests the possibility that the total width of these states is determined by the sum of the spreading width to more complex compound nucleus states and the single-particle width.

The mutual inelastic scattering and inclusive $2_1^+ \rightarrow 0^+$ cross sections exhibit different energy dependences below $E_{\text{c.m.}} = 22$ MeV. In particular, the 10^+ and 12^+ resonances either are not observed or they are only partially observed in the mutual inelastic channel. This effect may result partially from the lower center-of-mass energy relative to the Coulomb barrier in the mutual inelastic channel or may reflect an inhibition of this channel related to the dynamics of the doorway-state production. Assuming spins 14^+, 16^+, and 18^+ for the resonances at $E_{\text{c.m.}} = 25$, 30.5, and 37.1 MeV yields ratios of $\sigma/2(2J+1)\pi\lambda\!\!\!^-{}^2 = 0.16$, 0.17, and 0.11, respectively, for the resonant cross section to the appropriate unitarity limit. These numbers are obtained after subtracting a smooth nonresonant background from the data of Fig. 2. Furthermore, the resonant cross sections extracted from the present data place limits on the elastic and mutual inelastic widths, Γ_c and $\Gamma_{2^+,2^+}$, and determine[20] an upper limit for the sum of the compound nucleus damping width (Γ_{CN}) and single inelastic width (Γ_{2^+}). These quantities are given in Table I. It is clear that the present data imply Γ_c or $\Gamma_{2^+,2^+}$ widths on the order of 1 MeV which further indicates the quasimolecular nature of the resonances.

The results discussed above suggest that the gross features of the observed resonances may indeed be attributable to molecular shape resonances. A fine structure is also observed which in many cases seems to be correlated with known resonances in various light-particle decay chan-

TABLE I. Comparison of the experimentally observed resonant energies and widths with the molecular band calculations.

	Experiment					Molecular band calculations			
J^π	$E_x(^{24}\text{Mg})$ (MeV)	Γ_{tot} (MeV)	$\frac{\sigma_{2^+2^+}}{2(2J+1)\pi\lambda\!\!\!^-{}^2}$	Γ_c, $\Gamma_{2^+2^+}$ (MeV)	$\Gamma_{2^+}+\Gamma_{\text{CN}}$	$E_x(^{24}\text{Mg})$[a]	Γ_{tot}[a] (MeV)	$E_x(^{24}\text{Mg})$[b]	Γ_{tot}[b] (MeV)
10^+	28.5	1.8				27.0	0.7	28.6	1.1
12^+	33.0	2.9				32.0	2.0	32.8	2.0
14^+	39.0	2.3	0.16 ± 0.03	$0.10 \leq \Gamma_c,\ \Gamma_{2^+2^+} \leq 2.2$	1.4	37.8	3.3	37.8	3.4
16^+	44.70	3.0	0.17 ± 0.03	$0.13 \leq \Gamma_c,\ \Gamma_{2^+2^+} \leq 2.87$	1.76	44.0	5.0	43.5	4.5
18^+	51.0	4.3	0.11 ± 0.02	$0.12 \leq \Gamma_c,\ \Gamma_{2^+2^+} \leq 4.18$	2.87	51.8	8.5	50.0	5.0

[a]Yale potential, Ref. 16.

[b]Energy-dependent potential, Ref. 17.

nels. If, as suggested in Ref. 14, this fine structure corresponds to individual isolated doorway states, then the fact that all such states (i.e., the whole molecular shape resonance) are observed in the mutual inelastic and single inelastic channels tentatively suggests that these channels are important components of the doorway-state wave function. These observations provide the first direct, albeit incomplete, experimental evidence in support of a model[21,22] of the $^{12}C+{}^{12}C$ molecular resonances at high energies in which doorway states are created by coupling the molecular shape resonances of the elastic channel to more tightly bound channels containing one or both of the ^{12}C excited to the 2_1^+ state.

The authors wish to acknowledge several helpful discussions with Professor Peter Paul.

*Work supported in part by the National Science Foundation.

[1]E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 4, 515 (1960).

[2]E. Almqvist, D. A. Bromley, J. A. Kuehner, and B. Whales, Phys. Rev. 130, 1140 (1963).

[3]E. R. Cosman, T. M. Cormier, K. Van Bibber, A. Sperduto, G. Young, J. Erskine, L. R. Greenwood, and O. Hanson, Phys. Rev. Lett. 35, 265 (1975).

[4]K. A. Eberhard, E. Matliak, J. Stettmier, W. Trombik, A. Weidinger, L. N. Wuesterfeld, and K. G. Bernhardt, Phys. Lett. 56B, 445 (1975).

[5]N. R. Fletcher, J. D. Fox, G. J. Kekelis, G. R. Morgen, and G. A. Norton, Phys. Rev. C 13, 1173 (1976).

[6]L. R. Greenwood, R. E. Segel, K. Raghunathan, M. A. Lee, H. T. Fortune, and J. R. Erskine, Phys. Rev. C 12, 156 (1975).

[7]M. Conjeaud, S. Harar, S. M. Lee, A. Lepine, E. F. da Silveira, and C. Volant, in Proceedings of the European Conference on Nuclear Physics with Heavy Ions, Caen, France, 6–10 September 1976 (unpublished).

[8]K. A. Erb, R. R. Betts, D. L. Hanson, M. M. Sachs, R. L. White, P. P. Tung, and D. A. Bromley, Phys. Rev. Lett. 37, 670 (1976).

[9]Z. Basrak, R. Auger, B. Fernadez, J. Gastebois, and N. Cindro, J. Phys. (Paris), Lett. 37, L131 (1976).

[10]G. Kekelis and J. D. Fox, Phys. Rev. C 10, 2613 (1974).

[11]P. Sperr, D. Evers, K. Rudolph, W. Assman, E. Spindler, P. Konrad, and G. Denhofer, Phys. Lett. 49B, 345 (1974).

[12]H. T. Fortune, T. H. Braid, R. E. Segel, and K. Raghavan, Phys. Lett. 63B, 403 (1976), and Phys. Rev. C 14, 1271 (1976).

[13]P. Sperr, T. H. Braid, Y. Eisen, D. G. Kovar, F. W. Prosser, Jr., J. P. Schiffer, S. L. Tabor, and S. Vigdor, Proceedings of the Symposium on Macroscopic Features of Heavy Ion Collisions, Argonne National Laboratory, 1–3 April 1976 (unpublished).

[14]Herman Feshbach, J. Phys. (Paris), Colloq. 37, C5-177 (1976).

[15]T. M. Cormier *et al.*, to be published.

[16]$R=6.18$ fm, $a=0.35$ fm, $V=14.0$ MeV, $W=0$ MeV. See Adriano Gobbi, in *Proceedings of the Symposium on Heavy Ion Scattering, Argonne, Illinois, 1971*, edited by R. H. Siemssien (Argonne National Laboratory, Argonne, Ill., 1971), pp. 63–101.

[17]$R=6.18$ fm, $a=0.35$ fm, $V=8$ MeV$+0.25E_{\mathrm{c.m.}}$, $W=0$. See R. Malmin, Argonne National Laboratory Informal Report No. PHY-1972F, 1972 (unpublished); also G. H. Goritz and U. Mosel, Z. Phys. A 277, 243 (1976).

[18]B. Imanishi, Nucl. Phys. A125, 33 (1969), discusses the absorption appropriate to the energy and angular momentum region of molecular coupling.

[19]See also A. Arima, Gertrude Scharff-Goldhaber, and K. W. McVoy, Phys. Lett. 40B, 7 (1972).

[20]It is assumed that $\Gamma_{\mathrm{tot}}=\Gamma_c+\Gamma_{2^+}+\Gamma_{2^+,2^+}+\Gamma_{\mathrm{CN}}$.

[21]Imanishi, Ref. 18.

[22]B. Fink, W. Scheid, and W. Greiner, Nucl. Phys. A188, 259 (1972).