Partial Widths of Molecular Resonances in the System $^{12}C+^{12}C$

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Total-cross-section excitation functions for $^{12}C+^{12}C$ single and mutual inelastic scattering, and fusion, have been analyzed to yield partial widths of the $J^{\pi}=(10^+)$, (12^+), and (14^+) gross structure resonances. The results are shown to be consistent with the double-resonances picture in which the strongly collective 2_1^+ inelastic excitations act as doorway states.

Intermediate structure resonances with $\Gamma = 100$ to 800 keV have been observed for many years in the $^{12}C+^{12}C$ system over a very broad energy range. It has been recently noted by Feshbach[1] that these resonances are strongly clustered into groups of the same spin a few MeV in width and that the envelope of the individual resonances are well correlated with the gross structure oscillations seen in the $^{12}C+^{12}C$ total fusion excitation function.[2] The centroids of the gross structure resonances appear to follow a $J(J+1)$ rule[1,3] with a moment of inertia comparable to that of two tangent ^{12}C spheres. These features suggest[1] the existence of a band of isolated doorway states ($\Gamma = 2-4$ MeV) commencing at $E_x(^{24}Mg) \simeq 20$ MeV which are fragmented into individual states with $\Gamma = 100-800$ keV by weak coupling to the excited states of the system.

The observed gross structure resonances are considerably narrower, especially at higher excitation energies, than those expected in the reaction cross section from optical-model calculations.[4] The experimental total widths thus indicate the occurrence of intermediate processes corresponding to components in the resonant state wave function which are slightly more complicated than pure $^{12}C+^{12}C$ molecular shape resonances.

In reference to the original, very narrow ($\lesssim 100$ keV) sub-Coulomb $^{12}C+^{12}C$ resonances,[5] Nogami and Imanishi[6] first suggested that resonant coupling to the 2_1^+ inelastic channel could be responsible for the increased binding and subsequent reduction in total width of these states which carried a significant fraction of the $^{12}C+^{12}C$ single-particle strength. Fink, Scheid, and Greiner[7] extended this picture to higher energies and predicted the occurrence of double resonances, i.e., resonant collective excitation within windows defined by entrance-channel shape resonances.

The present Letter reports new experimental data of $^{12}C+^{12}C$ elastic and single 2_1^+ inelastic scattering which are sufficient to permit a complete partial-width decomposition of the $J^{\pi}=(10^+)$, (12^+), and (14^+) gross structure resonances in the elastic, inelastic, and fusion channels, respectively. We have measured the total cross section for $^{12}C+^{12}C$ single 2_1^+ inelastic scattering from $E_{c.m.} = 15-35$ MeV in steps ranging from $E_{c.m.} = 50-125$ keV using the Brookhaven National Laboratory MP-6 Tandem Van de Graaff. The total 2_1^+ cross section and the elastic deviation function were determined from excitation functions measured using a large Si surface-barrier detector array at sixteen equally spaced angles covering the range of $\theta_{c.m.} = 10°-90°$. The details of the excitation functions will be published elsewhere. Here we focus on the total cross sections and the deviation function of the elastic scattering as shown in Fig. 1. In this figure, the total fusion cross-section excitation function is from Ref. 2, and the total mutual $2_1^+2_1^+$ inelastic cross section is from Ref. 4. The present measurement of the total 2_1^+ inelastic cross section has been extended below $E_{c.m.} = 15$ MeV using the data of Emling *et al.*,[8] and above $E_{c.m.} = 35$ MeV using the data of Stokstad *et al.*[9]

The excitation function of $\sigma_{tot}(2_1^+)$ reveals simi-

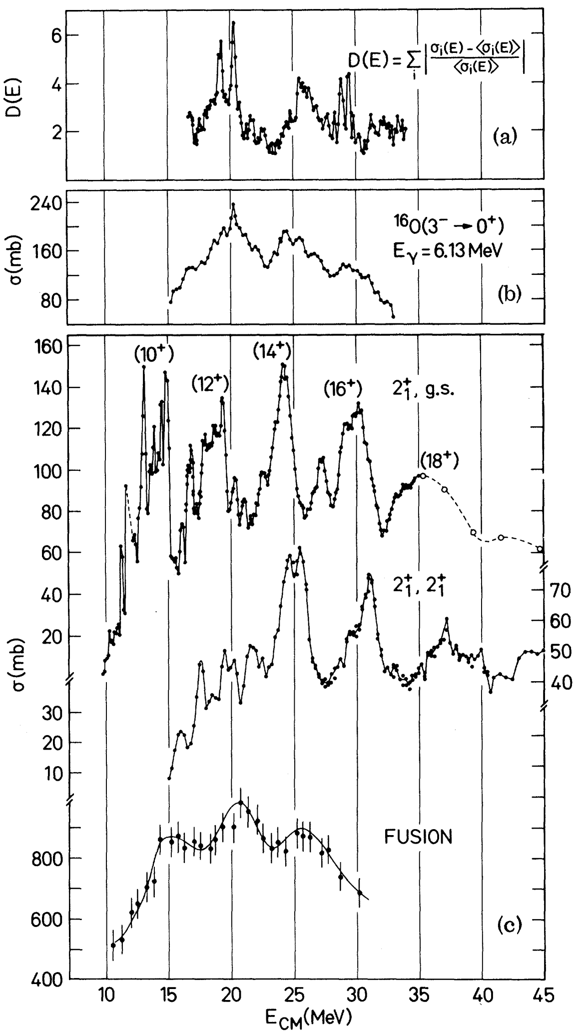

FIG. 1. (a) Deviation function, $D(E)$, calculated from sixteen elastic excitation functions using an averaging interval of 1.5 MeV. (b) Excitation function for the $^{16}O(3^- \to 0^+)$ γ ray (Ref. 11). (c) Total–cross-section excitation functions for single inelastic ($2_1^+ +$g.s.) scattering (present work), mutual inelastic ($2_1^+ + 2_1^+$) scattering (Ref. 4), and fusion (Ref. 2).

lar gross structure resonances to those seen in previous 4.43-MeV γ-ray singles data.[4] An important new feature, revealed by the higher-energy resolution of the present experiment, is the clear fragmentation of the two lowest-energy gross resonances into individual resonances with Γ varying between 100 and 600 keV. The spins indicated for the gross structure resonances in Fig. 1 are the tentative assignments of Ref. 4.

Figure 1 also shows the deviation function, $D(E)$, of elastic scattering calculated from the sixteen individual excitation functions measured in the present work. Two very prominent sharp resonances are superimposed on the $J^\pi = (12^+)$ maximum of $D(E)$ at $E_{\text{c.m.}} = 19.3$ and 20.3 MeV, both with $\Gamma \simeq 500$ keV. The latter is also the most prominent sharp resonance seen in $\sigma_{\text{tot}}(2_1^+)$ and corresponds to the well-known resonance seen in n, p, and d exit channels.[10]

We observe energy shifts between the centroids of the gross structure maxima in the various channels. To facilitate the comparison with the fusion data we show in Fig. 1 an excitation function[11] of the $E_\gamma = 6.13$-MeV, $^{16}O(3_1^- \to 0^+)\,\gamma$ transition. This transition is produced almost entirely from the fusion reaction $^{12}C(^{12}C, 2\alpha)^{16}O^*$ and is known to be almost exclusively responsible for the fusion maxima at $E_{\text{c.m.}} = 20$ and 25 MeV.[12] The energy shift relative to the fusion maxima is smallest at high $E_{\text{c.m.}}$ and is generally smaller for the $2_1^+2_1^+$ channel and larger for the 2_1^+ ground-state (g.s.) channel. The shifts are, however, everywhere $< \frac{1}{2}\Gamma$ and we therefore assume that differing energy dependence of penetrabilities in the $2_1^+2_1^+$ and 2_1^+ g.s. channel produce these shifts. This interpretation is supported by coupled-channels calculations.[13]

A partial-width decomposition for the $J^\pi = (10^+)$, (12^+), and (14^+) gross structure resonance is made by assuming that the experimental total width is given by

$$\Gamma = \Gamma_c + \Gamma_{2^+} + \Gamma_{2^+2^+} + \Gamma_{\text{c.n.}}, \tag{1}$$

and that

$$\sigma_i = 2(2J+1)\pi\lambda\!\!\!^{-2} \frac{\Gamma_c \Gamma_i}{(\Gamma/2)^2} \tag{2}$$

(with $i = 2^+, 2^+2^+$, and c.n.) relates the resonant total cross sections σ_i and the various partial widths. The compound-nucleus cross section $\sigma_{\text{c.n.}}$ and corresponding width $\Gamma_{\text{c.n.}}$ are identified with the resonant component of the fusion cross section[2] which we assume reflects the resonant strength in the n, p, d, and α channels. The error in $\sigma_{\text{c.n.}}$ due to background subtraction amounts to $\pm 25\%$ and is by far the largest source of error in the Γ_i.

The resulting two solutions to the system of quadratic equations (1) and (2) for the partial widths are given in Table I. The first solution is dominated by the inelastic widths and has $\Gamma_c/\Gamma = 0.18$ at $J^\pi = (12^+)$ while the second has $\Gamma_c/\Gamma = 0.80$. A study of the $E_{\text{c.m.}} = 19.3$ MeV fine-structure resonance as observed in the present elastic scattering data allows us to readily distinguish between these two alternatives. Thus Fig. 2

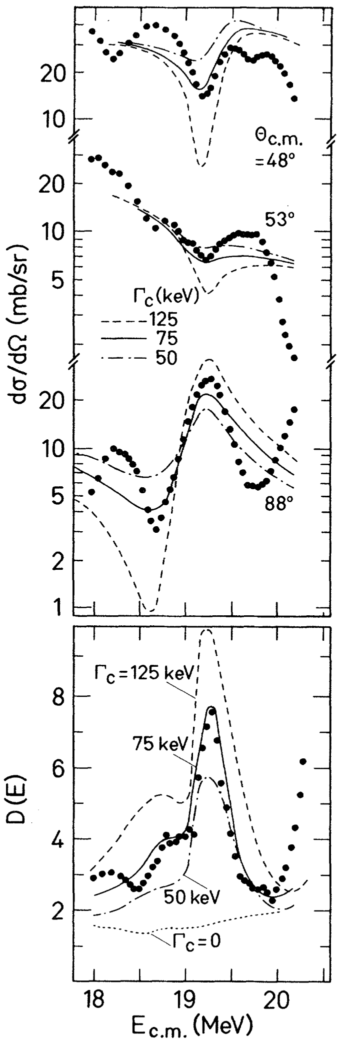

FIG. 2. Selected experimental and calculated excitation functions and deviation function (averaging interval = 3.0 MeV) for $^{12}C + ^{12}C$ elastic scattering in the vicinity of the $E_{c.m.} = 19.3$ MeV resonance.

shows single-level Breit-Wigner fits to selected excitation functions and to the elastic deviation function. The background S matrix (S_l) in these calculations has been generated with the usual optical models.[14] Extensive tests were made, however, to establish that the extracted Γ_c was not sensitive to details of the background S_l. The best fit is obtained for $\Gamma_c = 75 \pm 25$ keV ($\Gamma_c/\Gamma = 0.15 \pm 0.05$) where the error expresses the *maximum* uncertainty due to S_l and the resonance mixing phase. The elastic scattering thus rules out Solution 2 of Table I.

Reduced widths γ_{il}^2 for Γ_i of Solution 1 (with $i = c$, 2^+, and 2^+2^+) are defined by

$$\Gamma_i = \sum_l 2P_l \gamma_{il}^2. \qquad (3)$$

TABLE I. Two solutions for partial widths of the gross structure resonances. Typical errors are ± 25%.

J^π	Γ_{tot} (MeV)	Γ_c (MeV)	Γ_{2^+} (MeV)	$\Gamma_{2^+2^+}$ (MeV)	Γ_{en} (MeV)	Γ_c/Γ_{tot}
			First solution			
10^+	1.8 ± 0.2	0.60	0.31	≤ 0.07	0.82	0.33
12^+	3.0 ± 0.3	0.54	0.95	≤ 0.15	1.35	0.18
14^+	2.5 ± 0.2	0.55	0.93	0.45	0.56	0.22
			Second solution			
10^+	1.8 ± 0.2	1.35	0.11	≤ 0.01	0.13	0.75
12^+	3.0 ± 0.3	2.41	0.22	≤ 0.04	0.33	0.80
14^+	2.5 ± 0.2	1.94	0.27	0.13	0.16	0.78

The penetrabilities, P_l, are always somewhat problematic because of a sensitivity to the ill-defined matching radius. In the present case where all the channels of interest are comparably well matched it is sufficient to take $P_l \sim (1 - |S_l|^2)$ and avoid the problem of the matching radius. This procedure should reliably generate reduced-width ratios. We further make the usual assumption that the lowest allowed l value dominates the decay. The resulting reduced-width ratios are given in Table II from which it is seen that the inelastic channels make up the largest fraction of the resonant-state wave function.

In conclusion, the gross structure resonances of the $^{12}C + ^{12}C$ system have been studied in the elastic and single 2_1^+ inelastic channels. The experimental total widths are considerably smaller especially at high E_x than optical-model shape resonances for this system.[4] This points to the occurrence of ^{24}Mg intermediate structure states. A partial-width decomposition of the $J = (10^+)$, (12^+), and (14^+) gross structure resonances has been achieved on the basis of total resonant cross

TABLE II. Ratios of reduced widths, relative to the elastic channel, corresponding to the first solution of Table I. Typical errors, exclusive of pentrability uncertainties, are ± 25%.

J^π	c	2^+	2^+2^+
10^+	1.0	0.82	≤0.17
12^+	1.0	1.34	≤0.29
14^+	1.0	1.03	0.42

sections and elastic scattering results. We find that the reduced widths of the inelastic channels are comparable to those of the elastic channel. This latter observation is in agreement with the qualitative expectation of the Nogami-Imanishi model[6] of $^{12}C+^{12}C$ intermediate structure.

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[14]See Ref. 4 for a discussion of the potentials used here.

Periodic Structure in the Heavy-Ion Reactions $^{18}O+^{12}C$ and $^{18}O+^{16}O$

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Pronounced periodic structure has been observed in the inelastic scattering of ^{18}O on ^{12}C for energies between 10 MeV and 23.6 MeV (center of mass). A similar effect is also seen in the $^{18}O+^{16}O$ reaction.

In two recent articles[1,2] we have described experiments on fusion-evaporation reactions induced by ^{16}O bombardment of ^{12}C and ^{16}O, using γ-ray techniques. These studies were stimulated by the discovery of oscillations in the total fusion cross section of the $^{16}O+^{12}C$ reaction by Sperr *et al.*[3] and we have subsequently found a similar regular structure for the $^{16}O+^{16}O$ system also. In order to investigate whether parallel behavior might exist in neighboring systems we have repeated these experiments replacing the ^{16}O beam by ^{18}O, which, like ^{16}O, has spin 0, but whose first excited state (1.98 MeV, $J^\pi=2^+$) lies more than 3 times lower in excitation energy. We will report in this Letter how we have found that oscillation are still present in these systems but are much more apparent in the inelastic than in the fusion-evaporation channels.

The experimental method has already been described in our earlier articles,[1,2] though this time we have not attempted to determine the "total" fustion cross section by summing the intensities of all the ground-state transitions observed. This was rendered difficult by the presence of certain activities, notably from ^{28}Al and ^{29}Al. Moreover, in the case of the $^{18}O+^{12}C$ reaction the total fusion cross section has been measured by heavy-fragment detection techniques[4] and found to be relatively structureless for an energy range roughly the same as in the present experiments. Our intention, rather, was to determine whether structure might still appear in some individual channels, and the γ-ray techniques which we have employed are, for a number of reasons (high statistics, clean separation for different residual nuclei, weak angular-distribution effects), well suited to this purpose.

The ^{18}O beams were supplied by the Strasbourg MP tandem accelerator. The targets were made from natural carbon and oxygen: 40-$\mu g/cm^2$ carbon on a gold foil for the carbon target; and for oxygen, 250-$\mu g/cm^2$ Ta_2O_5 layer on tantalum.

