# Resonant and average behavior of the $^{12}C+^{12}C$ total reaction cross section: $5.6 \leq E_{c.m.} \leq 10.0$ MeV

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The gamma-radiation yields from the $^{12}C+^{12}C$ interaction were measured in steps of 50 keV over the bombarding energy range $11.8 \leq E_{lab} \leq 20$ MeV in order to study the energy dependence of the total reaction cross section. Several new resonances, occurring at $E_{c.m.} = 6.49$, 7.30, 7.45, 9.33, and 9.67 MeV, were identified in these yields. Carbon partial widths were determined for a number of resonances, and these widths demonstrate the quasimolecular nature of the corresponding structures. The average or background trend of the energy dependence of the reaction cross section was found to be adequately described by an incoming-waves boundary condition model, however, and no evidence was found in the energy-averaged yields for anomalous absorption in the $^{12}C+^{12}C$ system.

[NUCLEAR REACTIONS $^{12}C(^{12}C,\gamma)$, $E=11.8$–20.0 MeV; measured $\sigma(E)$, deduced total $^{12}C+^{12}C$ reaction cross section. Located five new narrow resonances. Measured total widths, estimated carbon partial widths of resonances. Optical model analysis of $\sigma_{React}$, using incoming-wave boundary condition model.]

## I. INTRODUCTION

A great many candidates for carbon quasi-molecular resonance structure have been identified recently through studies of various exit channel yields at energies just above the Coulomb barrier.[1-6] Because only limited data are available for cross-channel comparisons, however, many of these candidates may be interpreted either as resonances or as statistical fluctuations.[7] Additional data are therefore needed both to resolve this ambiguity and to permit the extraction of partial width information which would specify more precisely the nature of the structures.

In this paper we report measurements of the total gamma radiation from the $^{12}C+^{12}C$ interaction at closely spaced energies ranging from just below ($E_{c.m.} = 5.6$ MeV) to several MeV above ($E_{c.m.} = 10$ MeV) the Coulomb barrier. Over most of this energy range, the summed gamma yields closely approximate the $^{12}C+^{12}C$ total reaction cross section, and thus *narrow* structures observed in the measured excitation function may be identified with confidence as genuine resonances. Since the occurrence of these resonances in the total reaction cross section reflects their underlying carbon-carbon parentage, the present data may be used to obtain quantitative estimates of the resonant carbon partial widths and thus to study the quasimolecular character of the resonances.

The average or background energy dependence of the $^{12}C+^{12}C$ reaction cross section is also of considerable interest. Studies of sub-Coulomb cross sections have shown that fusion yields can change dramatically from system to system,[8] but comparisons of neighboring systems at energies just above the barrier have been hindered by inconsistent data. Thus, while the subbarrier $^{12}C+^{12}C$ data reported by several groups[9-13] are in general agreement (except for small differences in energy calibration and at the very lowest energies), discrepancies appear as the energy is increased above the Coulomb barrier. The present data clarify this situation and indicate that the average energy dependence of the $^{12}C+^{12}C$ fusion or reaction cross section in the region just above the Coulomb barrier is consistent with systematics derived from neighboring systems and from $^{12}C+^{12}C$ energy-averaged data obtained at both higher and lower energies.[14-16] Preliminary reports of the present work have appeared elsewhere.[17]

## II. EXPERIMENTAL PROCEDURE AND RESULTS

The gamma radiation resulting from $^{12}C+^{12}C$ interactions was measured in steps of 50 keV over the bombarding energy range $E_{lab} = 11.8$ to 20.0 MeV using a 35 cm$^3$Ge(Li) detector. The detector was placed approximately 3 cm from the target at an angle of 90° to the incident beam. The target consisted of a 5 $\mu$g/cm$^2$ natural carbon foil, mounted on a thick gold backing which stopped both the incident beam and the recoiling residual nuclei. The spread in beam energy introduced by the carbon portion of the target corresponds to a maximum averaging interval of 16 keV in the $^{12}C+^{12}C$ center of mass system.

Beam current integration was accomplished by collecting the charge deposited in the target and gold backing. Secondary electron emission was suppressed by biasing the target at a potential of +1000 V, and by surrounding it (except for a small beam port) with a cylindrical stainless steel mesh maintained at −1000 V. Tests carried out periodically during the experiment verified that the charge collected using this arrangement agreed within 1% with that measured by removing the target and collecting the beam in a well-isolated Faraday cup.

The effects of carbon buildup on the target were monitored by systematic repetition of measurements at selected beam energies; a small effect was observed and corrected for in the analyses of the data.

A typical gamma-ray spectrum is shown in Fig. 1. Aside from the peak associated with Coulomb excitation of the gold backing, the most intense yields in Fig. 1 correspond to radiation from the first-excited levels of $^{23}$Na (440 keV), $^{23}$Mg (451 keV), and $^{20}$Ne (1634 keV). This result is consistent with previous observations[9,10] that $^{23}$Na, $^{23}$Mg, and $^{20}$Ne are the principal residual nuclei produced in $^{12}$C + $^{12}$C interactions at these low bombarding energies (following proton, neutron, and alpha-particle emission, respectively, from the $^{24}$Mg compound system), and that a major fraction of the deexcitation radiation cascades through the respective first-excited states. Thus, the present yields represent a measure of the $^{12}$C + $^{12}$C reaction cross section. The conversion of this measure to an absolute cross section for the production of $^{23}$Na, $^{23}$Mg, and $^{20}$Ne is, however, complicated by a lack of precise information concerning both the fraction of nuclear reactions which contribute to the individual transitions observed, and also by angular distribution effects in the gamma deexcitation patterns. We have found, for example, in measurements made at several bombarding energies, that the decay radiation is not isotropic for the 440, 451, and 1634 keV transitions studied in the present work.

In an attempt to circumvent these difficulties, we have normalized the present 90° gamma yields directly to the results of earlier studies in which proton, neutron, and alpha-particle production cross sections were measured directly. The summed 440 and 451 keV gamma yields, corrected for detection efficiency, beam exposure, target thickness buildup, and electronic dead-time effects, were normalized by means of a single overall multiplicative factor to the summed $^{23}$Na and $^{23}$Mg production cross sections reported by Patterson, Winkler, and Zaidins (PWZ).[9] The results of this procedure are compared with the PWZ data in the lower part of Fig. 2, where it is demonstrated that excellent agreement is obtained over the entire range of energies studied here. The same overall normalization factor was applied to the 1634 keV gamma yields, producing the results plotted in the upper part of Fig. 2. This procedure yielded good agreement at the lower energies with the alpha-particle cross sections reported by PWZ (not plotted), but serious discrepancies were observed at higher energies where the PWZ cross sections increased much faster than our gamma-radiation yields with increasing bombarding energy. (In fact, the $^{20}$Ne yields reported by PWZ exceed the total $^{12}$C + $^{12}$C reaction cross section measured by Sperr *et al.*[18] at energies above $E_{c.m.}$ = 8 MeV.) In contrast, generally good agreement

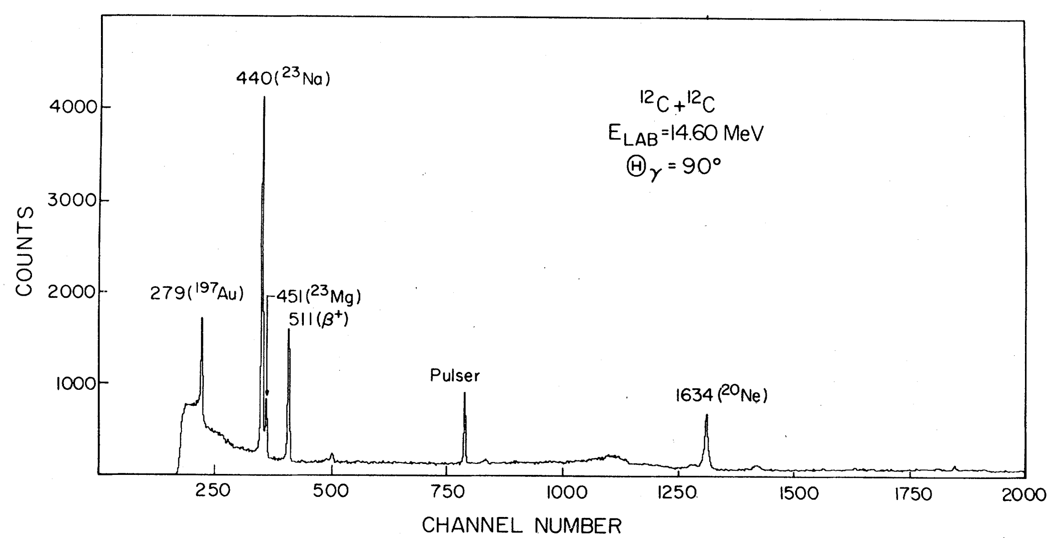


FIG. 1. Spectrum of gamma rays measured in the bombardment of $^{12}$C by $^{12}$C at 14.60 MeV.

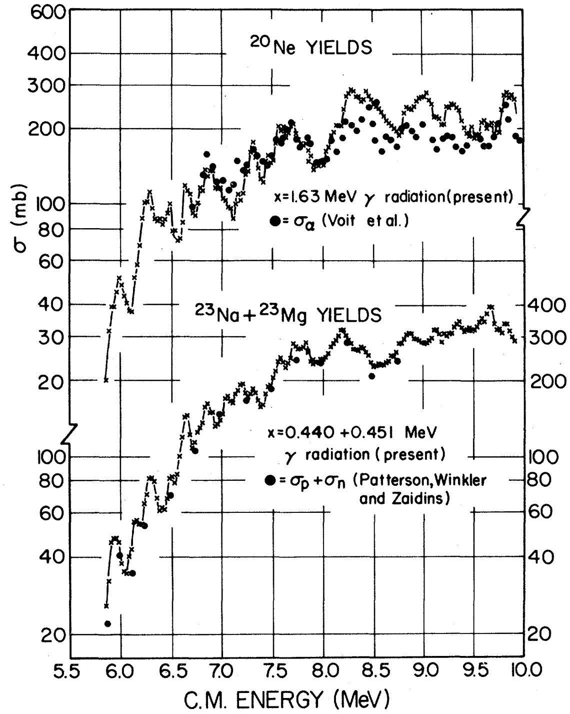


FIG. 2. Comparison of gamma-ray yields measured in the present study with the results of previous charged-particle measurements for the production of $^{20}$Ne (Ref. 3) and $^{23}$Na + $^{23}$Mg (Ref. 9). The gamma-ray yields shown were normalized by means of a single overall constant to reproduce the latter cross sections, as described in the text.

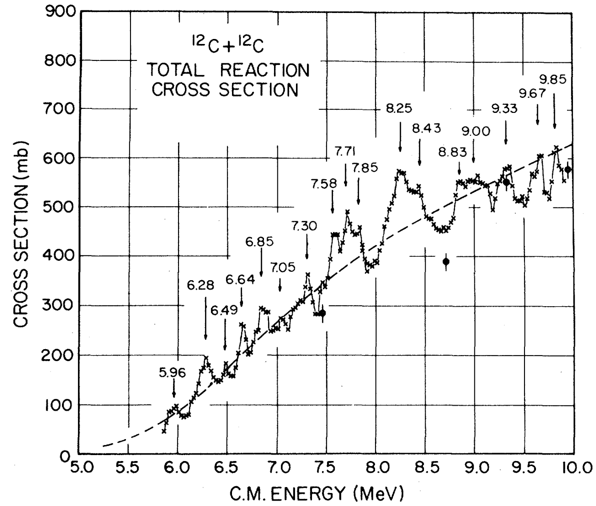


FIG. 3. Excitation function for the $^{12}C + ^{12}C$ total reaction cross section as determined in the present work. The charged-particle measurements of Ref. 18 are plotted as large dark circles for comparison. The dashed line is the result of an incoming-wave boundary condition model calculation (Ref. 14).

is obtained between our 1634 keV yields and the cross sections which were measured by Voit and collaborators[3] for the $^{12}C(^{12}C, \alpha)$ reaction resulting in the population of the first 11 levels of $^{20}$Ne. The latter results are compared with the present data in the upper portion of Fig. 2. Some differences appear at the higher energies, but these probably result primarily from an increasing cross section for $^{12}C(^{12}C, \alpha)^{20}Ne$ reactions leading to higher-lying states than those studied by Voit *et al.*

We note that a certain, albeit small, fraction of the particle-yield cross sections reported by Voit and PWZ cannot contribute to the gamma radiation observed in the present work—in particular that fraction corresponding to ground state reactions. The excellent agreement between the particle and gamma yields evident in Fig. 2 implies, however, that the cross section not reflected in the measured gamma-ray transitions has a bombarding energy dependence which is closely similar to that of the measured cross section. The unobserved cross section apparently can be accommodated by a single, implicit, normalization factor. The possibility of residual deviations from this general agreement cannot be excluded, and thus occasional errors may arise in the deduced excitation functions. While such errors would distort the measured resonance strength (i.e., partial widths), they would not affect the identification and location of the narrow resonances.

The summed cross sections for the production of $^{23}$Na, $^{23}$Mg, and $^{20}$Ne deduced from the gamma-radiation measurements are plotted in Fig. 3. Also shown in this figure are the total $^{12}C + ^{12}C$ cross sections measured at four different energies by Sperr *et al.*[18] Again, the agreement is quite acceptable, verifying that the normalized, summed gamma-radiation yields accurately reflect the total reaction cross section.

## III. DISCUSSION

### A. Average cross section behavior

The average bombarding energy dependence of the low energy $^{12}C + ^{12}C$ reaction cross section has been a subject of considerable controversy, involving both the experimental data and their theoretical interpretation. In examining the total cross section data then available, Michaud[19] concluded some time ago that these data implied the existence of a broad shape resonance in the $^{12}C + ^{12}C$ interaction between $E_{c.m.} = 3.5$ and 8 MeV, and also that only absorption at large separation distances (absorption under the barrier) could account for an apparent increase in the nuclear structure factor which had been reported[10] at the lowest energies. The need for absorption under the barrier was obviated, however, when subsequent, more precise, measurements by Kettner *et al.*[12] and High and Cujec[13] showed that the average $S$ factor does not increase with decreasing energy.

Christensen and Switkowski[14] found that a simple incoming-wave boundary condition (IWB) model could reproduce the average trend of the reaction cross section measured over the entire range below $E_{c.m.} = 6.5$ MeV. Since the absorption of the flux from the entrance channel was effected in these IWB calculations by imposing the boundary condition that the relative $^{12}C + ^{12}C$ motion consist of purely ingoing waves at small separation distances, rather than through the use of a complex optical potential, the average or background trend of the reaction cross section calculated in this model cannot be interpreted as reflecting either surface absorption or absorption under the barrier.

The question of broad shape resonances at somewhat higher energies (but still near the Coulomb barrier) remained open, however. In common with other nonresonant approaches, the IWB calculations of Ref. 14 failed to reproduce the energy-averaged magnitudes of the available cross-section data above $E_{c.m.} = 6.5$ MeV. The data obtained in the present experiment clarify this situation. The IWB model calculations of Ref. 14 are compared with our data in Fig. 3, demonstrating that the average trend of the measured reaction cross section is reproduced throughout the energy region where the earlier data had seemed to reflect the existence of a broad resonance. The IWB condition was imposed in Ref. 14 at radii within the pocket in the total $^{12}C + ^{12}C$ (real) interaction potential, preventing the formation of well-and-barrier resonances, and thus the energy dependence of the total reaction cross section calculated

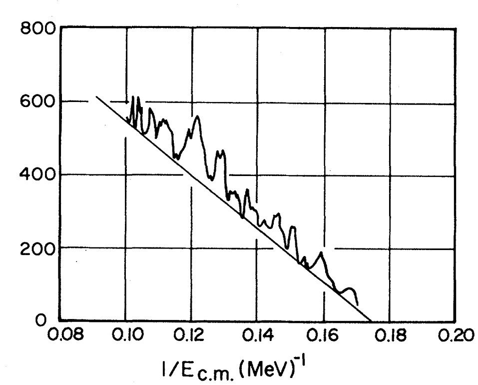


FIG. 4. The $^{12}C + ^{12}C$ total reaction cross section deduced from the gamma yields plotted vs $1/E$. The solid line representing the background yield was calculated using the Glas and Mosel parametrization (Ref. 15) with $V_B = 5.71$ MeV and $R_B = 6.36$ fm (see text).

in this model results simply from a combination of barrier penetrability factors and complete absorption at small radii. Whether the IWB model can reproduce the average energy dependence of the elastic scattering differential cross section remains an important open question awaiting future study. In any event, the resonances of the system appear in the present data, not as broad enhancements to be associated with anomalous potential scattering, but rather as narrow structures superimposed on (and possibly interfering with) components of a smoothly varying background.

Further evidence against the existence of broad resonances in the low-energy $^{12}C + ^{12}C$ total reaction cross section is obtained when our data are plotted vs $1/E$ as in Fig. 4. We see that the data are consistent with the existence of narrow resonances superimposed on a background which varies linearly with $1/E$—again suggesting that the background can be described adequately as reflecting the effects of barrier penetration followed by absorption to fusion as implied in the IWB calculations. In fact, following Glas and Mosel[15]—who parametrize fusion throughout the entrance channel barrier-dominated energy region by the expression

$$\sigma = \pi R_B{}^2(1 - V_B/E_{c.m.}) ,$$

where $V_B$ and $R_B$ specify the magnitude and location of the $s$-wave barrier—we obtain the background curve drawn in Fig. 4 using $R_B = 6.36$ fm and $V_B = 5.71$ MeV. These values are in good agreement with those of $R_B = 6.5 \pm 0.4$ fm and $V_B = 5.8 \pm 0.3$ MeV obtained from charged-particle measurements of the total $^{12}C + ^{12}C$ fusion cross sections at higher energies by Kovar *et al.*[16] We further note that our values for $R_B$ and $V_B$ are similar to those obtained for neighboring systems[16] in which resonance behavior is not observed in the barrier region. We conclude that the average behavior of the total cross section for the $^{12}C + ^{12}C$ system is unexceptional and that the only unusual aspects of the interactions in this system are the narrow resonances.

### B. Identification of resonances

Our experiment was undertaken primarily to identify and study the narrow resonances. The correlations which provide unambiguous signatures for $^{12}C + ^{12}C$ resonance behavior appear most clearly in the deviation function defined as

$$D(E) = \sigma(E)/\langle\sigma(E)\rangle - 1 .$$

This function was extracted from our data for the $^{20}Ne$ and the $^{23}Na + ^{23}Mg$ exit channels and also for the total reaction cross section, and the results

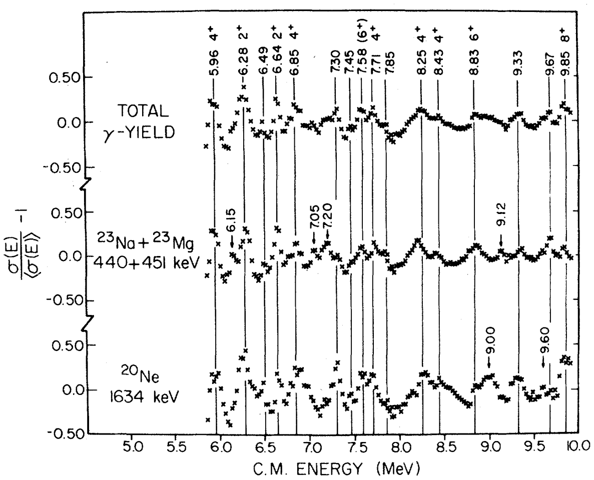


FIG. 5. Deviation functions described in the text plotted for the gamma yields measured in the present work. The observed resonances are also indicated.

are plotted in Fig. 5. A uniformly weighted average over a sliding interval of width $E_{\text{c.m.}} = 0.5$ MeV was used to calculate the quantities $\langle\sigma(E)\rangle$.

The structures indicated by the solid vertical lines in the deviation functions (Fig. 5) appear in all of the measured yields. In a few cases (for example, at $E_{\text{c.m.}} = 8.25$ MeV) small energy shifts in the positions of the peaks were observed in the different exit channels, but these perhaps may be attributed to the effects of interference between the resonances and the background. Several peaks appear prominently in either the ${}^{20}Ne$ or ${}^{23}Na + {}^{23}Mg$ yields, but not in both; these are also indicated in the figure. Although the latter are not so completely correlated among exit channels as to produce a well defined peak in the total cross section, their appearance in the summed yields for a given channel suggests that they may also be identified as ${}^{12}C + {}^{12}C$ resonances. We note that all resonances need not be coupled strongly to all open exit channels.

The resonance energies determined by the present data are listed in Table I. Also listed are resonances which have been identified previously in studies of individual exit channels. The probability that a peak in an excitation function reflects a statistical fluctuation varies inversely with both the number of independent reaction amplitudes which contribute to the measured yield and the magnitude of the resonantlike yield. Thus reliable indication of nonstatistical, or resonance, structure is obtained from measurements which examine many exit channels. The most extensive such measurements reported to date—those of Voit *et al.*[3]—involved the study of angle-integrated alpha-particle yields corresponding to the population of the lowest 11 levels of ${}^{20}Ne$ via the ${}^{12}C({}^{12}C, \alpha){}^{20}Ne$ reaction, and led to the first identification of several of the resonances observed in the present work. Branford,[7] however, carried out a statistical analysis of the data of Ref. 3 and concluded that of all the peaks identified by Voit *et al.* as resonances, only those at $E_{\text{c.m.}} = 8.46$, 9.84, and 10.63 MeV were inconsistent with normal statistical fluctuation phenomena, and that even for these three the departures from statistical expectations were not striking. Consequently, the reappearance of the previously identified resonance candidates in our total reaction cross-section data, and particularly in the total ${}^{23}Na + {}^{23}Mg$ yields, is significant. With correlated behavior thus observed in a considerably greater number of exit channels, a resonance interpretation of our excitation function peaks seems inescapable. The data obtained in our work also reveal the presence of previously unobserved resonances at $E_{\text{c.m.}} = 6.49$, 7.30, 7.45, 9.33, and 9.67 MeV.

### C. Carbon partial widths

In the vicinity of an isolated resonance superimposed on a slowly varying background, the nuclear scattering $S$ matrix may be expressed in the form

$$S_l(E) \equiv \eta_l e^{2i\delta_l} = \langle S_l(E)\rangle \left[1 + e^{i\varphi}\frac{i\Gamma_c}{(E-E_0) - i\Gamma/2}\right].$$

The averaged $\langle S_l(E)\rangle$ is to be associated with the (nonresonant) background scattering. Partial widths for carbon decay can be estimated from this equation with the aid of some simplifying assumptions for those resonances which appear clearly in the total ${}^{12}C + {}^{12}C$ reaction cross section.

We take the resonance mixing phase $\varphi$ to be zero in the present analysis, and thus the above equation reduces at the resonance energies to

$$\eta_l(E) = \langle \eta_l(E)\rangle [1 - 2\Gamma_c/\Gamma], \quad \text{for } \Gamma_c < \tfrac{1}{2}$$

and

$$\sigma_{\text{reaction}} = \sigma_{\text{background}} + \sigma_{\text{resonance}},$$

$$\sigma_{\text{background}} = 2\pi\lambda\!\!\!^{-2} \sum_{l_{\text{even}}} (2l+1)(1 - \langle\eta_l\rangle^2).$$

We thus obtain at $E = E_0$

$$\sigma_{\text{resonance}} = 4\sigma_l\langle\eta_l\rangle^2(\Gamma_c/\Gamma)(1 - \Gamma_c/\Gamma)$$

and

$$\Gamma_c/\Gamma = \tfrac{1}{2}[1 - (1 - \sigma_{\text{res}}/\sigma_l\langle\eta_l\rangle^2)^{1/2}], \tag{1}$$

with

$$\sigma_l = 2\pi\lambda\!\!\!^{-2}(2l+1).$$

TABLE I. Resonances observed in the gamma-ray yields from the $^{12}C+^{12}C$ reaction. Resonance energies are given in column 1 while the corresponding spins, obtained from the references cited in the last column, are listed in column 2. Deduced resonance properties discussed in the text appear in columns 3–6, and statistical model estimates for carbon partial widths are given for comparison in column 7. Information from previous work concerning these and nearby resonances is summarized in columns 8–11.

| | Present work | | | | | | Previous work | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_{c.m.}$ MeV (±20 keV) | $J^\pi$ Assumed | $\Gamma$ keV | $\sigma_{res}$ mb | $\Gamma_c$ (Min) keV | $\Gamma_c$ keV | $\langle\Gamma_c\rangle$ keV | $E_{c.m.}$ MeV | $J^\pi$ | $\Gamma_c$ keV | Ref. |
| 5.96 | $4^+$ | 100 | 35 | 3 | | 1.2 | 6.0 | $4^+$ | 4 | 23 |
| (6.15) | | | | | | | | | | |
| 6.28 | $2^+$ | 125 | 80 | 16 | | 0.9 | 6.25 | $2^+$ | | 3 |
| 6.49 | | $\geqslant 50$ | 38 | | | | | | | |
| 6.64 | $2^+$ | 100 | 85 | 15 | $40\pm8$ | 0.7 | 6.64 | $2^+$ | $29^{+6}_{-9}$ | 6 |
| | | | | | | | 6.83 | $4^+$ | $11\pm3$ | 6 |
| 6.85 | $4^+$ | 125 | 68 | 7.5 | $14\pm4$ | 0.8 | 6.87 | $4^+$ | | 3 |
| (7.05) | | $\geqslant 75$ | ~25 | | | | | | | |
| (7.20) | | | | | | | | | | |
| 7.30 | | ~75 | 70 | | | | | | | |
| 7.45 | | ~75 | ~40 | | | | | | | |
| | | | | | | | 7.50 | $6^+$ | | 2 |
| 7.58 | $(6^+)$ | 110 | 115 | 9 | | 1.3 | | | | |
| 7.71 | $4^+$ | 125 | 145 | 22 | | 0.6 | 7.71 | $4^+$ | | 1, 3 |
| 7.85 | $4^+$ | | | | | 0.6 | 7.90 | $4^+$ | | 3 |
| 8.25 | $4^+$ | 175 | 165 | 39 | | 0.5 | 8.26 | $4^+$ | | 3 |
| | | | | | | | 8.45 | $6^+$ | | 2 |
| 8.43 | $4^+$ | | | | | 0.4 | 8.46 | $4^+$ | | 3 |
| | | | | | | | 8.85 | $8^+$ | | 2 |
| 8.83 | $6^+$ | ~125 | 80 | 8.5 | | 0.8 | 8.86 | $6^+$ | | 3 |
| (9.00) | | | | | | | 9.05 | $6^+$ | | 31 |
| | | | | | | | 9.06 | $6^+$ | | 3 |
| (9.12) | | | | | | | | | | |
| | | | | | | | 9.25 | | | 2 |
| 9.33 | | ~125 | 80 | | | | | | | |
| (9.60) | | $\geqslant 75$ | ~55 | | | | | | | |
| 9.67 | | 100 | 80 | | | | | | | |
| 9.85 | $8^+$ | 100 | 105 | 7.5 | | 1.7 | 9.84 | $8^+$ | | 3 |
| | | | | | | | 9.98 | $6^+$ | | 31 |

We have chosen to investigate the solutions of the quadratic equations corresponding to $\Gamma_c/\Gamma<\frac{1}{2}$, partly to avoid an *a priori* bias in favor of molecular resonances, and partly because there is evidence that $\Gamma_c/\Gamma>\frac{1}{2}$ is inconsistent with the magnitudes of yields observed at higher energies in individual nonelastic channels.[20] It may be noted that in the limit $\langle\eta_l\rangle^2=1$ (no background absorption in partial wave $l$) the above expression for $\Gamma_c/\Gamma$ reduces to the familiar result obtained from the expression

$$\sigma_{\text{reaction}}\ (E=E_0)=8\pi\lambda^2(2l+1)\frac{\Gamma_c(\Gamma-\Gamma_c)}{\Gamma^2}\ .$$

The presence of background decreases the prominence of a resonance with a given value of $\Gamma_c/\Gamma$ in the total reaction cross section, as required by unitarity; conversely, a lower limit for $\Gamma_c/\Gamma$ may be obtained by setting $\langle\eta_l\rangle^2=1$ in the comparison of Eq. (1) with the data. In addition to lower limits, actual values for the resonant carbon widths could be extracted from the present data if detailed information were available concerning the behavior of the background scattering. The possibility of using optical model calculations to deduce the $\langle\eta_l(E)\rangle$ was explored, but it was found that the sensitive dependence of the results on poorly determined optical parameters rendered this approach too ambiguous to be useful. A detailed phase shift analysis of the $^{12}C+^{12}C$ elastic scattering data has been reported by Korotky *et al.*,[6] over the restricted energy range $6.5\leqslant E_{c.m.}\leqslant 7.0$ MeV, and the background parameters determined in that analysis were used in conjunction with the present data to obtain carbon partial widths for the resonances observed at 6.64 and 6.85 MeV. The extracted widths agree with those reported in Ref. 6. For the remaining resonances observed in the present work, lower limits for the carbon partial widths were deduced using Eq. (1) with $\langle\eta_l(E)\rangle^2=1$, and the results so obtained are summarized in Table I.

The spins of several resonances observed in the present data have not yet been measured, making the extraction of partial widths impossible. For this reason we have included the measured values of the resonant cross sections, $\sigma_{res}$, in Table I. With this information the corresponding partial widths can be calculated readily, once the spins are known. In a few other cases ($E_{c.m.}=8.43$, 8.83 MeV), we have had to choose between the conflicting assignments deduced from independent measurements of $^{12}C(^{12}C,\alpha)^{20}Ne$ angular distributions; we have adopted the spin assignments made in the more recent work of Voit *et al.*[3] Finally, we have tentatively identified the resonance which we observe at $E_{c.m.}=7.58$ MeV with the $6^+$ structure placed at $7.50\pm0.05$ MeV by Basrak *et al.*[2]

The particular importance of the carbon-carbon configuration in the structure of the resonances is reflected in the values of the carbon partial widths deduced in the present work. Limited by a lack of precise information concerning the average background scattering parameters $\langle\eta_l(E)\rangle^2$, we have for the most part been able to determine only lower limits for these important partial widths, but even these minimum values greatly exceed the widths which would result if the carbon-carbon configuration merely played a statistically determined role in the decay of the resonances. Partial widths corresponding to the latter situation may be estimated in a statistical compound nucleus model using the standard relation[21]

$$T_l^c(E)=2\pi\langle\Gamma_c\rangle_J/D_J(E)\,, \qquad (2)$$

where $T_l^c(E)$ is the transmission coefficient in the carbon channel, $\langle\Gamma_c\rangle_J$ is the statistical partial width, and $D_J(E)$ is the average level spacing in the compound ($^{24}Mg$) system. The latter quantities were calculated using the level density expression given by Lang[22] with parameters which, in conjunction with the Hauser-Feshbach model, have been found to describe accurately[23] a number of compound nucleus reactions proceeding through $^{24}Mg$. Although our choice of $\langle\eta_l\rangle^2=1$ in calculating lower limits for $\Gamma_c$ corresponds to $T_l(E)=0$, we have instead chosen $T_l(E)=0.5$ in Eq. (2) in order to obtain a conservatively large estimate of the statistical partial width. The resulting values for $\langle\Gamma_c\rangle_J$ are included in Table I.

The values of the carbon partial widths (lower limits) deduced in the analysis of the data are generally much larger than statistical estimates. This demonstrates the greatly enhanced carbon-carbon parentage of the resonances. We therefore conclude that these are quasimolecular resonances, similar in nature to the resonances originally identified by the Chalk River group[24] at energies just below the $^{12}C+^{12}C$ Coulomb barrier.

## IV. CONCLUSIONS

The gamma-radiation yields from the $^{12}C+^{12}C$ interaction were measured over the energy range $5.6\leq E_{c.m.}\leq 10.0$ MeV and were found to provide a convenient and accurate measure of the total $^{12}C+^{12}C$ reaction cross section. A number of resonances appeared prominently in these data, including several which had been identified previously in studies of various individual exit channels. Thus we confirm the nonstatistical character of these excitation function structures. In addition, several previously unobserved resonances were found at $E_{c.m.}=6.49$, 7.30, 7.45, 9.33, and 9.67 MeV.

Quantitative lower limits on the corresponding carbon partial widths were extracted from the data and were found to be much larger than carbon widths calculated for purely statistical processes. This result establishes the carbon-carbon quasimolecular character of the corresponding resonances.

No evidence was found for the existence of broad shape resonances in the $^{12}C+^{12}C$ interaction in the energy range under investigation. Apart from the narrow resonances, the variation of the measured cross section with energy was found to be consistent with systematics derived from measurements on neighboring systems. In particular, the average energy dependence of the present data is described adequately by the incoming-wave boundary condition model calculation of Christensen and Switkowski, which involves only normal barrier penetration followed by complete absorption.

It is interesting to compare this situation with the behavior of the $^{12}C+^{12}C$ system at higher collision energies, where narrow peaks are observed superimposed on broad structure in elastic[25] and inelastic[20,26] excitation functions. This broad structure has been described adequately in terms of both nonresonant diffractive[27] and molecular resonance[28,29] models, and experiments capable of distinguishing between these conceptually different descriptions have not yet been reported. The narrow structure is presumed to reflect the importance of certain internal degrees of freedom of the $^{12}C+^{12}C$ system,[30] but experiments have not yet revealed which of these should be incorporated in the theoretical models.

We suggest that additional attention should be focussed on the narrow resonances. For example, using the carbon widths determined in the present work for the Coulomb-barrier resonances, partial widths for additional channels ($\Gamma_i$) may be determined through the dependence of the corresponding yields on the product $\Gamma_c \Gamma_i$, and thus a detailed empirical description of the structure of these resonances may be obtained.

Note added: Excitation functions for the $\gamma$ decay of $^{20}$Ne, $^{23}$Na, and $^{23}$Mg produced in the $^{12}C + ^{12}C$ reaction have been reported by Andritsopoulos *et al.*[32] The relative cross sections reported in Ref. 32 and the present data are in good agreement.


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