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Gamma-ray studies of the $^{12}C+^{12}C$ system

L. J. Satkowiak, P. A. DeYoung, J. J. Kolata, and M. A. Xapsos
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556

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Excitation functions for the yields of ten residual nuclides from the $^{12}C+^{12}C$ reaction have been measured over the range $E_{c.m.}=5.25-20.0$ MeV in steps of 125 keV, using γ-ray techniques. Nearly all of the reaction channels, including those with light-particle evaporation, showed strong narrow structures. A qualitative statistical analysis performed on the data gave useful information about the locations of possible nonstatistical structure, based primarily on the very strong cross-channel correlation observed in the data set.

[NUCLEAR REACTIONS ^{12}C (^{12}C,x); $E_{c.m.}=5.25-20.0$ MeV; measured $\sigma(E)$ for production of $A=16-23$ reaction products; statistical analysis presented; deduced evidence for nonstatistical structure.]

I. INTRODUCTION

The $^{12}C+^{12}C$ reaction is one of the most studied "light"-heavy ion reactions, and one of the most interesting. Since the first reported[1,2] sub-Coulomb-barrier structure in the gamma ray and light-particle yields, much experimental work has been done on this system. Recent work[3-33] has shown considerable structure both above and below the Coulomb barrier. The question is whether any of these fluctuations can be identified with intermediate-structure resonances. Previous work by Kolata *et al.*[3] investigating the $^{12}C+^{12}C$ reaction from $E_{c.m.}=14$ to 31 MeV showed evidence for unresolved structure in the excitation function of the total fusion cross section, as well as in the yields of individual reaction channels. Some of these strong structures were very narrow, on the order of 250 keV, which was equal to the center-of-mass energy step size used in that experiment. The object of the present work was to connect the various experimental results by covering the energy range from below the Coulomb barrier into the region previously investigated in Ref. 3, and to do it in smaller energy steps to resolve the narrow structure previously noted. A qualitative statistical analysis of the extracted data, carried out in an attempt to ascertain the extent of correlations between the various reaction channels, will also be presented.

II. EXPERIMENTAL METHOD AND RESULTS

The experiment was performed with 10.5–40.0 MeV ^{12}C ions from the University of Notre Dame three-stage Van de Graaff accelerator. The target was a natural carbon foil of approximately 20 $\mu g/cm^2$ thickness on a gold backing. To help reduce the problem of carbon buildup during the experiment, the target was surrounded by a liquid nitrogen-cooled shroud which completely enclosed it except for a 1 cm diameter beam entrance aperture. Excitation function data were taken over the center-of-mass energy range from 5.25 to 20 MeV, in steps of about 125 keV, using standard γ-ray techniques. A 104 cm^3 Ge(Li) detector was placed at 55° with respect to the beam, and the primary relative normalization for the γ-ray spectra so obtained was derived from Coulomb excitation of the gold backing, with charge collection serving as a secondary standard. The absolute cross section scale was determined by normalizing to the data of Kolata *et al.*[3] over the region in which the two data sets overlapped. For further details of the experimental method, see Ref. 3.

Excitation functions for the ten major nuclides produced in the $^{12}C+^{12}C$ reaction were extracted from the yield of characteristic γ radiation. The energies of the γ rays whose yields were measured in the present experiment are listed in Table I, and the seven strongest reaction channels are shown in Figs. 1–3. The three yield curves not shown each had less than a 10 mb maximum cross section. Figure 1 shows the excitation functions for residues resulting from single-particle evaporation from the ^{24}Mg compound system. The three resonances first seen by Bromley *et al.*[1,2] in the γ ray, proton, and alpha-particle exit channels are indicated by asterisks. Single-proton evaporation from the compound system forms ^{23}Na, and the arrows on the ^{23}Na excitation function (Fig. 1) indicate structures studied

TABLE I. Ground-state gamma-ray transitions observed from the $^{12}C+^{12}C$ reaction and included in the total fusion cross section.

Nuclide	Evaporated particles	E_γ (keV)
^{16}O	2α	6130.7
^{18}F	αpn	937.0[a]
^{19}F	αp	197.2, 1235.8
^{19}Ne	αn	238.3, 275.2
^{20}Ne	α	1633.7
^{21}Ne	$2pn$	350.5[a]
^{22}Ne	$2p$	1274.6
^{22}Na	pn	583.0, 890.9, 1527.9
^{23}Na	p	439.8
^{23}Mg	n	450.7

[a] Maximum cross section less than 10 mb.

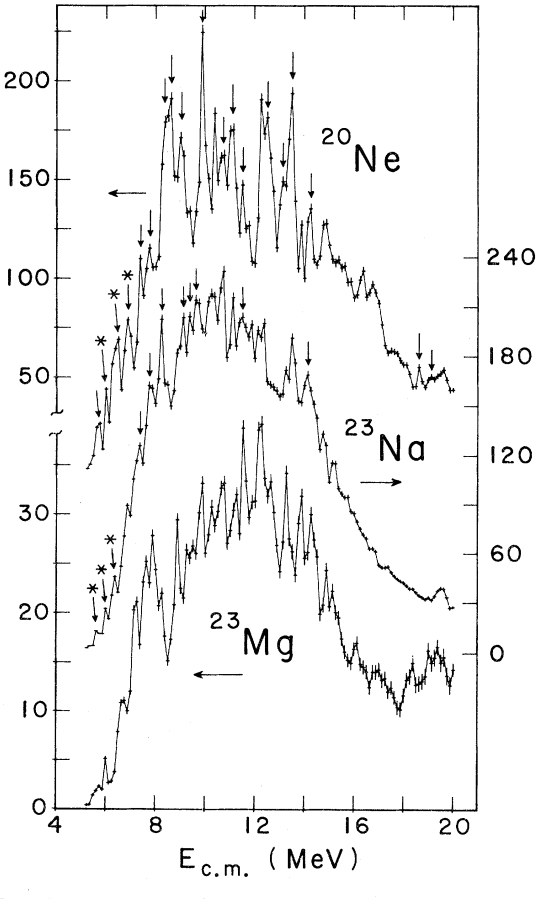

FIG. 1. Excitation functions for the production of the single-particle-evaporation residues of ^{20}Ne, ^{23}Na, and ^{23}Mg from the $^{12}C+^{12}C$ reaction, as measured in the present experiment.

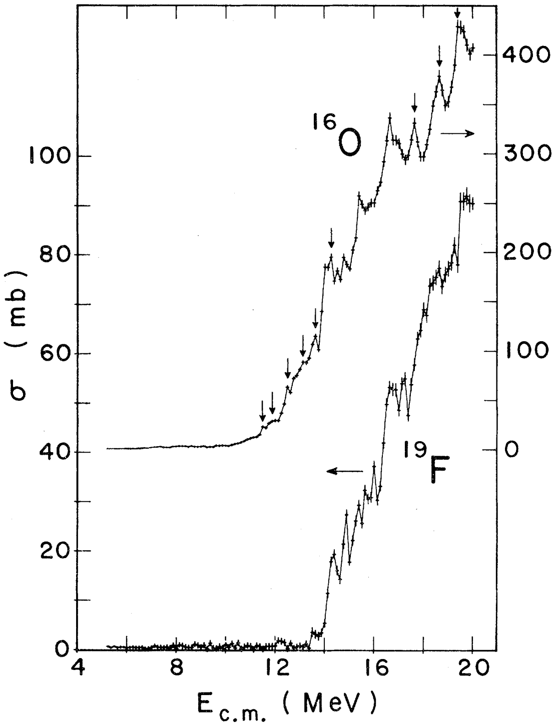

FIG. 2. The excitation functions for the production of ^{16}O and ^{19}F measured in the present experiment.

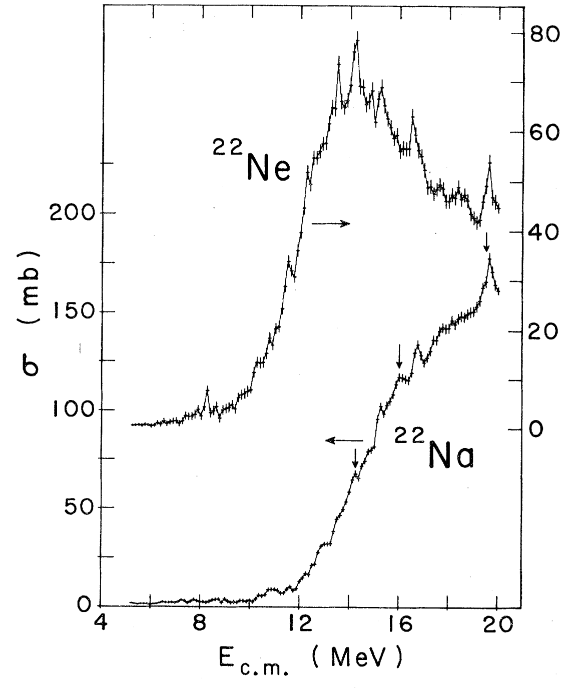

FIG. 3. The excitation functions for the production of ^{22}Ne and ^{22}Na measured in the present work.

in previous work (Refs. 6, 17, 20, 21, and 30) on the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reaction. Note that all of these fluctuations appear in the present data, and that several new structures are also apparent. The yield of $^{23}\mathrm{Mg}$ (single-neutron evaporation) is very similar to the $^{23}\mathrm{Na}$ yield, but smaller in magnitude. The third excitation function shown in Fig. 1 is the $^{20}\mathrm{Ne}$ single-α evaporation residue. Of all the $^{12}\mathrm{C}+^{12}\mathrm{C}$ reaction channels, $^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ has been studied the most extensively (Refs. 1, 2, 5–7, 9–11, 14–17, 22, 25, 27, and 33). The remaining arrows in Fig. 1 indicate structures that have previously identified in α-particle detection experiments. For example, Erb *et al.*[13] identified structures in their excitation functions at $E_{\mathrm{c.m.}}=6.49$, 7.30, 7.45, 9.33, and 9.67 MeV that exhibited a "nonstatistical character" and, to within our energy resolution, we apparently see the same structures. Treu *et al.*[14] observed resonances at $E_{\mathrm{c.m.}}=11.4$, 13.12, and 13.43 MeV which are quite prominent in the $^{20}\mathrm{Ne}$ excitation function of the present work (Fig. 1). Galster *et al.*[11,14,33] identified several "presumably nonstatistical structures" from a deviation analysis of their data (see Table II) and the agreement with this work is quite good. We note that all three single-particle evaporation yield curves contain more structure than previously noted, and that there appears to be a very high degree of correlation between these reaction channels.

The two-particle evaporation residues $^{16}\mathrm{O}(2\alpha)$, $^{19}\mathrm{F}(p\alpha)$, $^{22}\mathrm{Ne}(2p)$, and $^{22}\mathrm{Na}(pn)$ are shown in Figs. 2 and 3. Of these, the $^{16}\mathrm{O}$ yield is the largest, reaching over 400 mb at $E_{\mathrm{c.m.}}=20$ MeV. The arrows in Fig. 2 indicate structures noted in previous $^{12}\mathrm{C}(^{12}\mathrm{C},^{8}\mathrm{Be})^{16}\mathrm{O}$ work (Refs. 8, 12, 16, 18, and 19). The excitation function for production of $^{19}\mathrm{F}$ (Fig. 2) shows correlated structure, but the peak yield is only about 25% as large. Figure 3 illustrates the excitation functions for the $^{22}\mathrm{Ne}$ and $^{22}\mathrm{Na}$ yields, which also show strongly correlated anomalies. The structures noted by Lumpkin *et al.*[29] in their study of the $^{12}\mathrm{C}(^{12}\mathrm{C},d)^{22}\mathrm{Na}$ reaction are indicated by arrows. Finally, the total reaction yield for the $^{12}\mathrm{C}+^{12}\mathrm{C}$ system, determined by summing the partial yields, is shown in Fig. 4. Note in particular the profusion of narrow structures, as well as the broader anomalies which are likely to contain some as yet unresolved structure.

TABLE II. Resonantlike structure observed in the gamma-ray yields from the $^{12}\mathrm{C}+^{12}\mathrm{C}$ reaction.

$E_{\mathrm{c.m.}}$ (MeV)[a]		References to previous work
5.6		2, 10, 26, 31
6.0		2, 5, 10, 12, 13, 18, 26
6.5		2, 10, 12, 13, 18, 26
6.85		11, 12, 13, 26
7.4		6, 13, 17, 18
7.8		7, 11, 13, 17, 18, 33
8.25		11, 12, 13, 17, 18, 33
8.9	(9.0)	9, 11, 13, 17, 18, 33
9.1		6, 11, 13, 17, 18, 33
9.9		7, 11, 13, 17, 18, 28, 33
10.4		8, 18
10.6	(10.75)	8, 11, 18
10.9		8, 11, 18, 33
11.1		8, 9
11.5		8, 11, 14, 15, 21
12.2		8, 33
12.5		
13.1		14, 33
13.4		8, 14, 33
13.8[b]		3, 9
14.3		3, 8, 21, 29, 30
14.8		30
15.3		8
16.0[b]		3, 8
16.6		
17.1		8
17.3[b]		3
18.4[b]		8, 27
18.6		8, 16, 19, 27
19.3		3, 20, 21, 22, 27
19.6		29

[a] The energies of the structures noted in the present work are given, along with references to previous experiments.
[b] Weak structures which in some cases are also not well correlated.

III. ANALYSIS AND DISCUSSION

A statistical analysis of the measured excitation functions, involving the calculation of individual deviation functions, a deviation function averaged over all reaction channels, and an energy-dependent cross correlation function, was performed to identify possible correlations among the structures observed in the excitation functions. However, no quantitative statement will be made regarding the probability that a specific fluctuation is or is not of statistical origin. This quantitative analysis has been omitted due to questions regarding the applicability of standard Ericson theory[34] to excitation functions for which the number of open exit channels is a rapidly changing function of energy, as is the case for many of the production cross sections measured here. For example, the effective number

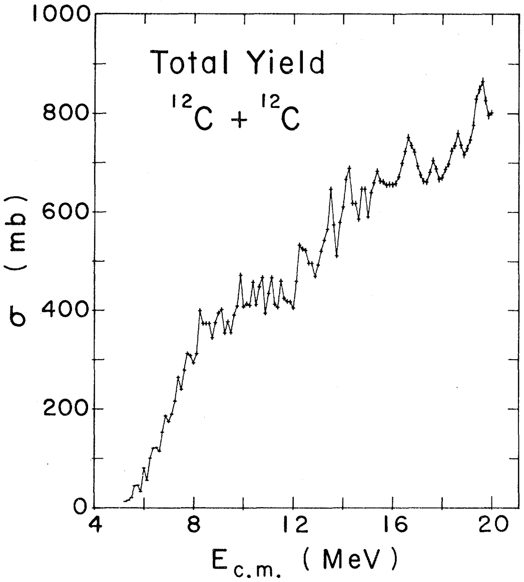

FIG. 4. The excitation function for the total fusion cross section for the $^{12}C+^{12}C$ reaction.

of channels calculated from the ^{22}Ne autocorrelation function for the first and last half of the measured energy range is 10 and 440, respectively. If one assumes that statistical fluctuations will not be correlated among the various reaction channels, then a qualitative analysis may still give an indication of the probable origin of the observed structures. This is due to the fact that the random nature of the fluctuations implies that in a sum of a large number of excitation functions the structures of statistical origin will average out and leave only correlated nonstatistical structures. From this one might then infer that the structures which are strongly correlated from exit channel to exit channel may be of nonstatistical origin. It should be noted, however, that under certain conditions statistical fluctuations may be correlated between channels due to unitarity effects,[35] and thus even strong correlations cannot be regarded as a *definitive* test of the nature of the observed anomalies.

A deviation function $D_i(E)$ was formed for each excitation function according to the prescription:

$$D_i(E)=\frac{\sigma_i(E)-\langle\sigma_i(E)\rangle}{\langle\sigma_i(E)\rangle}\ , \tag{1}$$

where $\sigma_i(E)$ is the measured cross section for the ith reaction channel as a function of energy, and $\langle\sigma_i(E)\rangle$ is a local average over the same excitation function. Usually, the average cross section, $\langle\sigma(E)\rangle$, is calculated with the techniques of Pappalardo.[36] With this method the average behavior of σ is determined by averaging over a limited energy range at each point. The size of this limited energy range is determined by examining the autocorrelation coefficient. The average cross section $\langle\sigma_i(E)\rangle$ was calculated by employing fast Fourier transform (FFT) techniques in an effort to obtain an average yield which is less subject to the influence of large local fluctuations than other methods.[36] The FFT technique consists of determining coefficients χ_k according to

$$\chi_{k+1}=\sum_{j=0}^{N-1}\sigma(E_{j+1})\exp(2\pi ijk/N)$$

$$\text{for } k=0,1,\ldots,N/2 \tag{2}$$

and

$$\chi_{N+2-j}=\chi_j^*\quad\text{for } j=2,\ldots,N/2\ ,$$

where N is the number of data points, χ_j^* is the complex conjugate of χ_j, and $i=\sqrt{-1}$. These coefficients can be used with the inverse transform:

$$\sigma(E_{k+1})=\frac{1}{N}\sum_{j=0}^{N+1}\chi_{j+1}\exp(-2\pi ijk/N)$$

$$\text{for } k=0,1,\ldots,N \tag{3}$$

to regenerate the original data. To form the average cross section $\langle\sigma(E)\rangle$, the real parts of the terms in the sum of Eq. (3) which correspond to high frequency behavior are set to zero (digital filter). The remaining terms are those for which

$$0\le j\le j_{\text{cutoff}}$$

and

$$N-j_{\text{cutoff}}+1\le j\le N\ .$$

The value of j_{cutoff} is adjusted to achieve a satisfactory average behavior, in analogy with the adjustment of the averaging interval in the method of Ref. 36. In some cases, such as excitation functions for the yields of ^{19}F or ^{16}O shown in Fig. 2, the data exhibit a sharp break in the slope of the cross section as the channel opens. The average cross section calculated with the FFT method then tends to oscillate in the region below the break. Such regions were excluded from subsequent analysis [i.e., $D_i(E)=0$ for $E<E_{\text{break}}$] on the assumption that the channel was not open below the observed E_{break}, so that oscillatory behavior of $\langle\sigma_j(E)\rangle$ was of no concern. Examples of the results obtained with the FFT method and the method of Ref. 36 are shown in Fig. 5 for the ^{23}Na channel. The averaging interval needed for the method of Ref. 36 was determined from the autocorrelation coefficients of the

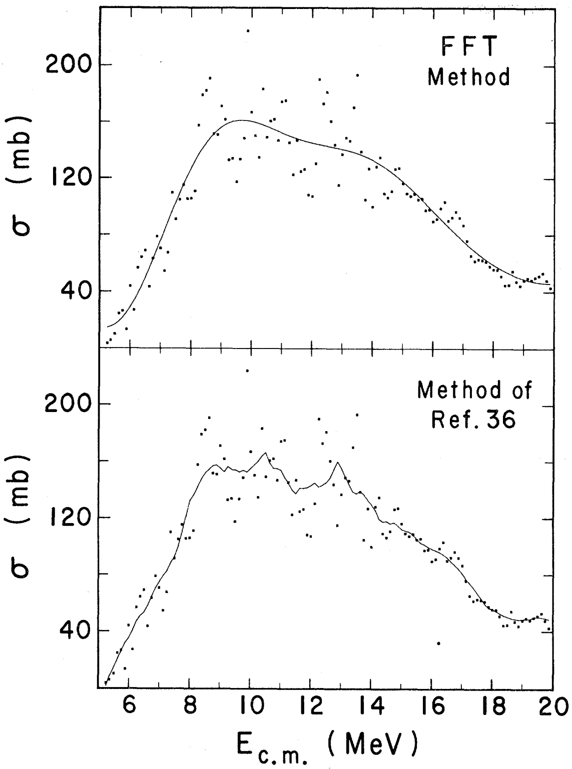

FIG. 5. The average cross section calculated using the fast Fourier transform (FFT) technique and the method of Ref. 36.

total fusion excitation function. The averaging interval was varied to find the first plateau and this value was subsequently applied to the measured excitation functions of the various residual nuclei. It can be seen that the FFT method gives a smoother average cross section, which is not so much influenced by strong local fluctuations. On the other hand, one cannot be as precise about the "averaging interval" used as in the method of Ref. 36. It was found that the qualitative analysis was not strongly sensitive to the averaging method used.

The average deviation function $D(E)$ was formed by taking a weighted average at each point of the eight independent deviation functions $D_i(E)$. The assumed random nature of statistical fluctuations implies that in this combination only correlated structures of nonstatistical origin should survive, all statistical fluctuations being averaged out or strongly attenuated. The energy dependent cross correlation function $C(E)$ is defined by:

$$C(E)=\frac{2}{N(N-1)}\sum_{i>j=1}^{N} D_j(E)D_i(E)\times[R_iR_j]^{-1/2}\ , \tag{4}$$

where N is the number of independent deviation functions, and R_i is an autocorrelation coefficient of the form

$$R_i=\langle D_i(E)^2\rangle-\langle D_i(E)\rangle^2\ , \tag{5}$$

where the averages are taken over the full range of data. Again one can appeal to the random nature of statistical fluctuations to suggest possible significance for those anomalies which appear strongly in this function. Note that the formulation given in Eq. (4) is essentially identical to that of Ref. 37. However, one extension of this procedure was made with regard to the treatment of correlated minima. With the definition of $C(E)$ given in Eq. (4) it can be seen that correlated minima will result in a positive peak in $C(E)$. This behavior somewhat complicates the interpretation of $C(E)$. If no significant anticorrelations $[C(E)<0]$ are observed or expected, it is convenient to shift all the deviation functions so that $D_i(E)$ is everywhere greater than or equal to zero. This will result in an energy dependent cross-correlation function in which only correlated maxima appear as peaks, but at the expense of eliminating any information regarding anticorrelations.

The various deviation functions, as well as the energy-dependent cross correlation function $C(E)$ defined above, are shown in Fig. 6. A high degree of correspondence between the curves is immediately evident. In the following, we discuss features which are especially noteworthy.

5.6, 6.0, and 6.5 MeV. These three resonances noted by Bromley *et al.*[1,2] gave the first indication of narrow structure in light heavy-ion collisions. The three structures are well correlated in all open exit channels. Fluctuations at these energies are seen in all single-particle-evaporation deviation functions as well as in the summed total deviation function and $C(E)$.

6.85 MeV. This resonance was first noted by Voit *et al.*[11] in an alpha particle experiment. In our data set, this structure is well correlated in all the open channels (except ^{23}Mg), and in $D(E)$ and $C(E)$.

7.4 and 7.8 MeV. The 7.4 MeV anomaly is correlated in the ^{20}Ne and summed total deviation functions as well as in $C(E)$ and $D(E)$. The 7.8 MeV resonance, assigned $J^{\pi}=4^{+}$ by Erb *et al.*,[7,13] is correlated in the deviation functions of all the open channels, and in $C(E)$ and $D(E)$.

8.25 MeV. This structure is strong in many channels. However, the multiplet nature noted previously[11,13,17,18,33] is only apparent in the ^{20}Ne exit channel.

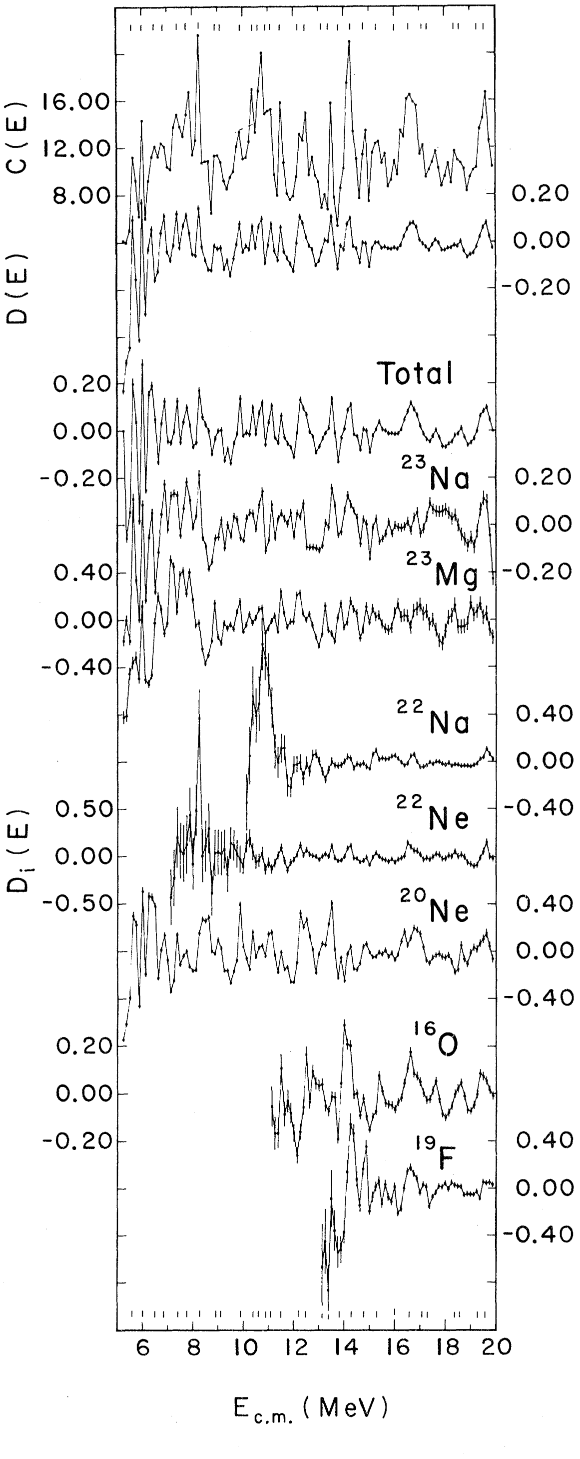

FIG. 6. The deviation function $D_i(E)$ determined from the cross sections of the various residues, the average deviation function $D(E)$, and the energy dependent cross correlation function $C(E)$ are shown here. The "tic" marks at the top and bottom are situated at energies discussed in the text.

8.9 and 9.1 MeV. Evidence for the existence of this doublet comes mainly from previous α-particle work.[11,13,17,18,33] The present data show a broad structure centered at 9.0 MeV in several channels in agreeement with the assumed doublet nature.

9.9 MeV. This structure has been noted in the literature[17,18,30,33] as being a doublet. The present data are consistent with a single anomaly, and are well correlated in all open channels except the ^{22}Ne and ^{23}Na exit channels.

10.4 MeV. This structure was seen by Wada *et al.*[18] and Fletcher *et al.*[8] in the ^{16}O exit channel. The present work shows that it is highly correlated among the deviation functions of all the open channels, as well as in $C(E)$ and $D(E)$.

10.75 MeV. The present data indicate only a single structure located at 10.75 MeV, although a doublet nature was noted in previous work.[11,18,33]

11.1, 11.5, 12.2, and 12.5 MeV. The anomalies at these energies are well correlated in many exit channels. This correlation is also evident in the deviation functions shown in Fig. 6. The doublet nature of the 12.2–12.5 MeV structure was not noted in previous work,[8,33] but is evident in the present data set.

13.1 and 13.4 MeV. Our data confirm the existence of structures at 13.1 and 13.4 MeV that were previously noted by Treu *et al.*[14,33] The 13.4 MeV anomaly shows a high degree of correlation among all the exit channels and in $C(E)$ and $D(E)$. The structure at 13.1 MeV is also well correlated.

14.3 and 14.8 MeV. The resonance at 14.3 MeV was first seen by Cosman *et al.*[21,30] and later by Fletcher *et al.*[8] The structure is well correlated in the deviation functions of all channels and in $C(E)$. Cosman *et al.*[21,30] also made a tentative identification of a structure at 14.8 MeV, which is quite evident in the present work, and is well correlated between the various exit channels.

15.3 MeV. The structure at 15.3 MeV is correlated in most of the exit channels, although the results from the ^{23}Na and ^{23}Mg residues may indicate a somewhat lower energy (15.2 MeV).

16.6 MeV. The broad structure located at 16.6 MeV is well correlated in all the deviation functions and $C(E)$. There is apparently no previous mention of it in the literature. The width of this new anomaly may indicate a multiplet nature.

18.6, 19.3, and 19.6 MeV. The broad structures at these energies show a high degree of correlation in all the open channels. The widths of the anomalies at 18.6 and 19.6 MeV suggest possible multiplet characteristics. Fortune *et al.*[27] assign four resonances in this region, at $E_{\text{c.m.}} = 18.4$, 18.6, 19.0, and 19.4 MeV, respectively. On the other hand, Dennis *et al.*[37] find only a single broad structure at $E_{\text{c.m.}} = 18.5$ MeV, and suggest that the apparent maxima at 19.0 and 19.4 MeV may be due to a correlated minimum at $E_{\text{c.m.}} = 19.2$ MeV reported by Greenwood *et al.*[22]

The very strong channel-to-channel correlations observed in the present data set tend to reinforce the conclusions of other authors (see, for example, Ref. 33) that a large part of the anomalies observed in ^{12}C+^{12}C excitation functions above the Coulomb barrier is probably of nonstatistical origin. We note that most of these earlier studies involved cross correlations among excitation functions to several excited states of a particular reaction product. In some cases, it was not even possible to obtain angle-integrated cross sections so that measurements taken at only a few angles were compared. In contrast, we have analyzed angle-integrated yields for the ten major nuclides produced from the ^{12}C+^{12}C reaction, summed over all final states except for direct ground-state yield. These inclusive production cross sections should already have much of the statistically fluctuating component averaged out. Nevertheless, strong signals persist in both the summed deviation function and the energy-dependent cross correlation function at most of the "known" resonance energies (Table II), and the corresponding structures are usually found to be well correlated in most, if not all, of the open reaction channels.

IV. CONCLUSION

Excitation functions for the formation of ten major reaction products from the ^{12}C+^{12}C system have been measured in the c.m. energy range from 5.25 to 20 MeV in steps of 125 keV, as an extension of previous work.[3] It was observed that the resulting yield curves are highly structured, and that the structure is very strongly correlated from one channel to another. An attempted quantitative statistical analysis of the data was unsuccessful, primarily because the local average cross section, and thus the effective number of open exit channels, is a rapidly varying function of energy for many of the production cross sections measured. On the basis of present results, it is estimated that a quantitative analysis would require data with an energy step size of less than 25 keV. On the other hand, a more qualitative approach was able to demonstrate that strong correlations do exist in the data set. One new feature of this analysis was the use of the FFT technique to generate the local energy-dependent average cross section $\langle \sigma_i(E) \rangle$, in a manner which is less subject than previous methods to the influence of the large local fluctuations that characterize the ^{12}C+^{12}C excitation functions. The results of this qualitative statistical analysis indicate that, to the extent that strong cross-channel correlations are a signature of nonstatistical structure, a large number of the anomalies observed in ^{12}C+^{12}C excitation functions in this and previous experiments is probably of nonstatistical origin. This includes structures which occur both below and above the ^{12}C+^{12}C Coulomb barrier. Of course, we have not shown that these anomalies are isolated resonances, and in fact out data suggest that at least some of them are doublets or multiplets. A crucial point here is the need to assign unique spins and parities (if possible) to these structures,[30] which we cannot address on the basis of the present experiment.

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