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Reaction cross sections for $^{12}C + ^{12}C$

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The yields of the eleven most abundant nuclides produced in the $^{12}C + ^{12}C$ reaction were determined in the energy range from 14–31 MeV (c.m.) via γ-ray techniques. Several reaction channels, including a few which involve only light-particle emission, show strong structure. Some of these anomalies are very narrow, having widths $\lesssim 250$ keV (c.m.). The 3α evaporation cross section, as well as the yield of ^{12}C via direct inelastic scattering, is determined. Further information is presented on the nature of a process leading to anomalously large α-particle yields from the $^{12}C + ^{12}C$ reaction at low energies. The strong gross-structure features of the fusion and total reaction cross sections are discussed in the context of the optical model, and also with reference to the limiting angular momentum for fusion. The latter analysis leads to some insight into the origin of the gross structure, but also suggests a striking correlation between the fusion cross section and the extended ground state band of ^{24}Mg at high energies. This correlation, if it is not coincidental, has interesting consequences with regard to the behavior of ^{24}Mg at high angular momentum and energy.

NUCLEAR REACTIONS Complete fusion, $^{12}C + ^{12}C$, $E_{c.m.} = 14-31$ MeV, measured $\sigma(E)$ for production of 11 nuclides; γ measurement, Ge(Li) detectors and natural target; deduced total fusion, 3α evaporation, and direct inelastic scattering σ; deduced limiting angular momenta for fusion; discussed anomalous α-particle yield from $^{12}C + ^{12}C$ at low energies.

I. INTRODUCTION

The present work is part of a sequence of measurements[1-4] designed to investigate the complete fusion cross sections for interactions of ^{12}C and ^{16}O projectiles and targets using γ-ray techniques. This study was motivated by the discovery[5] that fusion cross sections for several "light" heavy-ion systems displayed prominent, unexpected structure, the origin of which was not well understood. In previous work[2,4] we have shown that the $^{16}O + ^{16}O$ fusion yield is also characterized by broad, rather striking resonantlike structures which can be understood in the context of the optical model using angular-momentum-dependent potentials. However, attempts to reproduce the $^{12}C + ^{12}C$ gross structure on this basis[5,6] have so far failed, and the present experiment was designed to explore possible explanations for this lack of success. In addition, we hoped to be able to reconcile some discrepancies between two published heavy-particle detection experiments[5,6] on the $^{12}C + ^{12}C$ fusion yield.

II. EXPERIMENTAL METHOD AND RESULTS

The experiments were performed with 28–62 MeV ^{12}C ions from the Strasbourg MP-tandem accelerator, and with similar beams from the University of Notre Dame three-stage tandem accelerator.[7] Care was taken to prevent ^{12}C buildup on the target, which typically consisted of 45 $\mu g/cm^2$ of natural C evaporated onto a thick Au backing. Particularly important in this respect was the liquid-nitrogen-cooled shroud which completely enclosed the target except for a 1 cm diam. beam entrance aperture. Relative normalizations were derived from Coulomb excitation of the Au backing, and are estimated to be accurate to better than ± 0.5% based on the internal error computed from observed scatter of repeated observations. These primary normalizations also agreed to within better than ± 2% (rms deviation) with secondary normalizations obtained from charge collection. The absolute normalization was determined from the yield of ^{20}Ne in the $^{16}O + ^{12}C$ reaction at 40 MeV (lab) measured with the same target used in a previous experiment,[1,3] and has an estimated uncertainty of ± 7%. For further details of the experimental technique, see Refs. 1–3.

Excitation functions for production of 10 of the 11 nuclides produced in the $^{12}C + ^{12}C$ reaction are shown in Figs. 1–6, and some of these will be discussed in more detail in the following paragraphs. First of all, note that the production

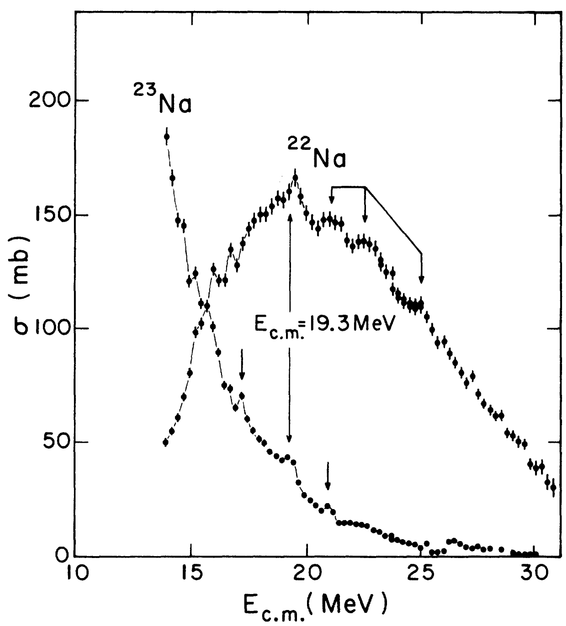

FIG. 1. Excitation functions for the production of Na isotopes in the $^{12}C+^{12}C$ reaction. Note the strong anomalies at 17.3, 19.3, and 21 MeV in the ^{23}Na yield, and at 19.3 MeV in the ^{22}Na yield. Also visible is a sequence of broad oscillations in the ^{22}Na yield beyond 20 MeV. The ^{23}Mg channel (not illustrated) is very similar to ^{23}Na, but is only 25% as strong. The arrows indicate features discussed in this caption.

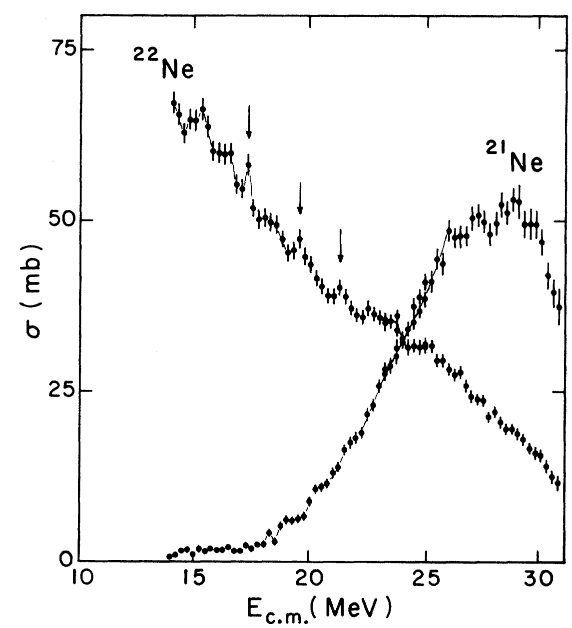

FIG. 2. Yield of heavy Ne isotopes from the present experiment. Note that the 17.3, 19.3, and 21 MeV anomalies (see Fig. 1 caption) are also present in the ^{22}Ne channel ($2p$ evaporation), whereas the three-particle-emission ^{21}Ne channel has an excitation function which is essentially smooth at these energies.

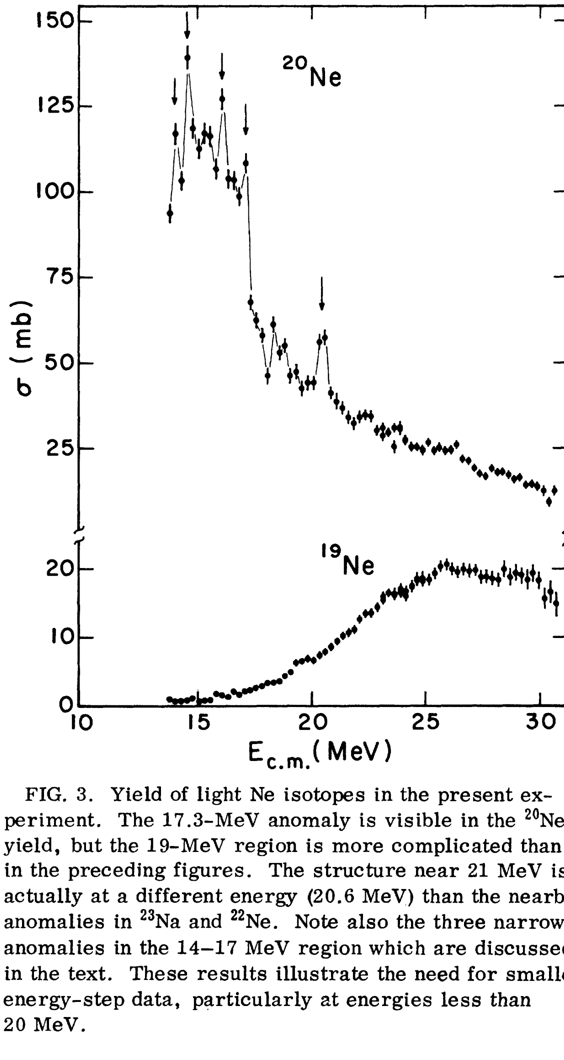

FIG. 3. Yield of light Ne isotopes in the present experiment. The 17.3-MeV anomaly is visible in the ^{20}Ne yield, but the 19-MeV region is more complicated than in the preceding figures. The structure near 21 MeV is actually at a different energy (20.6 MeV) than the nearby anomalies in ^{23}Na and ^{22}Ne. Note also the three narrow anomalies in the 14–17 MeV region which are discussed in the text. These results illustrate the need for smaller energy-step data, particularly at energies less than 20 MeV.

cross section for ^{23}Na (Fig. 1) displays evidence for narrow structures (width less than the experimental beam-energy steps). The same can be said for the yield of ^{23}Mg (not illustrated), which has a nearly identical excitation function to that of ^{23}Na, but only $\frac{1}{4}$ the magnitude. It is of some interest that the ^{22}Na excitation function is also structured (Fig. 1), although this reaction channel corresponds to pn emission from the compound system. Some of the anomalies, indicated by arrows in Fig. 1, are correlated with similar structures in the ^{16}O yield (Fig. 5) and thus also with the total fusion cross section (since ^{16}O contributes almost 50% of σ_{fus} at all energies). Among these is the 19.3-MeV resonance of Cosman *et al.*,[8] which appears to be correlated in the ^{23}Mg, ^{23}Na, ^{22}Na, ^{22}Ne, ^{16}O, and ^{12}C reaction channels. In previous experiments,[1–4] strong structure has only been observed in reaction channels involving α-particle emission, thus suggesting a

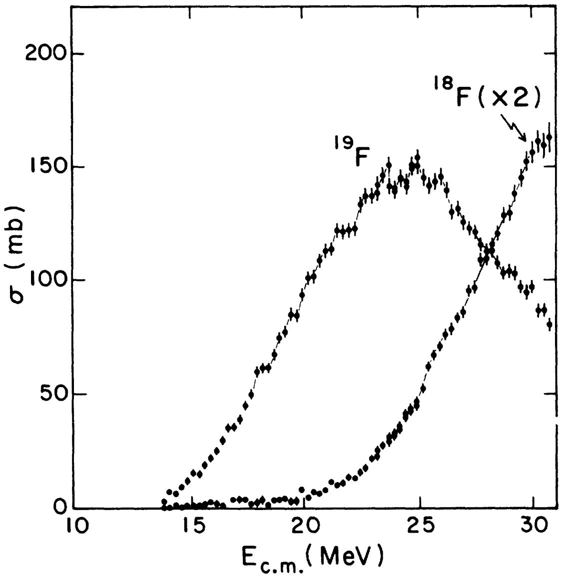

FIG. 4. Yield of F isotopes as observed in the present experiment. The structures near 18 MeV and in the 21–26 MeV region in the ^{19}F channel, though weak, are significant since they appear correlated in transitions from several ^{19}F states.

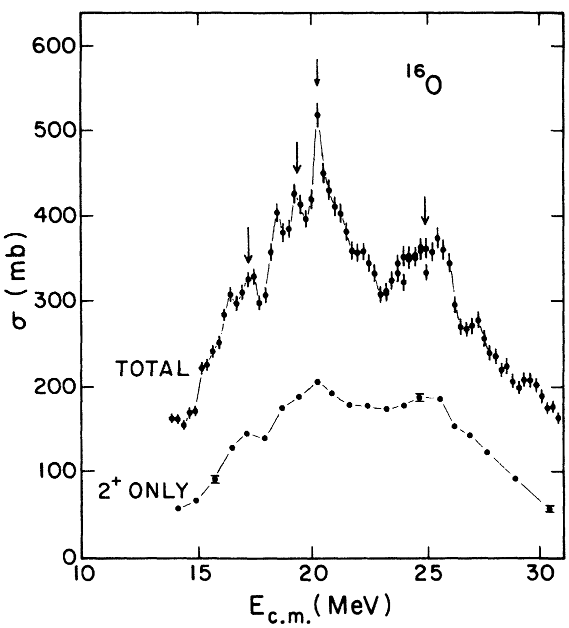

FIG. 5. Production cross section measured for ^{16}O. This is the sum of two separate measurements optimized to determine the yield of the 6.13-MeV ($3^- - 0^+$) and 6.92-MeV ($2^+ - 0^+$) γ-ray transitions. Note the strong anomaly at 20.6 MeV (correlated with ^{20}Ne) and the broad "double-resonance" at 25 MeV which is correlated with a similar structure in the ^{12}C yield (Fig. 6). The region from 16–20 MeV is quite complex, but the 17.3 and 19.3 MeV anomalies are clearly visible.

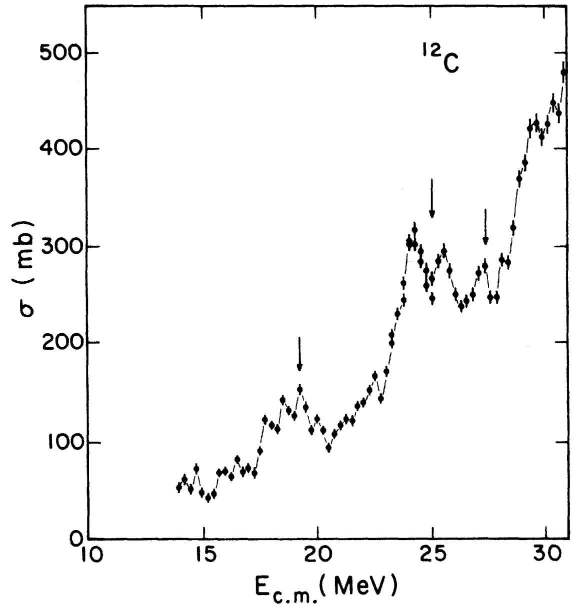

FIG. 6. Yield of ^{12}C (2^+, 4.440 MeV) as determined in the present experiment. Note the broad "double resonance" at 25 MeV and the structure at 27.1 MeV which are correlated with the ^{16}O channel (see Fig. 5). The 19-MeV region is again complex, though the 19.3 MeV structure is apparent.

correlation of structure with high partial waves which prefer to decay by α-particle emission. In the present case, several light-particle-emission channels also participate in forming the structures observed in the fusion yield.

Production cross sections for isotopes of Ne are illustrated in Figs. 2 and 3. Further evidence for very narrow anomalies in the $^{12}C + ^{12}C$ reaction below 20 MeV can be seen in the ^{20}Ne excitation function (Fig. 3), which behaves erratically at low energies. These seemingly random excursion correlate with previously known resonances in the $^{12}C + ^{12}C$ system. For example, the structures at $E_{c.m.} = 14.0$, 14.5, 16.0, and 17.3 MeV (arrows in Fig. 3) correlate quite well with anomalies at $E_{c.m.} = 13.85$, 14.3, 16.2, and 17.15 MeV observed by Fletcher *et al.*[9] (The 14.3-MeV structure was originally located by Cosman *et al.*[8]) Except for the 16.2-MeV resonance, which may be a multiplet, the resonance widths[8,9] are about 300 keV, i.e., approximately equal to the c. m. energy step size in the present experiment. It would seem to be worthwhile to reinvestigate the low-energy regime of the present experiment with much smaller beam-energy steps, in order to resolve these narrow anomalies in the single-α emission channel. The yield functions for other Ne isotopes, as well as those for the isotopes of F (Fig. 4), also show structure, although the incidence of narrow anomalies is somewhat less.

The production cross section for ^{16}O, illustrated in Fig. 5, was obtained from measurements performed at Strasbourg and at the University of Notre Dame. In previous experiments,[1-4] the yield of ^{16}O was taken to be that to the 3^- state at 6.13 MeV. No contribution from the short-lived 2^+ state at 6.92 MeV was observed, due to the fact that the corresponding γ-ray transition is highly Doppler broadened. However, in the present case the yield of ^{16}O is so large that it is possible to distinguish the 6.92 MeV transition from the background, and a separate experiment was designed and carried out at the University of Notre Dame to investigate in detail this high-energy region. It was found that the 2^+ state contributes about the same amount as the 3^- state to the total ^{16}O yield, in approximate agreement with a $2J+1$ model for the distribution of the cross section. The excitation function shown in Fig. 5 includes both components, but not the estimated (on the basis of the $2J+1$ model) 8% contribution of the 0^+ state at 6.05 MeV, which emits no characteristic γ ray.

The yield of 4.439-MeV γ radiation from the first excited state of ^{12}C measured in the present experiment is shown in Fig. 6. These data are in excellent agreement with the results of Cormier *et al.*[10] [obtained with a NaI(Tl) detector] both as to the absolute magnitude and the form of the excitation function. However, because we used a Ge(Li) detector, it was possible to resolve the question as to the contribution of the 4.43-MeV γ ray from ^{23}Na to the present data. This transition, from a short-lived state, is Doppler broadened and thus might be thought to be not easily separated from the ^{12}C γ ray which is also Doppler broadened. However, the kinematics of the reaction and the necessarily selective population of the magnetic substates of the 2^+ state in ^{12}C conspire to produce a distinctive, symmetric double-peak in the γ-ray spectrum, as discussed[11] some time ago for inelastic proton scattering from ^{12}C. The ^{23}Na transition, which is not subject to the same constraints, falls in the valley between these two peaks. A careful analysis of the peak shape then allows the separation of the ^{23}Na and ^{12}C components. It is found that less than $\frac{1}{2}$ of the "^{12}C" yield in Fig. 6, up to a c.m. energy of 16 MeV, might be due to ^{23}Na. The actual magnitude of this contribution, however, is poorly determined because of the low total yield throughout this energy region. On the other hand, for $E_{c.m.}>16$ MeV, the analysis shows that the ^{23}Na transition contributes a negligible fraction of the 4.44-MeV γ-ray, in agreement with the observation that the total yield of ^{23}Na (Fig. 1) is small and rapidly diminishing at these higher energies. Thus, the 4.43 MeV transition from ^{23}Na may safely be ignored throughout the energy range considered here, though not necessarily at lower energies.

III. DISCUSSION

A. Determination of the 3α evaporation yield

The $^{12}C(2^+$, 4.440 MeV) yield of Fig. 6 contains contributions from direct inelastic scattering as well as compound-nuclear formation followed by evaporation of three α particles. In order to determine the complete fusion cross section, it is necessary to separate these two components, which, however, cannot be done on the basis of data available from γ-ray experiments. It is possible to ignore the ^{12}C yield and present only the summed excitation function of the remaining 10 nuclides, according to the prescription followed in Ref. 5, and the result is shown as the "σ_{CF}-3α" curve in Fig. 7. However, previous work on similar systems[1-4,12,13] suggests that a large fraction of the ^{12}C yield above 20 MeV results from the fusion-evaporation reaction, so that a "fusion yield" which ignores this component will be misleading. This fact was recognized by the authors of Ref. 6, who include an estimate of the 3α component in their fusion yields on the basis of statistical-model predictions. No *experimental* data on this component of the fusion yield was available, however, until a recent study of inclusive α-particle emission from the $^{12}C+^{12}C$ system was com-

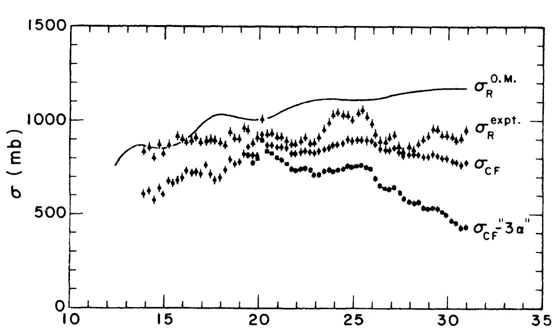

FIG. 7. Various reaction yields deduced from present results. The "σ_{CF}-3α" yield is the one to compare with results of previous experiments, which did not determine the 3α-evaporation yield back to ^{12}C. The σ_{CF} cross section includes the ***measured*** 3α evaporation; it does not differ from $\sigma_{CF}-3\alpha$ below 20 MeV. The "σ_R^{expt}" excitation function includes the direct ^{12}C inelastic scattering as well as the "anomalous" α yield (see text and Fig. 9). Finally "σ_R^{OM}" is an optical-model calculation of the reaction cross section using the Reilly potential (see text).

pleted.[14] The results of this study may be used to deduce the 3α yield using the following equation:

$$\sigma(3\alpha)=\tfrac{1}{3}\left[\sigma_\alpha-2\sigma(^{16}O)-\sigma(^{18}F)-\sigma(^{19}F)-\sigma(^{19}Ne)-\sigma(^{20}Ne)\right] .$$

In this expression, σ_α is the inclusive α-particle yield of Ref. 14, shown in Fig. 8, and the remaining terms are the indicated production cross sections from the present experiment. The assumption here is that ^{16}O production results from 2α emission from the compound system, that the F and $^{19,20}Ne$ isotopes are associated with emission of a single α particle, that 4α emission is negligible in the energy region of this experiment, and that direct inelastic scattering to α-breakup states in ^{12}C at 7.66 and 10.1 MeV may also be neglected.[15] The effective 3α-emission yield deduced in this manner is shown in Fig. 9. Referring first of all to the data above 20 MeV in this figure, it can be seen that the 3α yield increases rapidly from threshold at about 20 MeV to more than 350 mb at the highest energy investigated. This behavior is consistent with previous observation[1-4,12,13] on similar systems and with statistical-model calculations.[3,4,6] The yield function of Fig. 9 may also include a small contribution from the $2\alpha p$ emission process to ^{15}N, which should become important at $E_{c.m.}>25$ MeV. An estimate of the magnitude of this cross section, based on a search for the (Doppler broadened) γ-ray transitions from ^{15}N, gives an upper limit of 100 mb at $E_{c.m.}=30$ MeV, in good agreement with the results of Refs. 6 and 12. (The corresponding transition in ^{15}O, resulting from $2\alpha n$ emission, would not be Doppler broadened and was not observed.) However, the σ_{CF} yield function of Fig. 7 includes production of ^{15}N and ^{15}O to the extent they result from α-particle emission, because of the way in which the 3α cross section is derived.

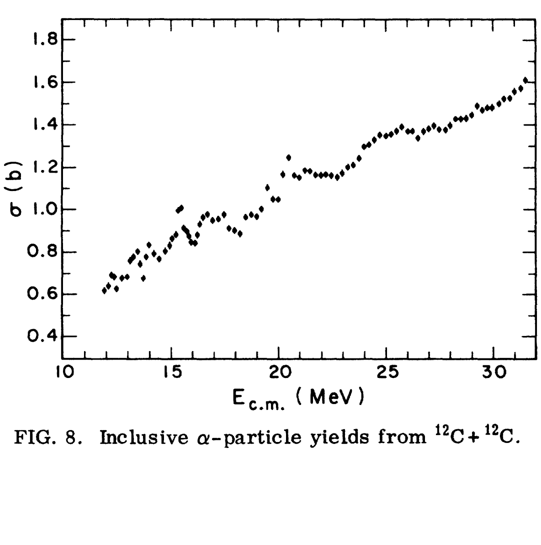

FIG. 8. Inclusive α-particle yields from $^{12}C+^{12}C$.

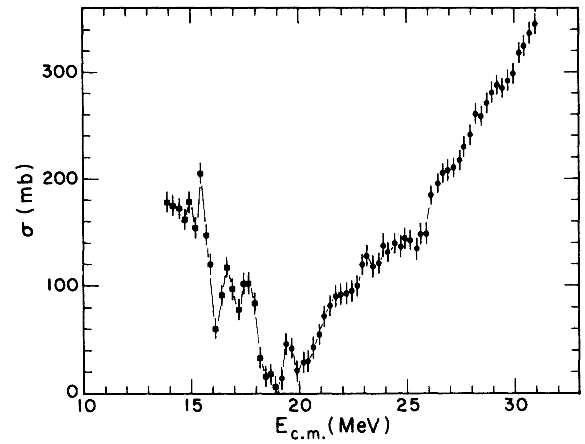

FIG. 9. The 3α-evaporation (solid circles) and anomalous α-yield (solid squares) components of the reaction cross section as deduced from the present results and those of a previous experiment (see text). Note the relative absence of structure in the 3α component, except for a 25-MeV "plateau" region. In contrast, the anomalous α yield appears to be highly structured.

As compared to the ^{12}C yield of Fig. 6 (which is a completely independent data set, not used in deducing the cross sections shown in Fig. 9), it can be seen that the 3α component is not highly structured. There is evidence for broad anomalies at about 22 and 27 MeV (c.m.), and for a "plateau" in the yield curve at about 25 MeV where the ^{12}C production cross section (Fig. 6) shows a spectacular double resonance, but in general the excitation function may be characterized as "smooth." In contrast, we now consider energies less than 20 MeV in Fig. 9. This constitutes the region of "anomalous" α yield discussed in Ref. 14, and it can be seen that the corresponding cross section is highly structured and increasing rapidly as the c.m. energy is decreased. In addition, comparison of Figs. 6 and 9 shows that most (if not all) of the anomalous yield is *not* associated with the emission of γ radiation. The reaction mechanism(s) responsible for this behavior are open to speculation, but fusion-evaporation is probably not the answer. Thus, we will ignore the anomalous α yield for the moment, and proceed with an analysis of the 3α fusion-evaporation component. In particular, it is important to ask the question as to whether our separation of the direct and "3α" components in the excitation function of Fig. 6 is consistent with previous work, such as the cross section for direct (i.e., two-body) scattering to the first excited state of ^{12}C presented in Ref. 16. Figure 10 illustrates a direct inelastic scattering excitation function, deduced from the results of the present experiment and of Ref. 14 by sub-

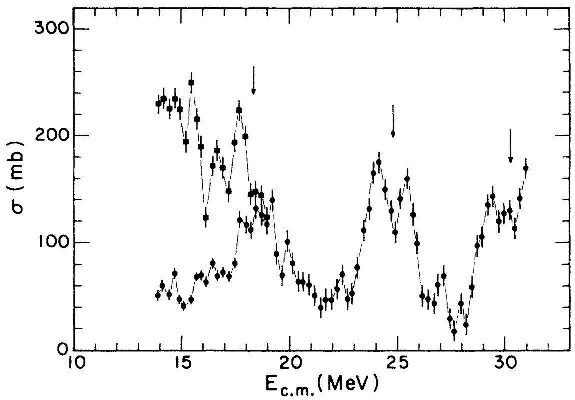

FIG. 10. Direct ^{12}C (2^+, 4.44 MeV) yield (solid circles) as deduced from present results. Note the prominent "double-resonances" at 18, 25, and 30 MeV. Also illustrated (solid squares) is the total direct yield, formed by summing the ^{12}C direct inelastic scattering and the anomalous α yield (Fig. 9). Note that it does not differ from the ^{12}C yield beyond 20 MeV (c.m).

tracting the effective 3α yield (Fig. 9 for $E_{c.m.} > 19$ MeV) from the total ^{12}C (4.440 MeV) production cross section (Fig. 6). Comparison with the data of Ref. 16 shows that two excitation functions are remarkably similar. In fact, the only point of disagreement seems to be the extent to which the observed resonances are doubled, with the present data set showing a more pronounced doubling of each resonance.

B. Comparison with other experiments

As mentioned above, two previous measurements of the ^{12}C + ^{12}C fusion cross section,[5,6] both of which result from heavy-particle detection experiments, are in disagreement on a number of points: (i) the "20 MeV" maximum occurs approximately 1 MeV higher in c.m. energy in Ref. 5 as compared to Ref. 6; (ii) the "25 MeV" maximum is much stronger in the data set of Ref. 5; (iii) the excitation function below 18 MeV shows more structure in Ref. 6; and (iv) there is a small difference in the absolute fusion yields of Refs. 5 and 6 which, however, is within the mutual errors of the two experiments. In the following paragraphs, we address these points one at a time.

First of all, the location of the "20 MeV" maximum in our data set is in agreement with the results of Ref. 6. In addition, the absolute magnitude of the "25 MeV" maximum in Fig. 7 is in good accord with the excitation function presented in Ref. 6, although this maximum is more clearly defined in our data set owing to a smaller beam-energy step size. To summarize, the results of the present experiment confirm the reaction cross section measurements of the Saclay group at c.m. energies greater than 18 MeV.

The differences between the Argonne (Ref. 5) and Saclay data at energies less than 18 MeV (c.m.) are of more interest, since they bear directly on the question of the anomalous α-yield discussed above. Comparison of Fig. 7 with the corresponding figure of Ref. 6 suggests that the present experiment is in better agreement with the relatively structureless Argonne data at low energies. However, we have already noted that the anomalous yield shown in Fig. 9 is *not* associated with γ radiation, so that we would not expect it to appear in the fusion cross section of Fig. 7. The present work and the observation of the Saclay group imply that the anomalous α yield is associated with heavy particles, and specifically with the emission of ^{16}O during the reaction. The lack of observable γ radiation then implies that the ^{16}O nucleus is formed directly in its ground state, or in the 6.05 MeV 0^+ state. We expect that each such event is accompanied by the emission of *two* α particles and we have used this assumption to calculate the yield illustrated in Fig. 9 (for $E_{c.m.} < 19$ MeV). An internal check on this assumption is provided by the fact that the yield deduced for multiplicity 2 is about what is needed to bring our data and that of the Saclay group into agreement as to the amount of ^{16}O produced at $E_{c.m.} = 15$ MeV.

It might be argued on the basis of the discussion presented in the previous paragraph that the anomalous yield of Fig. 9 should be included in the fusion cross section. However, a comparison of the ^{16}O yield function (Fig. 5) with similar 2α-evaporation yields in other experiments[1,2] suggests that all of the expected evaporation yield is actually being observed in the γ-ray experiment. This viewpoint is supported by the fact that evaporation-model calculations[3,4] predict an ^{16}O excitation function very similar in shape to that presented in Fig. 5, and furthermore predict a relatively small ground-state cross section. Therefore, we prefer to classify the anomalous yield as "direct" and include it with the ^{12}C direct yield in Fig. 9. It must be recognized, however, that unambiguous identification of this yield with a direct process cannot be made on the basis of present information.

The present experiment is in reasonably good agreement with both previous experiments as to the magnitude of the maximum fusion yield. The data of Fig. 7 are consistently 7% lower than the corresponding cross sections as measured by the Saclay group, but that is well within mutual experimental error. The Argonne data require an even larger maximum fusion yield, but still within experimental error. The weighted average of the maximum fusion yields from the three experiments (essentially the yield at $E_{c.m.}=20$ MeV) is $\sigma_f(\max)=920\pm30$ mb, and all three measurements agree with the average within experimental error. The agreement between these experiments and Ref. 12 is not as good. We find "σ_{CF}-3α"$=750\pm60$ mb at $E_{c.m.}=22.5$ MeV. The corresponding cross sections from Refs. 5 and 6 are 850 ± 40 and 890 ± 30, respectively, although exact comparisons are difficult to make since our data set shows that the cross section changes more rapidly between 20 and 23 MeV than indicated in the other experiments. The weighted averaged of these measurements is 845 ± 45 mb, compared to the 1020 ± 100 mb given in Ref. 12.

C. Energy dependence of the fusion and reaction yields

In the previous paragraphs, the "σ_{CF}-3α" cross sections of Fig. 7 were compared with the "complete fusion" yields of Refs. 5 and 6. The definition of the fusion yield in these latter experiments specifically excluded 3α emission back to ^{12}C due to the fact that the $3\alpha+^{12}C$ yield could not be evaluated from available information. We have experimentally determined the 3α yield (Fig. 9), and find that the actual fusion cross section is considerably larger than that presented in Ref. 5 for $E_{c.m.}>20$ MeV, so that σ_{CF} decreases only very slowly beyond this energy (Fig. 7). This behavior is in good accord with that expected from data on other light systems[1–4,13]. In fact, σ_{CF} as measured in the present experiment is nearly identical to the "corrected" σ_{CF} given in Ref. 6 on the basis of an estimation of the 3α component from evaporation-model calculations and previous experience. Thus, it is the σ_{CF} curve in Fig. 7 which should be compared with theoretical calculations of the fusion yield. For example, an optical model calculation of the total reaction cross section using the Reilly potential[17] is illustrated in Fig. 7. We have shown[2,4] that such calculations with appropriate potentials can reproduce the shape of the $^{16}O+^{16}O$ fusion excitation function extremely well, although the measured yield is always somewhat smaller than the predicted reaction cross section. However, there seems to be little if any relationship between the experimental and calculated curves in Fig. 7, as was already pointed out in Refs. 5 and 6. Of course, it might be argued that the fusion cross section is not the reaction cross section, so that one would *a priori* not expect such a relationship. Indeed, the most striking difference between the $^{12}C+^{12}C$ and $^{16}O+^{16}O$ systems is the very strong inelastic scattering yield in the former system.[10,16] Thus, we illustrate in Fig. 7 an experimental reaction cross section determined from present data by adding the "direct" components (Fig. 10) to σ_{CF}. Some direct cross section must still be missing from this accounting, but perhaps not more than in the $^{16}O+^{16}O$ case. Nevertheless, agreement with the theoretical reaction cross section is still not obtained, though the situation is somewhat improved (Fig. 7). There remains at least one possible explanation for the remaining discrepancies. Given the very strong inelastic channel, a coupled-channels calculation is likely to be required. The Saclay group attempted such a calculation using the Reilly potential, and found that explicit inclusion of the strong inelastic channel greatly affected the energy dependence of the fusion yield.[6] However, they could not obtain even qualitative agreement with either the observed inelastic yield or the complete fusion cross section. It is still possible that a systematic attempt to fit the elastic, inelastic, and fusion data simultaneously in the framework of a coupled-channels analysis might succeed, but on the basis of present knowledge it is not clear whether a potential model can adequately represent the available data.

There is, however, another way to analyze the complete fusion data of Fig. 7. In a recent paper,[18] Glas and Mosel compare the limiting angular momentum for fusion of several light systems, including $^{12}C+^{12}C$, on the basis of data then available. We plot in Fig. 11 the excitation energy E^* in the compound system ($E^*=E_{c.m.}+13.9$ MeV) vs the cutoff angular momentum l_0, given in a sharp cutoff model by

$$\sigma_{CF}=\pi\lambda\!\!\!^{-2}(l_0+1)(l_0+2)\ .$$

It can be seen that the trajectory of l_0 has distinct discontinuities in slope at $l_0\simeq 8$, 10, 12, and 14 which correspond, of course, to the gross structure in the fusion yield (Fig. 7). It is natural to interpret these discontinuities as due to the more or less sudden opening of successive partial waves. On the other hand, it must be said that this identification does *not* imply a unique "spin assignment" to the gross structure. As an example, one would only say that $l=10$ and 12 should dominate the region from $E^*=32$–36 MeV ($E_{c.m.}=18$–22 MeV), in agreement with the conclusion of Fletcher *et al.*[9] Despite this ambiguity, Fig. 11 suggests a clear relationship between the gross-structure features in the $^{12}C+^{12}C$ and $^{16}O+^{16}O$ systems.[2,4]

What is perhaps more remarkable about Fig. 11 is the behavior of the limiting angular momentum near $l_0=14$ and $E^*=40$ MeV, which was noted by Glas and Mosel.[18] Since these authors used the data set of Ref. 5, which specifically omits the 3α evaporation channel, it was expected that the effect

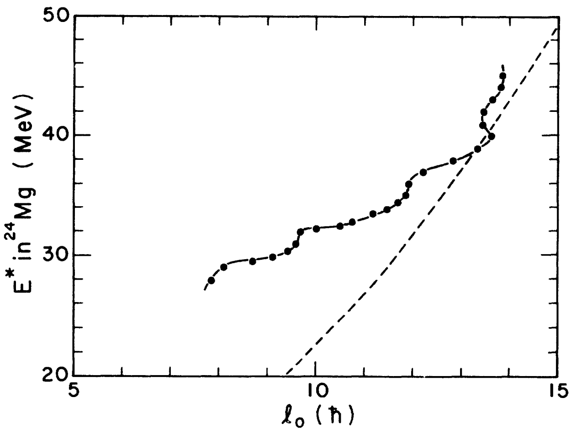

FIG. 11. Trajectory of the limiting angular momentum for fusion. Note the distinct changes in slope near $l_0 = 8$, 10, and 12. The dashed curve is the ground-state band of ^{24}Mg, extrapolated from its known members.

would disappear when all of the fusion cross section was included. As can be seen, this was not the case. Of course, $l = 14$ has already been identified as a critical angular momentum value for the ^{22}Na compound system,[19] so that it should not be surprising to find a similar result for ^{24}Mg. What is surprising, however, is the fact that the trajectory of l_0 changes dramatically at $E^* = 30$–40 MeV, where it crosses the extended ground-state band of ^{24}Mg (dotted line in Fig. 11). Thereafter, l_0 appears to track the ground-state band at a fixed separation of about 2 MeV. It may be that this is a purely accidental feature, having no relationship to the structure of ^{24}Mg at high energies and angular momenta. After all, Glas and Mosel[18] calculate that the $J^\pi = 14^+$ yrast state in ^{24}Mg lies at much lower energies than 40 MeV, and it is difficult to see why the fusion cross section would be correlated with any particular band of states except for the yrast band. Furthermore, the considerable success achieved by the band-crossing model[20] of Kondo, Abe, and Matsuse could not be understood if the ground-state band were yrast beyond the required band crossing at $J^\pi = 10^+$. On the other hand, existing large-basis shell-model calculations[21] suggest that the yrast line in ^{24}Mg lies very close to the extension of the ground-state band up to at least $J^\pi = 12^+$, despite the fact that the calculated in-band and crossover electromagnetic transition strengths point to a dissolution of the collective nature of this band near $J^\pi = 8^+$. (These calculations are, however, limited to an *sd*-shell model space.) It would seem that measurements of σ_{CF} to higher energies and including all open evaporation channels would be extremely valuable to clarify the relative importance of yrast line vs entrance channel limits to fusion. In particular, the experiment of Ref. 12 should be repeated with a smaller energy-step size, especially in the critical c.m. energy region from 30–50 MeV.

IV. CONCLUSION

Excitation functions for the yield of the eleven most abundant nuclides produced in the ^{12}C + ^{12}C reaction were determined in the energy range from 14–31 MeV (c.m.) via γ-ray techniques. Some of these reaction channels showed evidence for correlated narrow structure (width less than or equal to the experimental beam-step size of 250 keV c.m.). A unique feature of the ^{12}C + ^{12}C reaction, as compared with other light systems, is the fact that several light-particle-emission channels (e.g., *pn*) participate strongly in forming the structures observed in the total fusion yield.

The total ^{16}O yield from ^{12}C + ^{12}C was found to be nearly equally divided between the (3^-, 6.13 MeV) and (2^+, 6.92 MeV) states. A separate experiment was then designed and carried out to accurately measure the contribution of the ground-state transition from the latter state, which is severely Doppler broadened. The yield of 4.439-MeV γ radiation from the first excited state of ^{12}C measured in the present experiment was found to be in excellent agreement with a previous measurement. The extent to which the 4.43-MeV γ ray from ^{23}Na contributes to this yield was found to be negligible throughout the energy range investigated.

The production of ^{12}C via the 3α evaporation process has been experimentally measured in the present work. The 3α cross section increases rapidly from threshold at about 20 MeV to more than 350 mb at the highest energy investigated, at which point it accounts for nearly $\frac{1}{2}$ of the fusion-evaporation yield. The "direct" component of the ^{12}C (2^+, 4.44 MeV) production cross section was also determined, and found to be in good agreement with previous measurements.

The complete fusion cross section measured in the present experiment (minus its 3α component) is found to be in good agreement with the heavy-particle detection results of the Saclay group, both as to the magnitude and shape of the excitation function. An important exception to this agreement occurs for the production of ^{16}O at low energies, a portion of which we suggest to be associated with another process (not fusion) which we have previously discussed in the context of the anomalous α-particle yield from ^{12}C + ^{12}C. Apparently, these anomalous events result from formation of ^{16}O in its ground state, accompanied by the emission of two α particles.

Attempts to understand either the fusion cross section (including its 3α component) or the total reaction cross section on the basis of optical-model calculations using parameters obtained from the literature have met with little success. On the other hand, a more limited analysis of the fusion cross section has given considerable insight into the origin of the gross structure in σ_{CF}. In particular, discontinuities in slope of the limiting angular momentum for fusion (in a sharp-cutoff model) occur at adjacent even l values, thus suggesting a close relationship between the gross structure features in $^{12}C+^{12}C$, and those which occur in the $^{16}O+^{16}O$ system.

Finally, we have shown that a rather remarkable change occurs in the "trajectory" of the limiting angular momentum near $l_0=14$ and at an excitation energy in ^{24}Mg of about 40 MeV. The nature of the change is such as to suggest that l_0 begins to follow the extension of the ground-state band in ^{24}Mg which intersects the trajectory at $l_0 \cong 14$ and $E^* \cong 40$ MeV. This observation, if it is not due to purely coincidental circumstances, would have interesting consequences with regard to the behavior of ^{24}Mg at high energy and angular momenta.

[1]J. J. Kolata *et al.*, Phys. Lett. 65B, 333 (1976).
[2]J. J. Kolata *et al.*, Phys. Rev. C 16, 891 (1977).
[3]J. J. Kolata *et al.*, Phys. Rev. C 19, 408 (1979)
[4]J. J. Kolata *et al.*, Phys. Rev. C 19, 2237 (1979).
[5]P. Sperr *et al.*, Phys. Rev. Lett. 37, 321 (1976).
[6]M. Conjeaud *et al.*, Nucl. Phys. A309, 515 (1978).
[7]E. D. Berners *et al.*, Rev. Phys. Appl. 12, 1407 (1977).
[8]E. R. Cosman *et al.*, Phys. Rev. Lett. 35, 265 (1975); K. Van Bibber *et al.*, *ibid.* 32, 687 (1974).
[9]N. R. Fletcher *et al.*, Phys. Rev. C 13, 1173 (1976).
[10]T. M. Cormier *et al.*, Phys. Rev. Lett. 38, 940 (1977).
[11]J. J. Kolata, R. Auble and A. Galonsky, Phys. Rev. 162, 957 (1967).
[12]M .N. Namboodiri, E. T. Chulick, and J. B. Natowitz, Nucl. Phys. A263, 491 (1976).
[13]R. G. Stokstad *et al.*, Phys. Rev. Lett. 36, 1529 (1976).
[14]J. J. Kolata, R. E. Malmin, P. DeYoung, S. Davis, and R. Luhn, Phys. Rev. C 21, 776 (1980), this issue.
[15]R. G. Stokstad *et al.*, Phys. Rev. C 20, 655 (1979).
[16]T. M. Cormier *et al.*, Phys. Rev. Lett. 40, 924 (1978).
[17]W. Reilly *et al.*, in *Proceedings of the Fifth International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, 1969*, edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 95.
[18]D. Glas and U. Mosel, Phys. Lett. 78B, 9 (1978).
[19]H. V. Klapdor, H. Reiss, and G. Rosner, Nucl. Phys. A262, 157 (1976).
[20]Y. Abe, T. Matsuse, and Y. Kondo, Phys. Rev. C 19, 1365 (1979); Y. Kondo, Y. Abe, and T. Matsuse, *ibid.* 19, 1356 (1979).
[21]A. Watt, D. Kelvin, and R. R. Whitehead, Phys. Lett. 63B, 385 (1976).