Inelastic Scattering of ^{12}C on ^{12}C[†]

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The elastic and inelastic scattering channels in the $^{12}C+^{12}C$ interaction have been measured for the angles $\theta_{lab} = 15.5°–50.5°$ over the energy range $E_{lab} = 40–60$ MeV in steps of 1° and 500 keV, respectively. The strength of the single and mutual excitation of the first excited state (4.43 MeV, 2^+) in ^{12}C was found to be comparable in magnitude to that of the elastic channel over the entire range of the measurement. The implications for the need of coupled-channel analysis of certain heavy-ion scattering systems are discussed, and comparisons between the predictions of certain coupled-channel reaction models and the data are presented.

I. INTRODUCTION

The study of nuclear interactions between large aggregates of colliding nucleons has produced evidence in recent years for a number of phenomena that remain to be fully understood. A particularly striking example has been the $^{12}C+^{12}C$ interaction, which has yielded a rich variety of nuclear phenomena over an extended energy range ($E_{lab}=6–80$ MeV). The well-known quasimolecular resonances, first seen by Bromley, Kuehner, and Almqvist,[1] and subsequently by Patterson, Winkler, and Zaidins,[2] and by Mazarakis and Stephens,[3] were found to occur at energies at and just below the Coulomb barrier. The precise nature of the binding in the assumed ^{12}C-^{12}C structure has not yet been conclusively established. Imanishi[4] has proposed a mechanism involving the virtual excitation of a ^{12}C to its first 2^+ level at 4.43 MeV during the interaction, while Michaud and Vogt[5] have suggested a quite different model based on residual interactions among the α-particle substructures of the two ^{12}C nuclei.

The same measurements that first identified the quasimolecular resonances near the Coulomb barrier also showed striking fluctuation behavior in the elastic scattering cross sections at higher energies (to some 14 MeV in center-of-mass bombarding energy). Similar cross-section fluctuations were also observed in the corresponding reaction channels in this energy range, particularly in $^{12}C(^{12}C, \alpha)^{20}Ne$, and detailed fluctuation analyses by Almqvist *et al.*[6] by Borggreen, Elbek, and Leachman,[7] and by Bondorf and Leachman,[8] have shown such behavior to be generally reproducible by a statistical compound-nucleus model for the reaction.

At yet higher energies (to 40 MeV in the center of mass), measurements by Reilly *et al.*[9] at this laboratory have shown that rather marked structure of a different type appears. The statistical fluctuation phenomena which characterized the $^{12}C+^{12}C$ elastic scattering data at lower energies appear largely damped; gross structure reminiscent of that observed in $^{16}O+^{16}O$ scattering in the same bombarding-energy region by Maher *et al.*[10] persists throughout; and finally, a rather remarkable periodic structure emerges with a characteristic width varying systematically from 0.6 to some 1.2 MeV in the range studied. This structure is clearly evident in Fig. 1, taken from the work of Reilly.

It is this intermediate structure which had prompted Scheid, Greiner, and Lemmer[11] to extend the earlier suggestion of Imanishi. The former suggest that strong coupling between elastic and inelastic channels through a double-resonance mechanism – involving, first, a virtual orbiting resonance associated with a particular grazing partial wave in the entrance and exit channels, and, second, a quasibound state in the potential well which is populated during the interaction by inelastic excitation of one of the ^{12}C nuclei – might be responsible for this structure of intermediate width observed in the elastic scattering at these higher energies. Earlier work in this laboratory has clearly established the importance of the grazing partial wave for the elastic potential scattering of heavy ions; a detailed discussion of this mechanism has been published in the case of the $^{16}O+^{16}O$ scattering.[12] In attempting to evaluate the proposed double-resonance mechanism, interest is now focused on the inelastic scattering channel.

Remarkably enough, prior to the present investigation few data had been obtained on inelastic scattering in the ^{12}C-^{12}C interaction. Perhaps understandably, the mainstream of effort to date has been directed toward elucidation of the two extremes of the reaction mechanism – elastic potential scattering on the one hand and statistical compound-reaction processes on the other, inasmuch as these have been the most amenable to direct experimental study and to parametrization through the most familiar models – the optical model and the Hauser-Feshbach statistical model, respectively.

While no systematic study of the inelastic scattering as a function of energy and angle has been previously undertaken, there have been isolated measurements done at a single energy. Wang, Baker, and McIntyre,[13] Garvey, Smith, and Hiebert,[14] and Chasman and Bromley[15] independently studied the elastic and inelastic scattering of $^{12}C + ^{12}C$ at $E_{lab} \sim 126$ MeV. In the early 1960's, using the Yale heavy-ion linear accelerator (HILAC) they observed strong excitation of the 2^+ first excited state (cf. Fig.2) in both single and mutual inelastic scattering processes. In the latter, both of the interacting nuclei are simultaneously excited to this excited state. While a more comprehensive study is essential to further understanding of the proposed double-resonance mechanism, there are also additional elements of interest. The shape of the inelastic excitation functions predicted by a coupled-channel calculation of the ^{12}C-^{12}C reaction should depend upon the specific assumptions made regarding the coupling mechanism. Confrontation of such predictions with the relevant inelastic scattering data then holds promise of providing new information on these coupling mechanisms. Furthermore, much effort has already been devoted to developing a systematic set of optical-model parameters appropriate to the description of elastic potential scattering for a whole family of heavy-ion projectiles and targets up to mass $A = 28$.[12] Fundamental to this approach is the assumption that each of the nonelastic channels is of relatively small magnitude, and that all can be adequately incorporated into the model through the imaginary, absorptive part of the potential. The testing of this assumption for many of the systems under consideration is thus important, since the presence of strong coupling to specific inelastic channels through a direct process could significantly modify the potential parameters required to reproduce any broad range of data. Our preliminary survey measurements[16] on the $^{12}C + ^{12}C$ inelastic scattering channels showed these cross sections to be roughly the same magnitude as the elastic cross section over the energy range of interest to the proposed double-resonance mechanism. This emphasized the need for the more detailed systematic investigation of these channels, which we report herein.

We have examined the elastic and inelastic channels involving the 2^+ state at 4.43 MeV in the $^{12}C + ^{12}C$ interaction for angles $\theta_{lab} = 15.5–50.5°$ (in 1° increments) over the energy range $E_{lab} = 40–60$ MeV in 500-keV steps. We have found that the single and mutual inelastic channels involving the 2^+ excited state at 4.43 MeV in ^{12}C are strongly coupled to the elastic channel. Coupled-channel analysis of the inelastic data using a code developed by Rickertsen and Ascuitto[17] indicates that the optical-model imaginary potential is reduced by some 60% over that obtained in a one-channel optical-model fit to the $^{12}C + ^{12}C$ elastic scattering. This has important consequences in terms of the

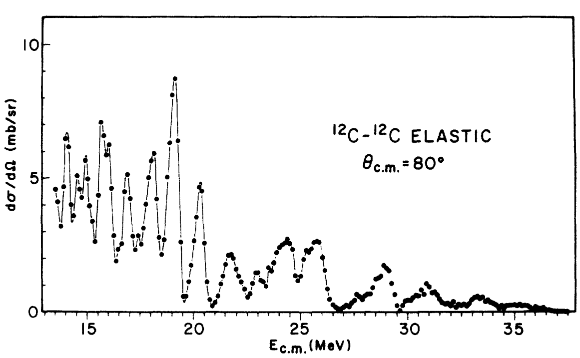

FIG. 1. Excitation function for the $^{12}C + ^{12}C$ elastic scattering measured at 80° c.m. The solid curve is drawn simply to guide the eye.

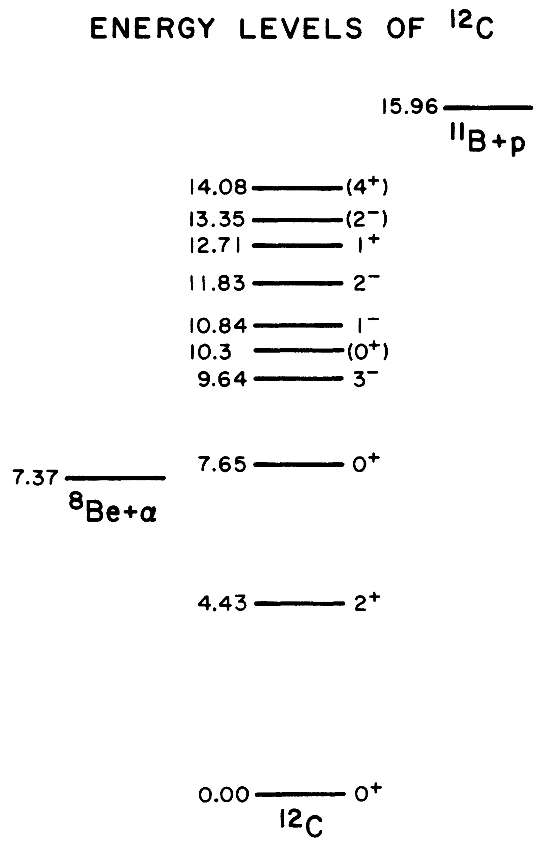

FIG. 2. Energy levels and decay thresholds in ^{12}C.

changes it implies for the model transmission coefficients appropriate to Hauser-Feshbach calculations of heavy-ion reaction channels proceeding through compound mechanisms.

The inelastic cross sections in the energy range measured here are not well reproduced by the Fink, Scheid, and Greiner[18] double-resonance model, which was successful in reproducing the structure of intermediate width in the $^{12}C+^{12}C$ elastic excitation functions at lower energy. Whether this implies that only minor modification of the Fink-Greiner model is necessary or that an alternate mechanism must be found to explain this structure remains an open question.

II. EXPERIMENTAL PROCEDURE

A negative ^{12}C-ion beam was produced in a duoplasmatron and lithium-vapor exchange canal ion source and accelerated by the Yale MP Van de Graaff accelerator to laboratory energies in the range 40–60 MeV. Subsequent momentum analysis of the emergent beam led to an energy resolution of better than two parts in 10^4. Currents of ~100 nA were delivered to a 100-$\mu g/cm^2$ self-supporting C target mounted inside the ORTEC 76-cm scattering chamber.

Beam collimation inside the chamber was furnished by a specially designed scattering table which also served to define the geometry of the scattering measurements. In order to permit an accurate relative normalization for measurements obtained at different beam energies, and an absolute cross-section determination, the number of incident particles scattered by a monitor target (~5 $\mu g/cm^2$ Au on a C backing) positioned in the ^{12}C-beam axis, 8 cm before the carbon target, was monitored by a standard Au-Si surface-barrier detector positioned 65 mm from the monitor target and at an angle of 45° with respect to the beam axis. Under these conditions, in the energy range of interest, the scattering from the gold could be assumed to be purely Rutherford in character.

The scattering events of interest were defined by a new position-sensitive detector (PSD) system[19] based on an extension of the well-known kinematic-recoil double-coincidence technique. In this system, the individual pairs of detectors used in earlier heavy-ion studies at this laboratory were replaced by two PSD's, one on either side of the beam axis. This is shown schematical-

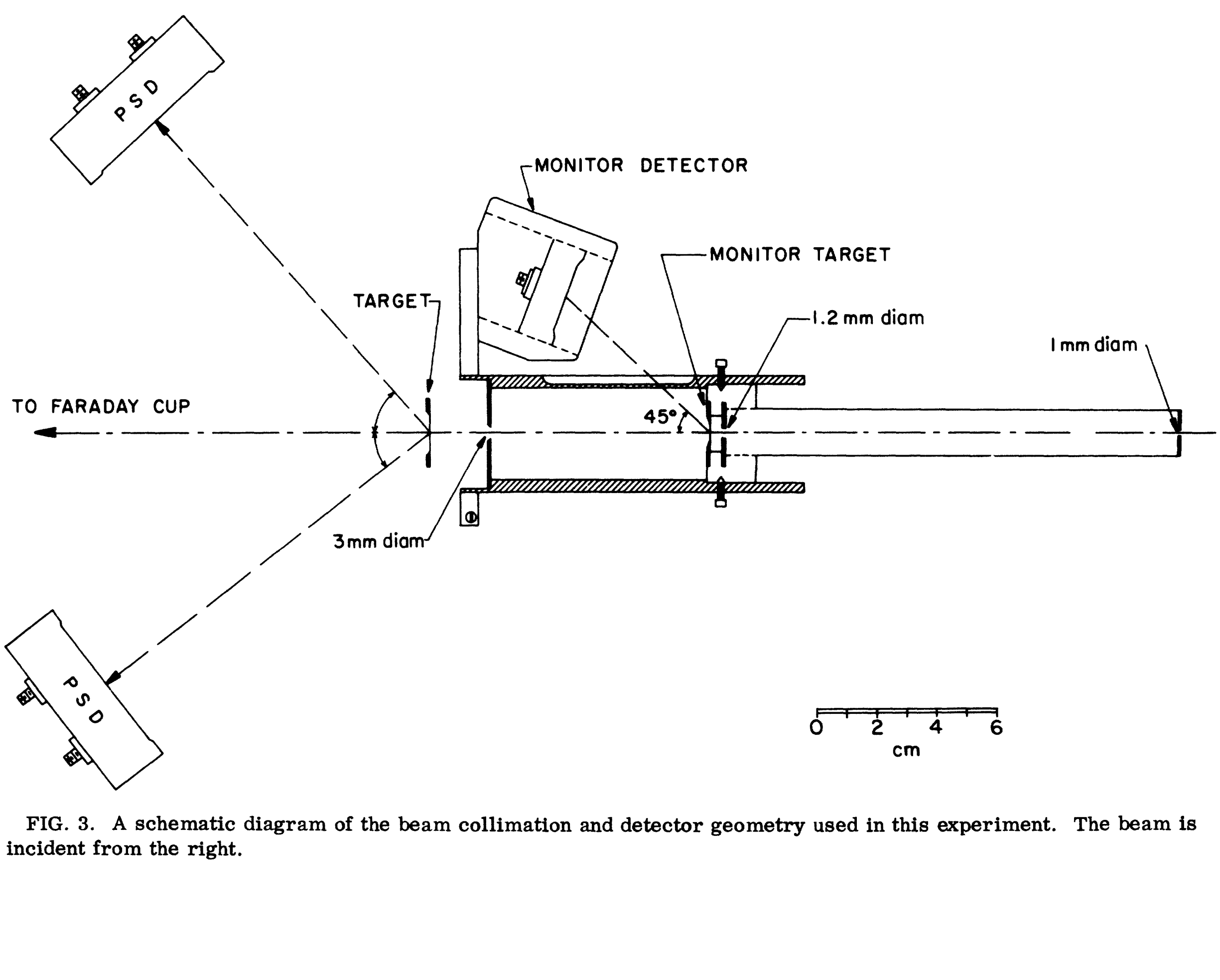

FIG. 3. A schematic diagram of the beam collimation and detector geometry used in this experiment. The beam is incident from the right.

ly in Fig. 3. This configuration has the advantage of providing relatively large solid angle, hence detection efficiency, while retaining good sensitivity and energy resolution for a number of interaction channels of particular interest.

The two position-sensitive detectors used in these measurements were manufactured by Nuclear Diodes, Inc. Each was 60 μm thick, and of sensitive area 10 mm × 50 mm, spanning, at a given setting, 20° in laboratory polar angle. The azimuthal angle of each detector was defined by two circular plates, concentric with the target and each set at an angle of ±2° with respect to the plane of the scattering table. An electrostatic sweeping potential of ±1 kV was established on the two plates to suppress the large number of electrons generated at the target, which would otherwise have reached the PSD's and reduced both their resolution and lifetime. Definition of the polar scattering angles was provided by a grid attached to the face of one of the PSD's. This grid was machined to provide 20 small rectangular apertures, each defining acceptance angles of 0.7° width, at intervals of 1.0°. The conjugate PSD remained unmasked in order to maximize coincidence-detection efficiency.

Each of the PSD's generated an energy pulse E, and a "position" pulse PE, where P is proportional to the position of the incident ion along the length of the detector. Figure 4 is a schematic diagram of the electronic instrumentation and computer interface network used to process these signals. The analog signals E_1, P_1, E_2, and P_2 were gated to the Yale-IBM 1024-channel ADC's by standard fast-slow timing generated from the E pulse of each PSD. The events defined by the observed coincidences were then processed and stored using the Yale-IBM nuclear data acquisition system.[20]

The scattering data were obtained in a series of measurements taken in energy steps of 500 keV over the range E_{lab} = 40–60 MeV. This range was covered three times, each with a different pair of detector angles. The three overlapping angular regions are shown in Fig. 5 superimposed on the over-all kinematic diagram for the interaction.

The data-analysis procedure is shown schematically in Fig. 6, where the P pulse has been obtained by digital division of the PE output of each detector by its associated E signal. Identification of the channels of interest, namely the elastic, and the single and mutual 2^+ inelastic channels, was accomplished through direct comparison of the experimental curves shown in Fig. 6(a) with the corresponding kinematic quadrant in Fig. 5. The background contribution to the yields was reduced from an average value of ~10% to a negligible amount by using the computer light pen to define a series of two-dimensional gates in each of the display parametrizations shown in Fig. 6(a), (b), (c), (d), enclosing the appropriate classes of events for a given channel. Subsequently, only those events whose parameters fell within these predefined limits were accepted for pulse-

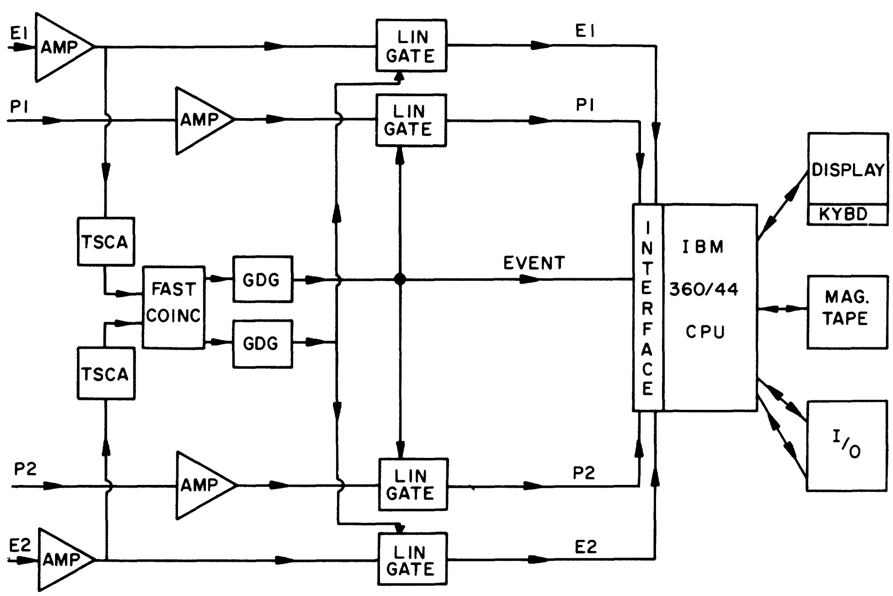

FIG. 4. A block diagram of the data-handling system (TSCA = timing single-channel analyzer, GDG = gate and delay generator).

height analysis in the P_1-P_2 plane [Fig. 6(e)]. A final projection on the P_1 axis yielded the raw angular yields [Fig. 6(f)] which were then extracted by summing the events in the individual count groups associated with each detector aperture opening. It should be noted here that the double-coincidence technique used here precluded observation of the single excitation of the 3^- state ($Q = -9.64$ MeV) in ^{12}C, since this state is unbound to α-particle decay to ^8Be by more than 2 MeV.

These yields were reduced to unnormalized differential cross sections by applying the appropriate solid-angle transformations and Rutherford-scattering normalizations. In this way, 246 independent points were obtained, corresponding to the above three channels measured over 41 energy steps and three separate PSD angular regions. Absolute cross sections were obtained by normalizing the elastic data obtained at 90° c.m. to the corresponding data measured by Reilly *et al.* The relative agreement between these two sets of data was excellent.

III. EXPERIMENTAL RESULTS

The differential cross sections for three channels: elastic, single, and mutual excitation of the 2^+ (4.43-MeV) state are compared in various ways in Figs. 7–9. A comparison of channel cross sections is shown for angular distributions at three energies (Fig. 7) and for excitation functions at six angles (Fig. 8). A continuous surface map of the data is shown in Fig. 9, where the cross sections have been subjected to a three-point interpolation in both energy and angle. In all cases, these cross sections are plotted on a logarithmic scale. The statistical uncertainties in the cross sections are typically 5%, increasing by a factor of two to three at the extreme minima found in the elastic channel. Considering the normalization to the elastic scattering from the gold on the monitor target, the normalization relative to the earlier measurements, and possible errors because of carbon-target deterioration, a value of 12% is found for the absolute estimated error limits on these cross sections. Tables of these cross

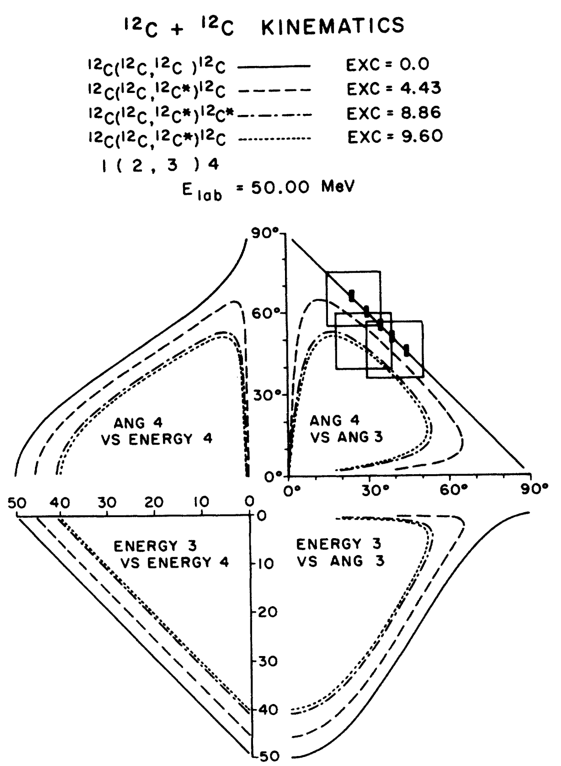

FIG. 5. Kinematics diagram for the channels of interest in the $^{12}C + ^{12}C$ interaction, for an incident ^{12}C energy of 50.00 MeV. The overlapping squares indicate the three geometries established by the position-sensitive detector configurations.

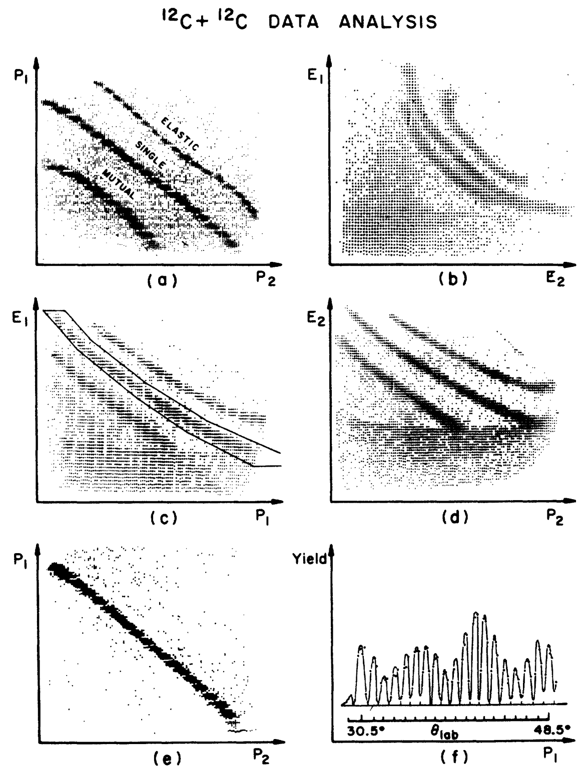

FIG. 6. Photographs taken directly from the data-acquisition display, indicating the procedure for the analysis of the data. A discussion of the individual photographs is given in the text.

sections are available on request.

At forward angles and low energies the single and mutual excitation are observed to be reduced in magnitude below the elastic scattering by factors ranging from 5–10. At larger angles and at higher energies, the situation is reversed, with the single and mutual excitation becoming predominant. The disappearance of pronounced structure in the single and mutual excitation may well simply reflect the increase in the number of partial waves that enter as a consequence of the coupling of nonzero channel spin with the orbital angular momenta.

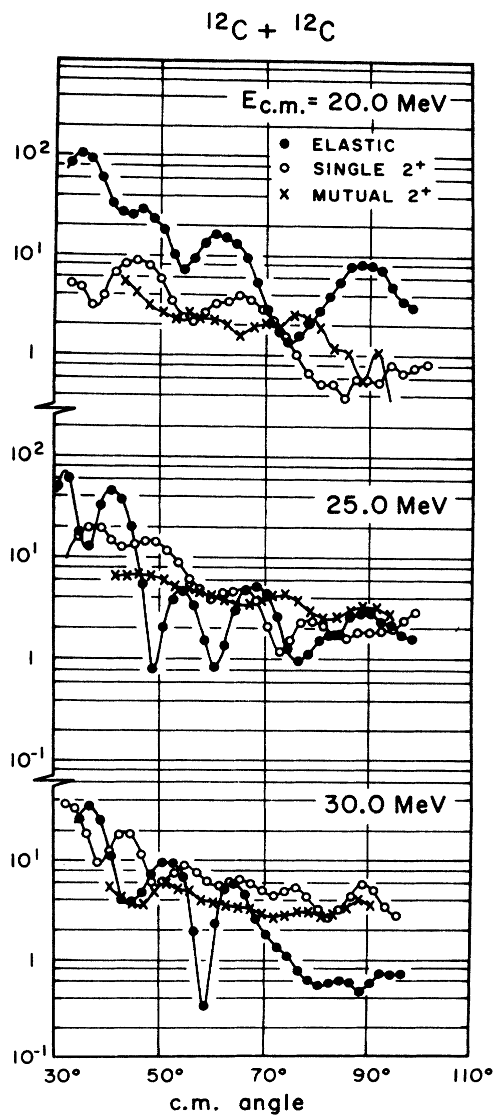

FIG. 7. Experimental angular distributions obtained at three representative energies, for the elastic and inelastic scattering channels in the $^{12}C + ^{12}C$ interaction.

IV. DISCUSSION

The most striking observation to be made upon examination of the cross sections shown in Fig 7–8 is that the inelastic channels – single and mutual – are comparable in magnitude to the elastic scattering channel. This has important consequences for the description and separation of the elastic potential scattering and the statistical compound processes involved in the interaction, as well as for the understanding of the proposed double-resonance mechanisms. As Vandenbosch[21] and Rawitscher[22] have emphasized independently in regard to the $^{16}O + ^{16}O$ and $^{18}O + ^{18}O$ systems, the one-channel optical model is simply not appropriate to a realistic description of such systems where one or more nonelastic channels are strongly coupled to the elastic channel. The data presented here indicate that ^{12}C-^{12}C scattering in the energy range studied is such a case.

An indication of the effect that explicit consideration of these inelastic channels may have on the earlier one-channel optical-model parameters, obtained by Reilly *et al.*,[9] is given by the results of a recent study by Rickertsen and Ascuitto on this system.[17] These authors have developed a coupled-channel analysis code for identical heavy-ion systems, and find that by explicitly including the first excited state (4.43 MeV) of ^{12}C, and allowing for single and mutual excitation of this level (yielding a 13-channel system) at the level found in our present experimental data, the strength of the imaginary optical-model potential is reduced to a value of 40% of the one-channel optical-model value. Several of the results of these coupled-channel calculations for $\theta_{c.m.} = 90°$ are shown in Fig. 10 – with the corresponding experimental cross sections. While Rickertsen and Ascuitto's calculations do not show a significantly improved fit to the elastic scattering excitation functions, over those obtained for the one-channel model, it can be expected that the optical parameters used by them will be much less dependent on the characteristics of the particular ions involved. Equivalent inelastic data on a series of heavy-ion systems are required before a systematic study of the improved coupled-channel parameters becomes possible. The present data already indicate a substantial modification of the one-channel optical-model parameters at least in cases such as $^{12}C + ^{12}C$ where relatively strong collective states are available for inelastic excitation. A further consequence of this observed strong coupling to the inelastic channels is that the transmission coefficients obtained from the one-channel optical model cannot be expected to yield reliable predictions when used in Hauser-

Feshbach calculations of the average compound cross-section contributions to various interaction channels. Already the experimental study of certain heavy-ion systems such as $^{12}C+^{12}C$ has advanced to the point where the partition of incident flux must be considered carefully if model calculations are to have any hope of reproducing the experimental data. This holds for the study of statistical processes as well as the direct. Preliminary statistical-model calculations (using optical-model transmission coefficients obtained from a fit to the elastic scattering) indicate sizable compound-nucleus contributions to the elastic and inelastic channels. Thus, the theoretical situation may be complicated by strong compound nuclear effects even if a full coupled-channel treatment is employed for the direct reactions. In addition, Böhning,[23] and Kawai, Kerman, and McVoy[24] have independently raised questions concerning the validity of the traditional Hauser-Feshbach approach to these statistical processes in high-energy heavy-ion collisions and further study in this regard is needed.

Finally, we return to the question of the structure of intermediate width in the elastic scattering cross sections and its possible relation to the occurrence of double-resonance quasimolecular processes. Fink, Scheid, and Greiner[18] have recently formulated a detailed description of these processes for the $^{12}C+^{12}C$ scattering case. The double-resonance mechanism begins schematically with a molecular potential which exhibits quasibound states inside the potential, and virtual states above the outer potential barrier. The quasibound states have very small widths and long lifetimes because of low barrier penetrability once they are formed. These states are considered to be the nuclear molecular states, and are

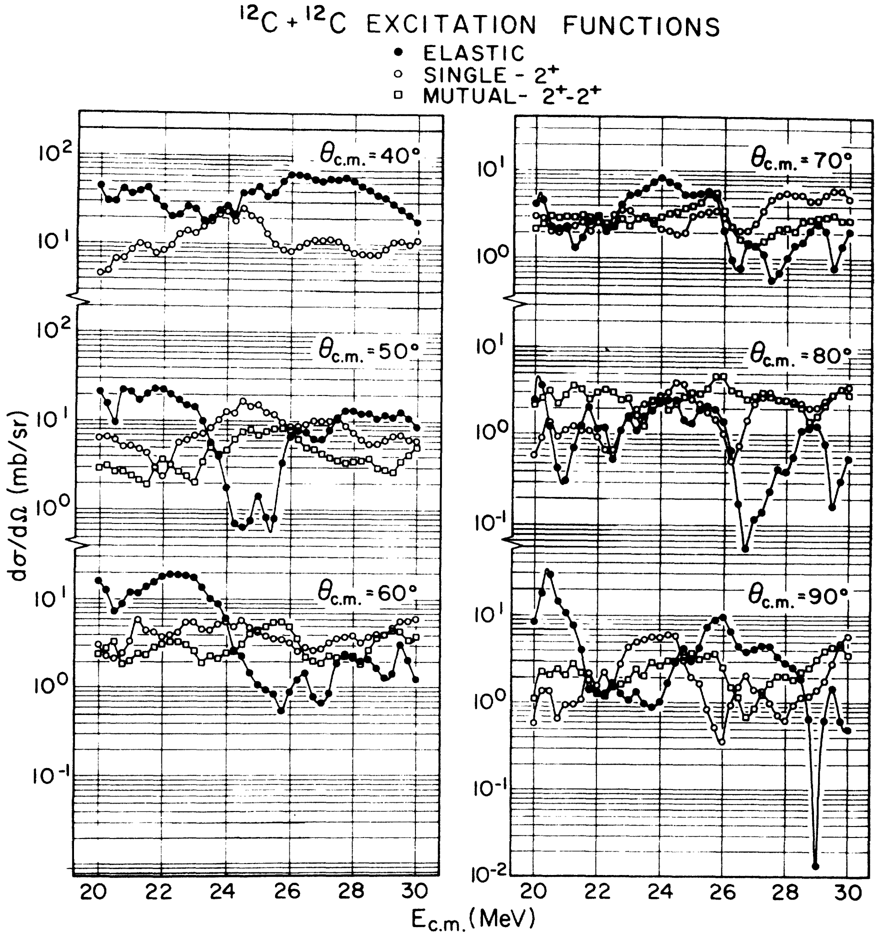

FIG. 8. Experimental excitation functions for the elastic and inelastic $^{12}C+^{12}C$ channels, shown at six representative center-of-mass scattering angles. In order to plot these data at constant c.m. angles, an interpolation in angle has been made where necessary. The experimental angular increment was a constant 1° in the laboratory system.

populated through the virtual scattering states acting as doorway states. The latter have large escape widths, being unbound, and yet can be enhanced through an orbiting or resonating partial wave. In this picture, the orbiting resonances are considered to generate the gross structure observed in the experimental elastic scattering excitation functions, and the narrower structure is generated, subsequently, by a particular incoming wave resonating in its corresponding virtual state which then feeds the lower-lying quasibound state through excitation of one or both of the ^{12}C nuclei involved. These authors have translated this schematic model into a coupled-channel formalism in which the real potentials – elastic and coupling – are calculated taking a sudden approximation for the scattering. This has been done with the recognition that the actual situation falls between the adiabatic and sudden approximations. The strength of the real coupling potential is obtained from an assumed δ-function surface interaction of 60 MeV between the two ^{12}C nuclei. The imaginary potential in the elastic channel is taken proportional to the density of states in the compound nucleus and to the volume of the overlap region during the collision. For the quasibound states, an extreme assumption is made that, since the number of compound states available for population is assumed to be small, and little energy is available near the ^{24}Mg yrast line for the formation of these states, the resulting absorptive potential will be small or nearly vanishing. Part of their resulting calculations are shown in Fig. 10, together with the experimental data and the predictions of Rickertsen. While Fink *et al.* have been able to introduce intermediate structure into the elastic channel, at energies lower than $E=20$

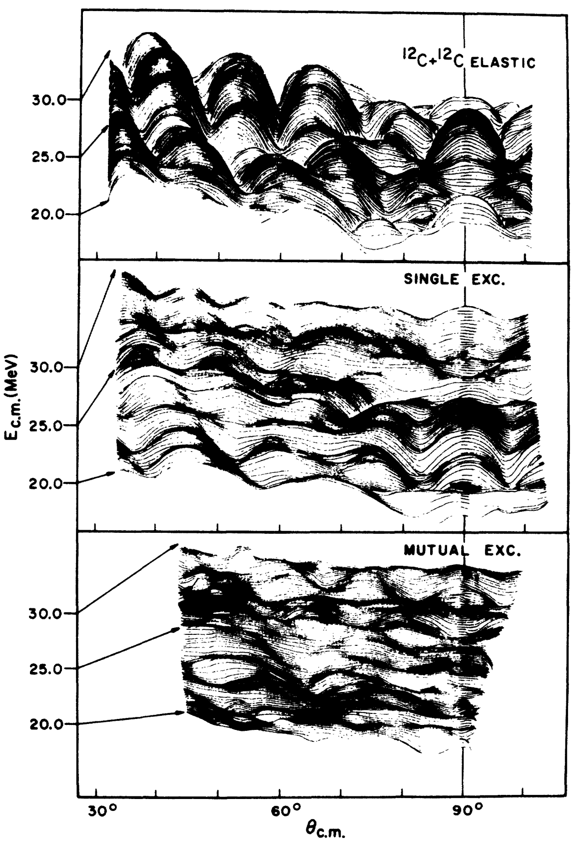

FIG. 9. Interpolated experimental cross sections for the $^{12}C+^{12}C$ interaction showing the elastic, single, and mutual excitation of the 2^+ state (4.43 MeV) in ^{12}C.

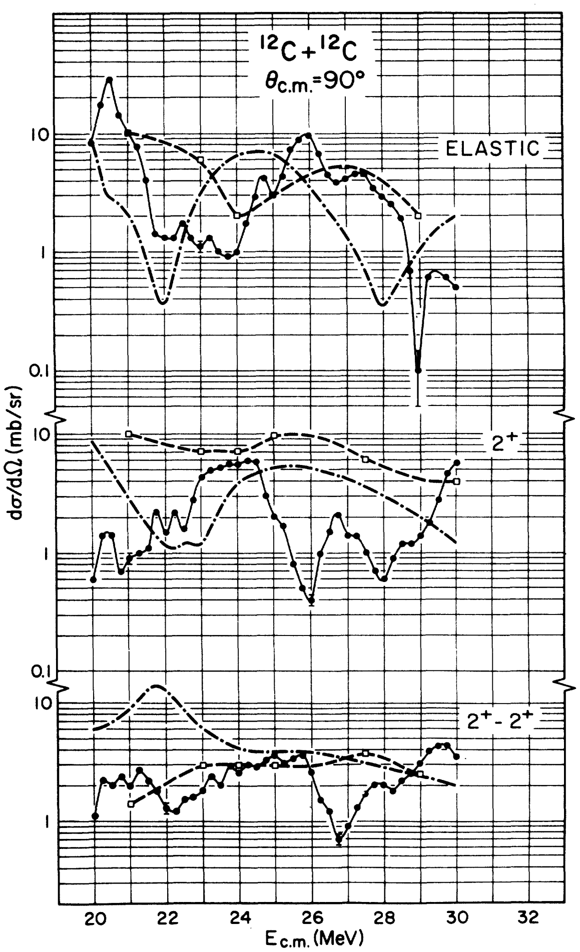

FIG. 10. A comparison of the theoretical coupled-channel predictions of Rickertsen (squares) and of Fink and Greiner (dot-dashed curve) with the experimental 90° c.m. excitation functions (dots) obtained for the elastic and inelastic $^{12}C+^{12}C$ channels. A solid curve has been drawn through the data points to guide the eye. A dashed line has been drawn through the calculated cross sections of Rickertsen to indicate better the trend of his results.

MeV, which qualitatively resembles the experimental structure observed, at the energies covered in this study there is no indication of such structure in their results, which is at variance with the data.

As is noted in Ref. 18, however, inclusion of coupling to higher excited states in ^{12}C could remedy this. These authors have also pointed out that the extent to which structure is present in their results is strongly dependent on the potential parameters employed. Thus, the use of a strong imaginary potential in the inelastic channel by Rickertsen and Ascuitto is presumably responsible for the lack of narrower structure in their calculation, even at lower energies. At the present stage, the evidence supporting the presence of double-resonance mechanisms in the ^{12}C-^{12}C system remains suggestive rather than conclusive. An alternative possibility which cannot be excluded would be that the observed structure reflects fluctuations in the amplitudes for compound inelastic scattering.[25] The elucidation of the relative contributions of these two different processes to the observed structure remains an interesting and difficult problem.

In summary, in the work presented herein we have demonstrated the importance of including inelastic channels in any realistic understanding of heavy-ion interactions. In particular, explicit inclusion of inelastic phenomena can modify the optical-model imaginary potential parameters in marked fashion – 60% in the case of ^{12}C. Similar effects can be anticipated in any nuclear system having significant collectivity. At the present time the double-resonance mechanism remains a most attractive possibility as an explanation for the structure of intermediate width in the excitation functions for elastic scattering. Further theoretical work will be required, however, before the mechanism can be considered as unambiguously established in the sense that it can account for the observations not only in the elastic, but also in the inelastic channels.

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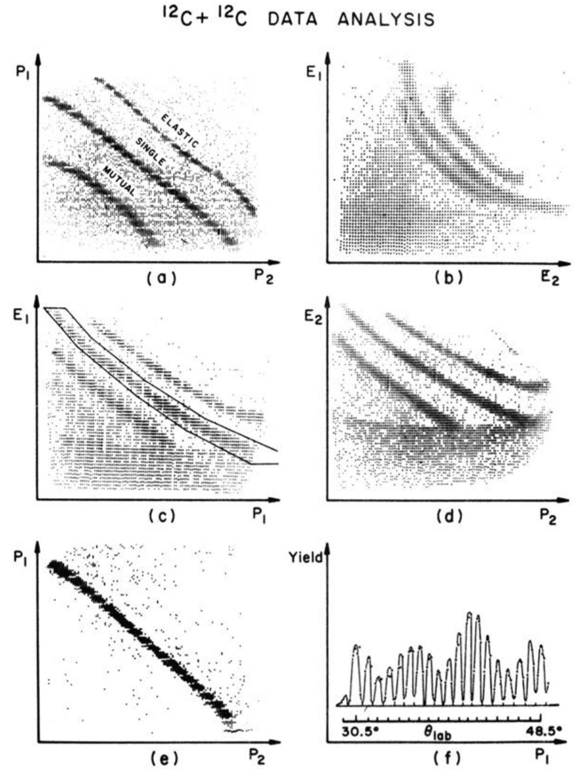

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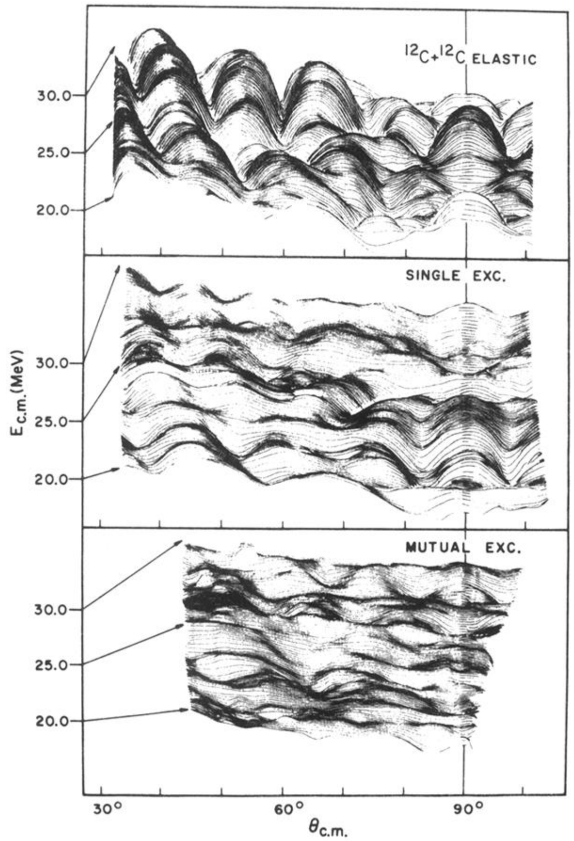

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