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QUASIMOLECULAR SINGLE-NUCLEON EFFECTS IN HEAVY-ION COLLISIONS

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QUASIMOLECULAR SINGLE-NUCLEON EFFECTS IN HEAVY-ION COLLISIONS*

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Single-particle motion in nuclei has traditionally been studied with spectroscopic tools such as one-step inelastic scattering and nucleon transfer reactions, using both light- and heavy-ion reactions. Such investigations have provided a wealth of information concerning the structure of isolated nuclei. Much less well understood is the extent to which the single-particle motion is modified in heavy-ion collisions by the approach and proximity of the collision partner. There is ample theoretical justification for expecting significant modifications in a variety of properties in low-energy collisions of heavy ions when the collision time is comparable to or longer than the characteristic nucleon rearrangement time.

In particular, the strong possibility exists that the modifications to single-particle motion could include the formation of di-nuclear orbitals, in which the nucleon bonds to both collision partners, and that this sharing of the nucleon would signal the (transient) existence of nuclear molecules. From a phenomenological point of view, such molecules would be different from the collective nuclear molecules discovered nearly 25 years ago by Bromley, Kuehner, and Almqvist.[1] But on a more fundamental level, the two kinds of structures bear a close relationship, particularly when viewed in terms of the two-center

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shell model concepts pioneered by the Frankfurt group.[2-4] Definitive studies of single-particle molecular orbital effects would refine the details of the two-center model and provide better input for model calculations of potential energy surfaces relevant to collective molecules.

1. MOLECULAR ORBITAL EFFECTS IN ELASTIC AND INELASTIC SCATTERING

Adriano Gobbi and collaborators[5] identified the phenomenon of elastic exchange in measurements of $^{12}C + ^{13}C$ elastic scattering angular distributions (Fig. 1). They showed that the natural explanation for the observed rise in yield at the larger angles is in terms of the exchange process illustrated schematically in Fig. 2. Direct elastic scattering is supplemented with the indistinguishable exchange process in which the extra-core neutron is transferred from the ^{13}C nucleus to the ^{12}C reaction partner. An extensive series of investigations was carried out by von Oertzen, Bohlen, and collaborators[6] to determine

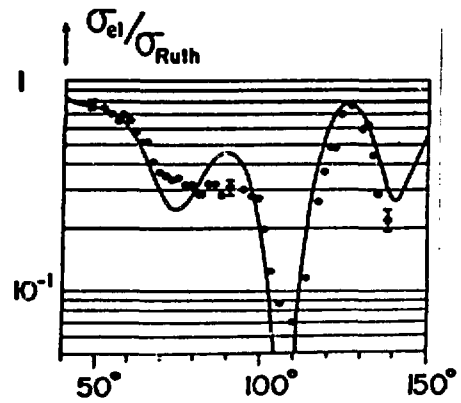

Fig. 1. $^{12}C+^{13}C$ scattering data (E_{cm} = 9.88 MeV) showing evidence for elastic exchange. From Gobbi et al.[5]

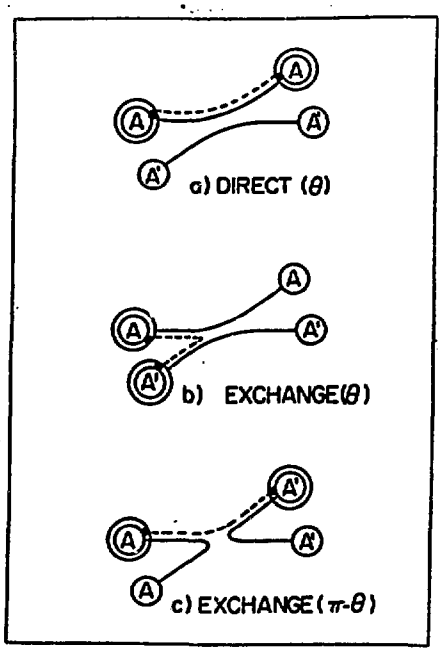

Fig. 2. Direct and exchange contributions to $^{12}C+^{13}C$ scattering.

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whether the exchange term in this and similar reactions could be understood in terms of ordinary direct transfer, or whether the data contained evidence for either enhanced or repeated transfer. Both of the latter processes would be natural consequences of the formation of molecular orbitals. These studies established elastic exchange as an important and very real physical phenomenon, but conclusive evidence for molecular orbital enhancement remained elusive. For most and probably all elastic scattering examples, alternate explanations involving modified optical potentials, different spectroscopic strengths, etc., can be found that permit reproduction of the data without the enhanced exchange and its concomitant molecular orbital implications.

Striking evidence for the formation of nuclear molecular orbitals in heavy-ion collisions appears in measurements and analysis of inelastic scattering in the $^{13}C+^{12}C$ system.[7-9] In these studies the cross section (Fig. 3) for excitation of a $1/2^+$ level of ^{13}C at 3.086 MeV was found to be significantly enhanced, and the corresponding angular distribution nearly symmetric about 90°. Both of these findings emerge as characteristic features of the molecular model calculations[8] that describe the data. When the overall system is in states of positive parity, polarized molecular orbits for the extra-core neutron are formed that have a greatly enhanced density along the line joining the centers of the colliding nuclei. Figure 4 depicts the calculated density from Ref. 8, and the similarity to a linear ^{12}C-n-^{12}C chain is remarkable. Configurations of this type naturally are conducive to

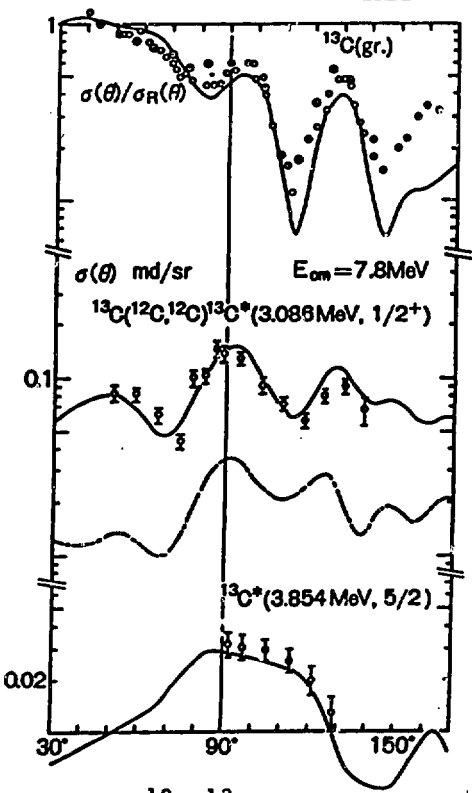

Fig. 3. $^{12}C+^{13}C$ elastic and inelastic data from Ref. 8. The enhanced and 90°-symmetric yields to the 3.086-MeV level are attributed to molecular orbital formation.

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transfer. In addition, the positive parity of the enhanced configuration is consistent with the observed angular distribution symmetry about 90°. Odd-parity states make little contribution to the transfer process, because the corresponding molecular orbitals have a density node between the two centers (Fig. 4).

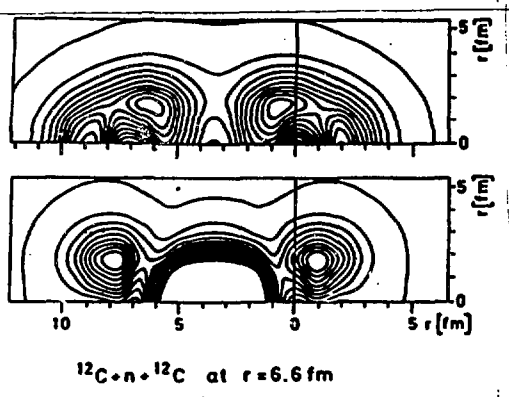

Fig. 4. Density distributions of a molecular neutron orbit, from Ref. 8. The top(bottom) panels correspond to states having total parity odd(even), that tend asymptotically to $p_{1/2}$ states in the separated system. The neutron density peaks on the line joining the cores in the even state.

Park, Greiner, and Scheid[10,11] have used the two-center shell model (TCSM) to predict molecular orbital effects such as nucleon promotion and transfer in terms of real and avoided level crossings in the two-center level diagrams. A typical level diagram from Ref. 11 that is relevant to $^{17}O+^{12}C$ interactions is reproduced in Fig. 5. For nucleus-nucleus separations near 7.5-8 fm, the diagram contains an avoided level crossing between the $\Omega=1/2$ branch of the $1d_{5/2}$ level (carrying the valence nucleon) in ^{17}O and the $2s_{1/2}$ level of the same nucleus. Thus, collision trajectories probing this region could result in the promotion of the valence nucleon via the nuclear Landau-Zener effect. Cindro et al.[12] have carried out a search for this process by measuring the energy and angle dependence of inelastic scattering to the 0.87 MeV, $1/2^+$ excitation of ^{17}O. Reasoning that trajectories having classical turning points near the separation distance of the avoided crossing will be affected the most, and also that only one partial wave at a time can satisfy this condition, Cindro et al. argue that enhanced yields and angular distributions characterized by

$$L = kR_c = \left[2m(E-V_{CB})/\hbar^2\right]^{1/2} R_c$$

would be good evidence for molecular orbital and level crossing effects in the two-center shell model. Some of the data from Ref. 12 are shown

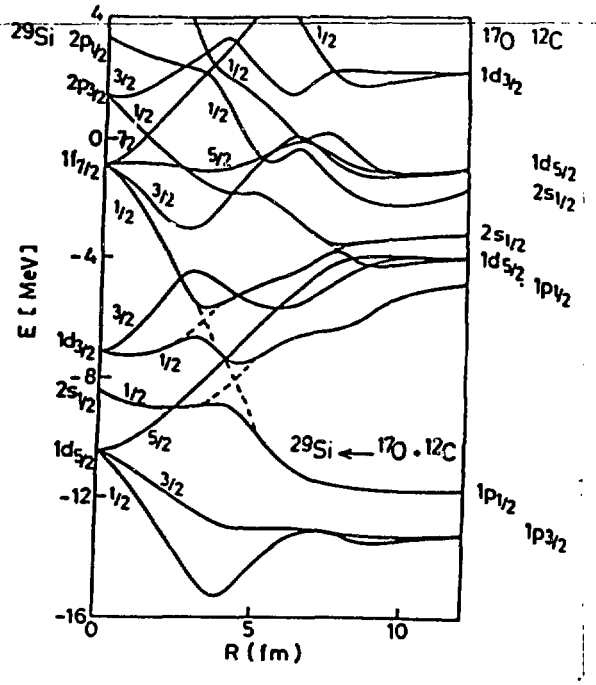

Fig. 5. TCSM level diagram for $^{12}C+^{17}O$ collisions, from Ref. 11.

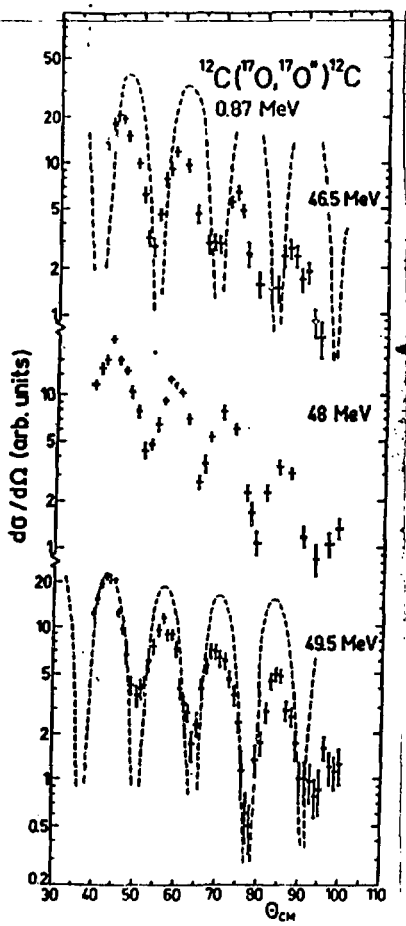

Fig. 6. Angular distributions of three energies for the $^{12}C(^{17}O,^{17}O^*$ 0.87 MeV) ^{12}C reaction, from Ref. 12. The dotted lines are $P_{12}^2(\cos\theta)$ (top) and $P_{13}^2(\cos\theta)$ (bottom) shapes.

in Fig. 6, where the close similarity between the measured angular distributions and pure Legendre polynomial shapes can be seen. These exciting recent data support the validity of the TCSM approach and should motivate considerable additional work along these lines.

2. MOLECULAR ORBITAL EFFECTS IN THE $^{13}C+^{13}C \rightarrow ^{12}C+^{14}C$ REACTION

The single-particle molecular orbital effects discussed above should have particularly pronounced effects in rearrangement reactions. We have indeed found this to be the case in a study of the $^{13}C(^{13}C,^{12}C)^{14}C$ reaction carried out at Yale[13] and discussed below.

For comparison, we note that a similar transfer process was

studied some time ago with a bombarding of 87 MeV by Liu et al.[14] At this relatively high energy there is too little time available for internal rearrangement of nucleon degrees of freedom to be significant. As a consequence, neutron transfer having appreciable parentage should proceed as a direct, one-step process, and be well described in terms of the DWBA. The reaction actually studied in Ref. 14 was $^{13}C+^{12}C$ elastic scattering, but the measurements were carried out in an angular region where the cross section is dominated by the neutron transfer amplitude, i.e., by the amplitude for $^{13}C(^{12}C,^{13}C)^{12}C$. The reaction involves angular momentum transfer of both $\Delta\ell = 0$ and $\Delta\ell = 1$, as the neutron is exchanged between $p_{1/2}$ orbits. DeVries[15] showed that the incoherent addition of the two contributions, each of which separately leads to highly structured angular distributions, nicely reproduces the observed rather flat angular distributions, as may be seen in Fig. 7. Inasmuch as a straightforward finite-range DWBA calculation, using standard parameters and spectroscopic strengths, provides a good account of the $p_{1/2}$ neutron transfer between ^{13}C and ^{12}C at high energy, any deviations observed at lower energy will be evidence for changes in the reaction mechanism.

In our study of $^{13}C(^{13}C,^{12}C)^{14}C$, the balance between the $\Delta\ell$=0 and $\Delta\ell$=1 transfer contributions would be changed significantly if, for example, our choice of bombarding energies near

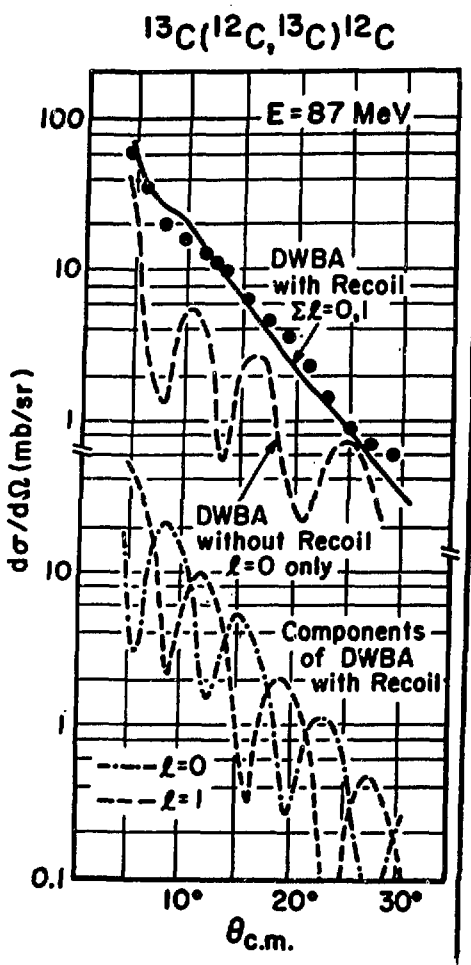

Fig. 7. Direct nature of neutron transfer at higher bombarding energy. The data are from Ref. 14 and the calculations from Ref. 15.

the Coulomb barrier enabled molecular orbital formation during the relatively long collision times available. The polarization phenomenon typified in the lower panel of Fig. 4 and discussed above would strongly favor $\Delta\ell = 0$, since the enhanced neutron density on the core-core axis carries an orbital angular momentum of zero. Moreover, any mixing of the asymptotic configurations in the linear-combination-of-nuclear-orbitals (LCNO) model tends to reduce[13] the binding energy differences between entrance and exit channel for configurations having channel spin S = 0, but to leave it essentially unchanged when S = 1. For $p_{1/2}$ to $p_{1/2}$ transitions leading to the $^{12}C+^{14}C$ ground state exit channel, S=0 configurations contribute only to $\Delta\ell=0$ transfer, and S=1 only to $\Delta\ell=1$. Thus, molecular orbital effects of this type would reduce the effective Q-value toward the optimum value $(Q_{opt}=0)$ for $\Delta\ell=0$ transitions and leave it unchanged for $\Delta\ell=1$.

Our $^{13}C(^{13}C,^{12}C)^{14}C$ measurements covered the range of bombarding energies from just above to approximately four times the Coulomb barrier $(8 < E_{cm} < 25$ MeV$)$. Energy-angle surfaces constructed from the measured and DWBA yields are compared in Fig. 8. Throughout the entire

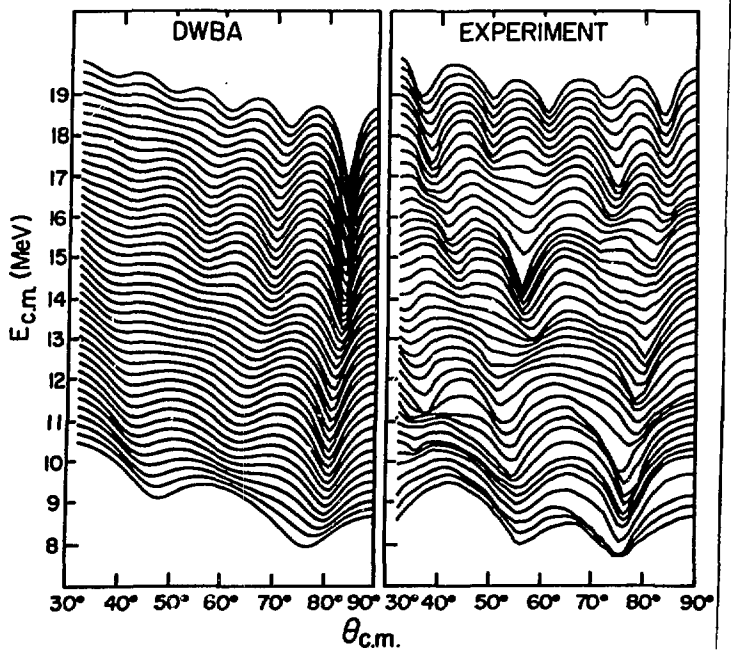

Fig. 8. Comparison of DWBA and experimental energy-angle surfaces for $^{13}C(^{13}C,^{12}C)^{14}C$

energy range under consideration, the measured angular distributions for the ground-state reaction are highly oscillatory, while the full finite-range, properly antisymmetrized DWBA calculations are relatively featureless. To fix the optical potential for the calculation, we carried out an extensive series[13] of $^{13}C+^{13}C$ elastic scattering measurements over the energy range $7.25 \leq E_{cm} \leq 35.5$ MeV and determined the following optical-model parameters:

$V_0 = 16.0$ MeV $\quad r_0 = 1.35 \quad a = 0.45$

$W = 0.22\ E_{cm} \quad r_i = 1.35 \quad a_i = 0.30$

Small changes in the parameters failed to improve the agreement between the DWBA calculations and the transfer data. From a phenomenological point of view, the basic problem with the DWBA is its failure to predict the correct $\Delta\ell$=0 to $\Delta\ell$=1 ratio. As Fig. 9 shows, each of the two cross-section components is highly oscillatory, but with phasing that results in featureless angular distributions when they are combined.

We attempted to extract the ratio of $\Delta\ell$=0 to $\Delta\ell$=1 strength directly from the data for comparison with theoretical models, using a phase shift analysis. The ratio could not be determined unambiguously, largely due to the fact that the contributing spherical harmonics are

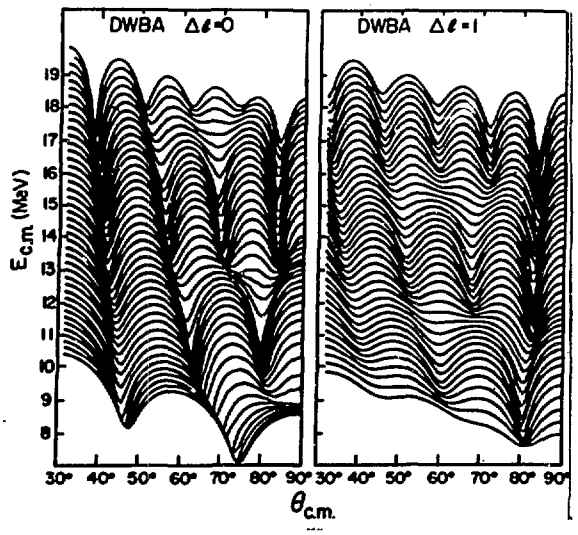

Fig. 9. Comparison of individual $\Delta\ell$=0 and $\Delta\ell$=1 contributions to the total DWBA shown in Fig. 8.

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not orthogonal over the limited angular range $30° \leq \theta \leq 90°$ where the data exist. We did find that an enhanced role for the $\Delta\ell=0$ component is required for an improved fit, and, in fact, at most energies adequate fits to the angular distribution data could be obtained assuming pure $\Delta\ell=0$ transfer. One such example is shown in Fig. 10.

The angular distributions from the $^{13}C(^{13}C,^{12}C)^{14}C$ ground-state reaction at relatively low energies thus require a different balance in the angular momentum transfer than is predicted by the DWBA, and the required change is qualitatively consistent with the $\Delta\ell=0$ enhancements expected from the systematics of known molecular orbital behavior (Fig. 4). The energy dependence of the data provides another important piece of information. Our measured 90° excitation function is plotted together with DWBA calculations in Fig. 11. The apparently periodic oscillations in the data are absent in the calculation, but perhaps more significantly, the measured cross section at the peaks of the oscillations remains relatively constant over a wide energy range, while the DWBA yields generally decrease with increasing bombarding energy. Using a two-pole parametrization suggested by Carlson and McVoy,[16] Korotky[13] first simulated the DWBA $\Delta\ell=0$ results and then showed that a much improved fit to the 90° excitation function data (Fig. 12)

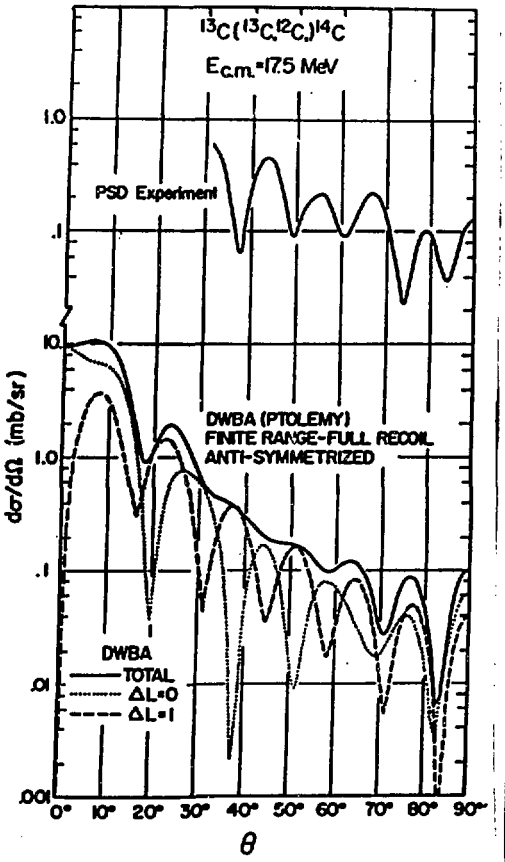

Fig. 10. The measured $^{13}C(^{13}C,^{12}C)^{14}C$ angular distribution (top) is better reproduced by the $\Delta\ell=0$ DWBA component than by the total DWBA.

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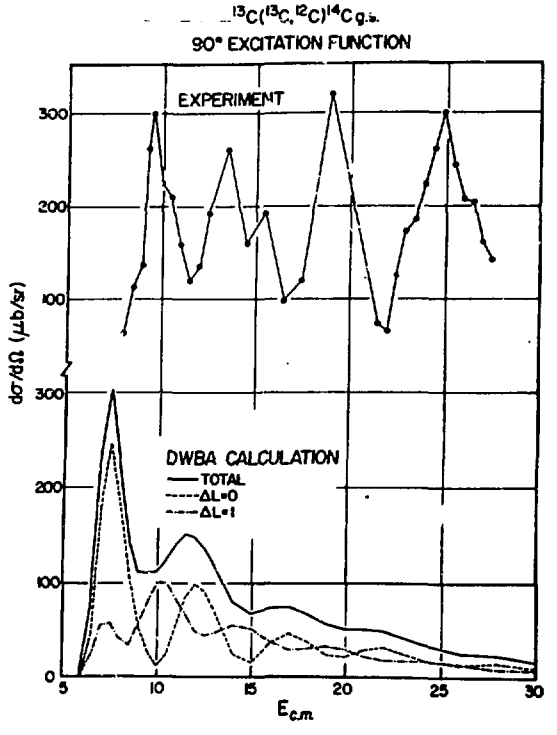

Fig. 11. Excitation functions at 90° measured and calculated for the $^{13}C(^{13}C,^{12}C)^{14}C$ reaction. The DWBA fails to reproduce the structure in the data, and seriously underpredicts the cross section magnitudes.

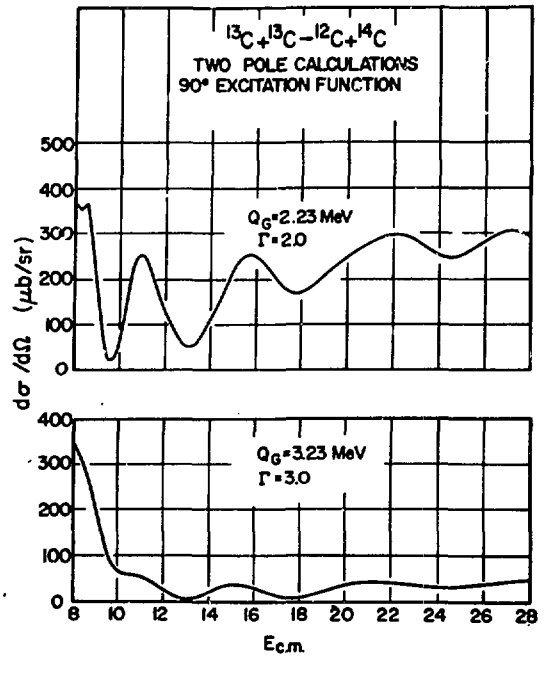

Fig. 12. Excitation function calculations for the $^{13}C(^{13}C,^{12}C)^{14}C$ reaction using the two-pole model. Only $\Delta\ell$=0 angular momentum transfer is considered. The lower panel shows a calculation using the asymptotic Q-value. The upper panel shows the effects of reducing the (effective) Q-value in the model calculation.

could be achieved by reducing the separation between the poles and moving them closer to the real axis. These shifts correspond to a reduction of the effective Q-value in the region of the barrier and an increase in the collision delay time, precisely as would be expected if molecular orbital formation were a dominant aspect of the reaction.

Taken together, these experimental findings--greatly enhanced $\Delta\ell=0$ transfer, evidence for a reduced effective Q-value, and increased collision time--leave little doubt that single-particle molecular effects are at work in the reaction $^{13}C(^{13},^{12}C)^{14}C$ at low bombarding energies.

An extensive dynamic two-center shell-model calculation for this reaction has been carried out recently by Könnecke, Greiner, and Scheid.[17] The optical-model parameters determined by Korotky and listed above were used, and couplings among neutron states that tend asymptotically to $p_{1/2}$ and $s_{1/2}$ orbits were included in the calculation. With the proper choice of a neck parameter that determines the height of the two-center potential at a point midway between the cores (i.e., ϵ = 0.65), a rather good reproduction of our transfer reaction angular distribution data is achieved, as may be seen in the lower panels of Fig. 13. In addition, the general

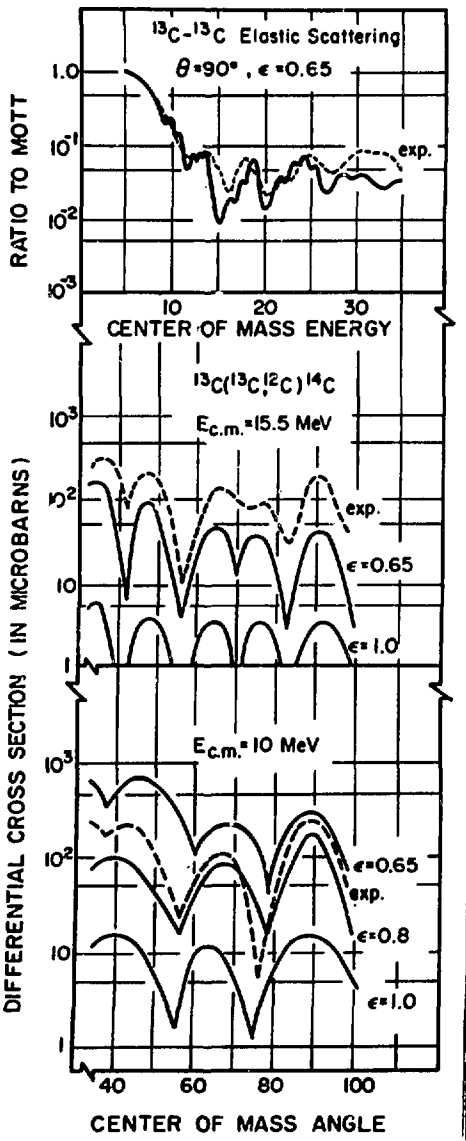

Fig. 13. Data (dashed lines, Ref. 13) and TCSM calculations (solid lines, Ref. 17) for yields from $^{13}C+^{13}C$ interactions.

features of the elastic scattering (Fig. 13, top panel) and transfer reaction excitation functions (Fig. 14) are described reasonably well. The molecular orbital model as implemented by Könnecke, Greiner, and Scheid thus provides additional quantitative evidence that neutron transfer in the $^{13}C+^{13}C$ system at low bombarding energies is governed by a molecular orbital rather than a direct (DWBA) mechanism.

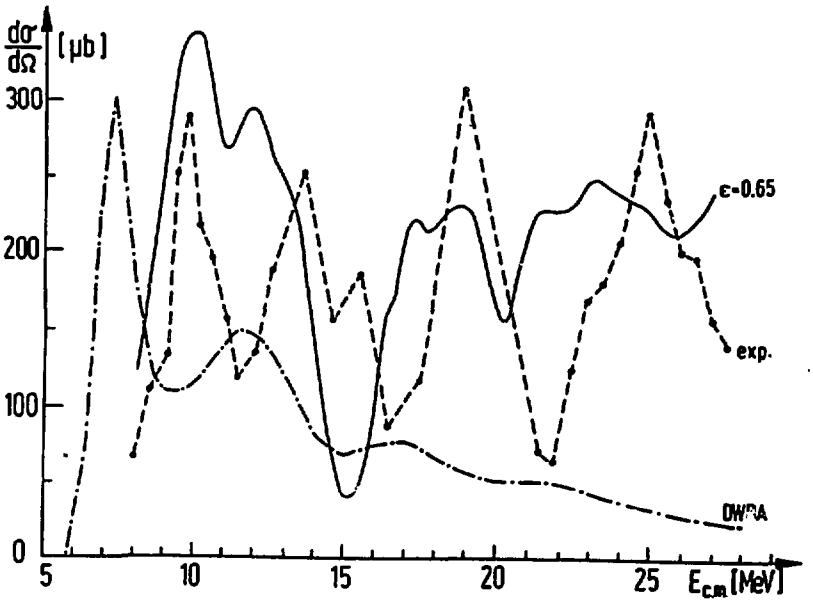

Fig. 14. $^{13}C(^{13}C,^{12}C)^{14}C$ 90° excitation function data (dashed lines, Ref. 13), DWBA calculations (dash-dot lines), and TCSM calculations (solid lines, Ref. 17).

These successes render it especially important to compare the inelastic yields from the calculations of Könnecke with new inelastic scattering data from Pennsylvania. Balamuth et al.[18] recently measured the yields from single and mutual excitation of the predominantly single-particle $p_{1/2}$ to $s_{1/2}$ transitions in the $^{13}C(^{13}C,^{12}C)^{14}C$ system, with results shown in Fig. 15. The cross section for mutual excitation of the 3.09 MeV $1/2^+$ level is approximately 25 times smaller than the single excitation of the same state, whereas the TCSM calculations of Terlecki et al.[19] predict that the two should be nearly equal. Balamuth found that the difference persists over the bombarding

energy range, $8 < E_{cm} < 25$ MeV. The discrepancy may indicate that the transfer coupling, which was included in the calculations of Könnecke et al. but not in the earlier work of Ref. 19, is a particularly important ingredient in the model calculations.

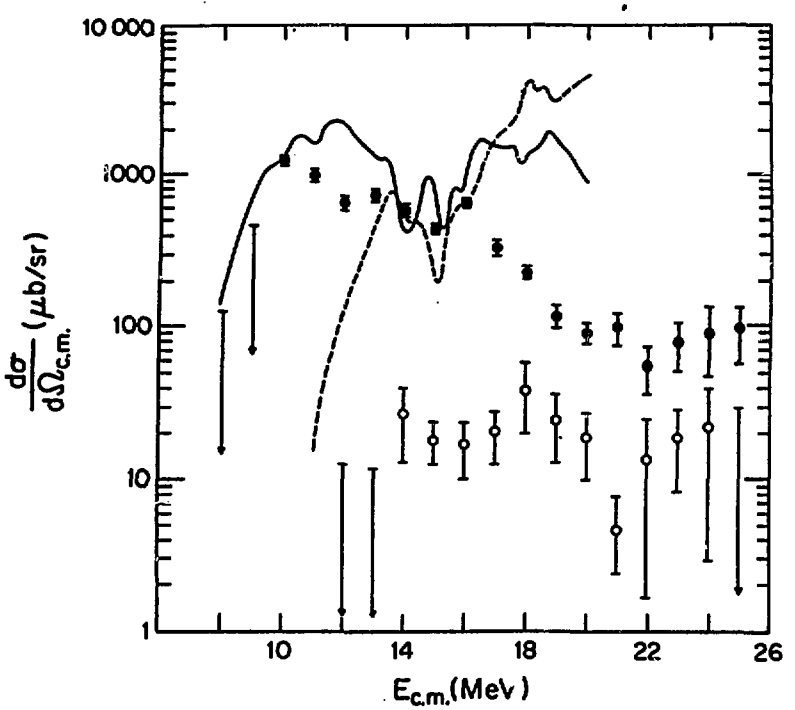

Fig. 15. $^{13}C+^{13}C$ single (filled circles and solid curve) and mutual (open circles and dashed curve) inelastic excitation functions (90°) to the $1/2^+$ 3.09-MeV level, from Balamuth et al. (Ref. 18). The calculations are from Ref. 19.

3. SUMMARY AND CONCLUSIONS

Several experimental examples have been discussed to illustrate that single-particle molecular orbital behavior has become an established reality in nuclear physics over the last several years. Theoretical progress is discussd in more detail in these proceedings by Prof. Scheid. Measurements and analyses of inelastic scattering in the $^{13}C+^{12}C$ and $^{17}O+^{12}C$ systems, and of neutron transfer in the $^{13}C(^{13}C,^{12}C)^{14}C$ reaction, show that the motion of valence nucleons can

be strongly and simultaneously influenced by both collision partners in heavy-ion collisions. This behavior is characteristic of a molecular (single-particle) rather than a direct (DWBA) mechanism: it demonstrates that the single-particle analog of atomic molecular motion plays an important role in nuclear reactions at bombarding energies near the Coulomb barrier. Such behavior may be even more pronounced in the collisions of massive nuclei that will be studied with the new generation of heavy-ion accelerators.

ACKNOWLEDGEMENTS

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