Molecular Interpretation of the Neutron Transfer in the Reaction $^{13}C(^{13}C,^{12}C)^{14}C$ within the Two-Center Shell Model

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On the basis of the two-center shell model a molecular reaction theory is applied to the reaction $^{13}C(^{13}C,^{12}C)^{14}C$. Prominent structures in the measured differential cross sections can be reproduced by this theory.

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Molecular single-particle effects in heavy-ion reactions have been considered up to now to be of minor interest in contrast to the molecular collective states which have been thoroughly investigated in experiment and theory because of their prominent signatures in the cross sections (gross and intermediate structures).[1] On the other hand, the underlying fundamental model for a nuclear molecule is the two-center shell model (TCSM) which describes the binding of the molecule in terms of molecular single-particle states.[2,3] Hence, molecular single-particle states should play an important role and a verification of their effects is called for.

There exists at present little experimental evidence for molecular single-particle effects. Recently, it was proved that the neutron orbits in the elastic transfer reaction of ^{12}C on ^{13}C are of molecular nature.[4] The excitation function for the neutron transfer reaction $^{13}C(^{13}C,^{12}C)^{14}C$, measured by Korotky *et al.*,[5,6] showed a large resonantlike behavior, which could not be reproduced by finite-range, full-recoil, single-step distorted-wave Born-approximation (DWBA) calculations.[6] This last result was our motivation for applying a molecular particle-core description to the reaction $^{13}C(^{13}C,^{12}C)^{14}C$. It is the aim of this paper to show that the resonantlike structures in the experimental differential cross sections can be satisfactorily explained as the transfer of a neutron occupying a molecular single-particle state during the reaction.

A molecular description of loosely bound nucleons has been worked out earlier on the basis of a molecular particle-core model and the TCSM for heavy-ion reactions.[7-13] These models are justified for the reaction considered since the characteristic collision time is considerably longer than the single-particle rearrangement time, namely by a factor 2–3 as estimated with the collision and Fermi energies.[13]

The neutron transfer process is described with the molecular particle-core model.[7,12] The ^{13}C and ^{14}C nuclei are thought to be constructed of ^{12}C cores and valence neutrons. The valence neutrons move in the mean field of all nucleons and are treated in the framework of the two-center shell model. The cores can also be excited, which may be described with collective models for core vibrations and rotations.

The Hamiltonian of the particle-core model in laboratory coordinates consists of the kinetic energies T_{C_i} of the cores, their interaction $W_{C_1C_2}$, the single-particle Hamiltonians $h_{\mathrm{TCSM}}(i)$ of the valence particles described by the TCSM, and the residual interaction V_{res} between the valence particles:

$$H = T_{C_1} + T_{C_2} + W_{C_1C_2} + \sum_{i=1}^{N} h_{\mathrm{TCSM}}(i) + V_{\mathrm{res}} - T_{\mathrm{c.m.}} \tag{1}$$

In our present calculations we assume inert ^{12}C cores frozen in their ground state. The residual interaction between the two valence neutrons is partially considered by using the experimental Q value in the ^{12}C-^{14}C channels for large internuclear distances. The diagonal parts of the potential energies in (1) yield the ^{13}C-^{13}C potential in the elastic channels and are replaced by an optical potential with parameters obtained by Korotky.[6] If $s=0$ denotes the ^{13}C-^{13}C fragmentation and $s=1$ and 2 the ^{14}C-^{12}C and ^{12}C-^{14}C fragmentations, respectively, the Hamiltonian (1), transformed to the rotating coordinate

system with the z axis defined by the direction of the relative coordinate between the nuclei, is given by[12]

$$H = H^{(s)} = -\frac{\hbar^2}{2\mu_s}\frac{1}{R_s}\left(\frac{\partial}{\partial R_s}+D_s\right)^2 R_s + \frac{1}{2\mu_s R_s^2}[\vec{I}(\varphi_s,\theta_s,\psi_s)-\vec{J}_s]^2 + W_s(R_s) + \sum_{i=1}^{N} h_{\mathrm{TCSM}}(i,s) - \frac{1}{2A_1^{(s)}M}\left(\sum_{i=1}^{N_1^{(s)}}\vec{p}_{\mathrm{c.m.},i'}\right)^2 - \frac{1}{2A_2^{(s)}M}\left(\sum_{i=N_1^{(s)}+1}^{N}\vec{p}_{\mathrm{c.m.},i'}\right)^2, \quad (2)$$

where

$$D_s = \frac{1}{A}\left(A_2^{(s)}\sum_{i=1}^{N_1^{(s)}}\frac{\partial}{\partial z_{\mathrm{c.m.},i'}} - A_1^{(s)}\sum_{i=N_1^{(s)}+1}^{N}\frac{\partial}{\partial z_{\mathrm{c.m.},i'}}\right). \quad (3)$$

The coordinates $\vec{r}_{\mathrm{c.m.},i'}$ of the valence particles are referred to the center of mass. For the other symbols we refer to Ref. 12.

For reasons of simplicity we have calculated the single-particle wave functions for all fragmentations with the symmetric TCSM. The parameters of the TCSM are adjusted by the requirement that the TCSM reproduce the single-particle levels of ^{13}C near the Fermi level (see Ref. 11). For the wave functions we choose the following *Ansatz*:

$$\psi_M^I = \mathcal{A}(1,2)\sum_{s,\alpha,l,J} R_{s\alpha lJI}(R_s)[i^l Y_l(\theta_s,\varphi_s)\otimes\Phi_{s\alpha J}]_M^{[I]}. \quad (4)$$

Here, the operator $\mathcal{A}$ antisymmetrizes the wave function in the two valence nucleons. In addition the wave function is assumed to be symmetrized with respect to the exchange of the ^{12}C cores. The wave function $\Phi_{s\alpha JM}$ describes the valence neutrons and is connected with the wave function $\tilde{\Phi}_{s\alpha(J)M}$ referred to the rotating coordinate system via the transformation

$$\Phi_{s\alpha JM} = \sum_{M'} D_{MM'}^{J\,*}(\varphi_s,\theta_s,\psi_s)\tilde{\Phi}_{s\alpha(J)M'}. \quad (5)$$

Here, $\tilde{\Phi}_{s\alpha(J)M}$ is built up with the wave functions of the TCSM. Projecting on $H\psi = E\psi$ with the channel wave functions, defined in Eq. (4), we obtain a set of coupled equations for the radial wave functions $R_{s\alpha lJI}$ which asymptotically determine the S-matrix elements and hence the cross sections.

In the matrix elements between the channel functions of different fragmentations we have neglected the recoil terms and the correction terms for the centers of mass shown in Eq. (2). The present calculations are restricted to the following channels: ^{13}C(g.s.) + ^{13}C(g.s.), ^{13}C(g.s.) + ^{13}C*($\frac{1}{2}^+$, 3.09 MeV), ^{13}C*($\frac{1}{2}^+$, 3.09 MeV) + ^{13}C*($\frac{1}{2}^+$, 3.09 MeV), ^{12}C(g.s.) + ^{14}C(g.s.). Therefore, the valence neutrons occupy the $1p_{1/2}$ and $2s_{1/2}$ states for large internuclear distances. The $2s_{1/2}$ level lies energetically lower than the $1d_{5/2}$ level in ^{13}C and is strongly coupled to the $1p_{1/2}$ state by an $E1$ transition.

Two coupling mechanisms between the intrinsic single-particle states play an essential role in all molecular reaction theories, namely the radial and Coriolis couplings. In the example chosen here, the radial-coupling matrix elements between the ground-state configurations ^{13}C + ^{13}C and ^{12}C + ^{14}C vanish because of selection rules and since we have used the same symmetric TCSM in both channels. Figure 1 shows typical radial matrix elements as functions of the internuclear distance for two choices of the neck parameter ϵ. This parameter gives the ratio of the barrier heights of the actual TCSM potential and the two-center oscillator potential.[2] With decreasing barrier heights (i.e., smaller ϵ) the radial-coup-

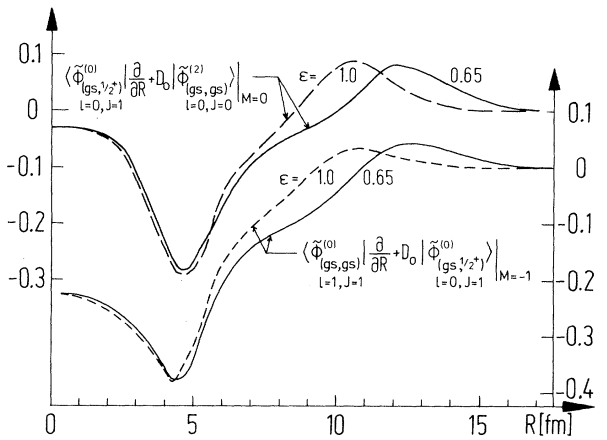

FIG. 1. Radial-coupling matrix elements for a transition from an excited ^{13}C + ^{13}C configuration to ground-state configurations of ^{13}C + ^{13}C (lower curves, right scale) and ^{12}C + ^{14}C (upper curves, left scale) for two values of the neck parameter ϵ.

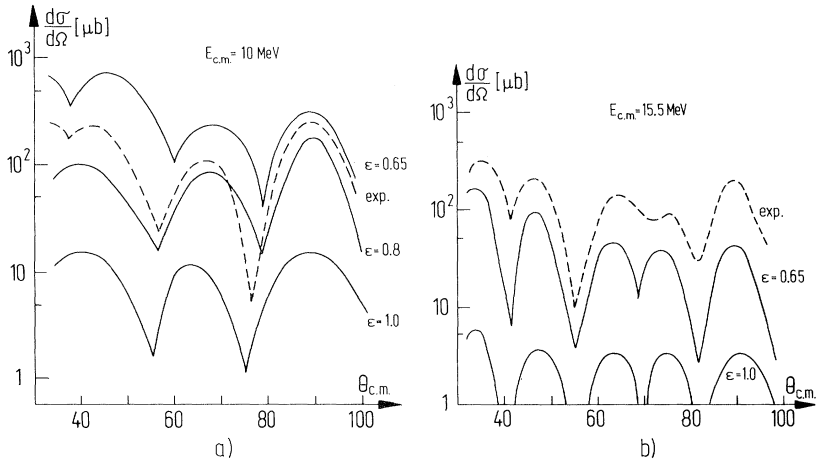

FIG. 2. Comparison of the calculated differential cross section for neutron transfer (solid curves) with the experimental data of Ref. 6 (dashed curves).

ling potential gets extended to larger internuclear distances.

Figure 2 shows the calculated and experimental differential cross sections for the neutron transfer between the ground-state configurations at an incident energy of $E_{c.m.} = 10$ and 15.5 MeV. With decreasing barrier height (smaller ϵ) the cross section becomes sensitively larger, showing that the main contributions to this channel arise from larger internuclear distances of about 7–11 fm, where the absorptive potential has dropped already to zero. Comparison with the experimental curves of Refs. 5 and 6 indicates that the only free parameter, ϵ, of our calculation should be chosen to be $\epsilon \approx 0.65$ in order to reproduce the experimental data. A similar value of $\epsilon = 0.68$ was obtained by Park, Greiner, and Scheid[13] in their calculation of level diagrams for the TCSM.

Finally, Fig. 3 shows the differential transfer cross section for neutron transfer at $\theta_{c.m.} = 90°$ as a function of the incident energy. The peak-to-valley ratio in the low-energy region is well pronounced compared with the experiment. At higher energies the calculated curve is too flat, probably as a result of the increasing imaginary potential in the elastic channel.

The structures in the calculated 90° differential cross section for neutron transfer can be grouped into gross and intermediate structures. The gross structures, which are similar to those observed in the elastic 90° excitation function, are generated by a smooth energy behavior of groups of partial waves. The intermediate structures with widths of about 0.5–1 MeV appearing in the calculated cross section arise from resonance states in the $^{13}C + ^{13}C$ and $^{12}C + ^{14}C$ potentials. A complete analysis of the S-matrix elements will be published.

In conclusion, we can sensitively test the properties of the internuclear barrier of the TCSM and confirm that a molecular reaction theory explains the data more satisfactorily than the one-step DWBA calculations of Korotky,[6] presented also in Fig. 3 for comparison. The remaining discrepancies between our results and the experimental data can probably be removed by taking more excited channels into account.

A nonmolecular multistep DWBA calculation may also reproduce the data. But when multistep processes play a role, the neutron has enough

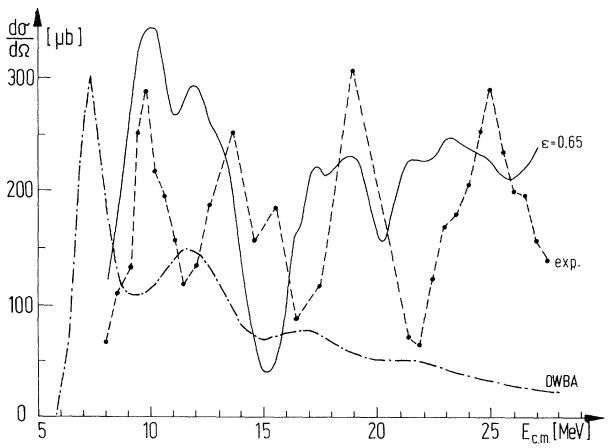

FIG. 3. Comparison of the calculated 90° differential cross section for neutron transfer (solid curve) with experimental data of Ref. 6 (points connected with a dashed curve) and a DWBA calculation of Korotky (Ref. 6) (dot-dashed curve).

time to rearrange during the collision and approach a molecular orbital. The nonmolecular reaction theories describe the polarization of the nucleon states in terms of the states of the separated nuclei. When molecular orbitals are actually formed in a reaction, as we presume in the present case, it is not advantageous to expand them into single-particle states of the separated nuclei. The superiority of the molecular theory is basically founded on the fact that the scattering wave function is expanded in states realized during the reaction (see Refs. 4, 10, and 11). In all valid cases the molecular theory clarifies our understanding of the reaction more than a theory using an improper set of basis functions although both types of theories should ultimately yield the same cross sections. In this sense the reaction considered in this paper seems to be a master example for the applicability of the molecular reaction theory, where, for the first time, a complete molecular coupled-channels calculation for neutron transfer has been carried out.

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