Molecular single-particle effects in the $^{12}C+^{17,18}O$ and $^{13}C+^{17}O$ reactions

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We have used the asymmetric two-center shell model to calculate the single-neutron energies in the $^{12}C+^{17,18}O$ and $^{13}C+^{17}O$ collisions as a function of the internuclear distance. The periodic resonancelike structures observed in the angle-integrated inelastic cross sections for these systems can be understood in terms of the nuclear Landau-Zener promotion of a loosely bound valence neutron from the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) state to the $2s_{1/2}$ state of the oxygen isotopes. Inclusion of the effects of a turning point in the Landau-Zener formula is found to give marked improvements in accounting for the observed angle-integrated inelastic cross sections for these systems. Intermediate structures in the cross sections are found to arise due to the energy-dependent oscillatory behavior of the partial cross sections. While some resonancelike peaks can be attributed to a single orbital angular momentum, many others arise due to the combined contributions of two or more angular momenta.

I. INTRODUCTION

One of the interesting aspects of reactions between light heavy ions is that nuclear molecules can be formed during the collision process.[1-3] The narrow resonances observed in the energy dependence of the $^{12}C + ^{12}C$ reaction have provided the first evidence for the existence of nuclear molecules.[1] A nuclear molecule is a system of two (or more) nuclei which are bound together on their surfaces in the quasibound states of a quasimolecular potential. In the microscopic two-center model[4,5] a nuclear molecule may, therefore, be understood as a state in which the outermost loosely bound (valence) nucleons orbit around both nuclei, just like homopolar or covalent bonding in atomic molecules, such as in O_2 or N_2 molecules. Since the bonding of the molecule is described in terms of molecular single-particle states, these states should play an important role in understanding the structure and formation of molecular configurations in heavy ion collisions.

Realistic two center level diagrams for single-particle states have been calculated[6,7] for several heavy ion systems using the asymmetric two-center shell model (TCSM).[5] There are two main excitation mechanisms between molecular single-particle states, namely those induced by the radial and rotational couplings. The enhancement of transitions at avoided crossings which are caused by the radial coupling is called the nuclear Landau-Zener promotion mechanism.[8,9] The Landau-Zener effect is well known in atomic physics.[10]

Four years ago, structure has been observed by the Strasbourg group[11] in the yield curve for the 871 keV γ ray of ^{17}O from the $^{13}C + ^{17}O$ reaction but absent for other observable transitions. Enhanced inelastic excitation of the first $\frac{1}{2}^+$ state of ^{17}O were predicted earlier by Park *et al.*[6] as a Landau-Zener promotion effect of the valence neutron in ^{17}O from the ground state to the first $\frac{1}{2}^+$ state at an avoided crossing between the levels near 7–8 fm.

It has been shown later by Abe and Park[12] that the characteristic resonancelike structure observed in the angle-integrated inelastic cross sections for the $^{13}C-^{17}O$ system can be understood as due to a new resonance mechanism based on the Landau-Zener formula and the interaction matrix element obtained from the TCSM levels at the point of avoided level crossing produced, without any free parameters, a series of resonances which could account for the observed structure qualitatively. Milek and Reif[13] used a TCSM which differs slightly from that of Abe and Park with the avoided level crossing situated inside of the potential barrier. Their semiclassical time-dependent calculation, with a set of four adiabatic molecular single-particle states, showed that the transition strength between the considered levels is rather spread over a wider range between 8 and 10 fm. Recent calculation[14] using a time-dependent semiclassical model with two diabatic single-particle states have shown that the structures in the angle-integrated inelastic cross section of the $\frac{1}{2}^+$ (871 keV) state of ^{17}O in the reaction of ^{13}C on ^{17}O can be interpreted as caused by the barriers of the angular momentum-dependent potentials and enhanced transition strength due to the Landau-Zener effect.

The angular distributions observed[15,16] for the inelastic transition of the ^{17}O state by ^{12}C have been also considered as another experimental evidence for the nuclear Landau-Zener effect in heavy ion reactions, although less direct than the periodic resonance structure in the energy dependence of the inelastic cross sections. Recent integrated cross section and angular distribution data[17] of the $^{12}C + ^{17}O$ collisions also suggest the presence of the Landau-Zener effect in the reaction,[15] although Voit and

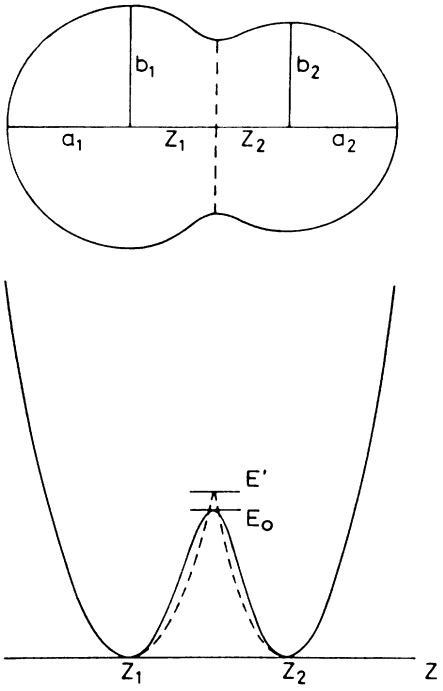

FIG. 1. Asymmetric two-center oscillator potential along the z axis and the associated nuclear shape.

von Oertzen[18] have shown recently that the angular distribution data at $E_{\rm lab}=50$ and 62 MeV can be explained in the framework of distorted-wave Born approximation.

In this paper we present the results for the inelastic cross sections leading to the first $\frac{1}{2}^+$ state of ^{17}O induced by ^{12}C and ^{13}C nuclei and those leading to the 2^+ state at 1.982 MeV of ^{18}O induced in the ^{12}C + ^{18}O reaction.

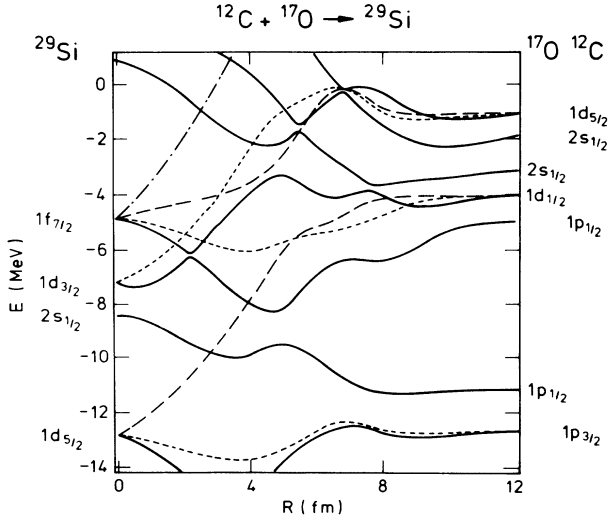

FIG. 2. The neutron level diagram for ^{12}C + ^{17}O→^{29}Si. The solid, dotted, dashed, and dash-dotted lines correspond, respectively, to the states with $\Omega=\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$, and $\frac{7}{2}$, where Ω is the quantum number of the angular momentum component in the direction of the internuclear axis.

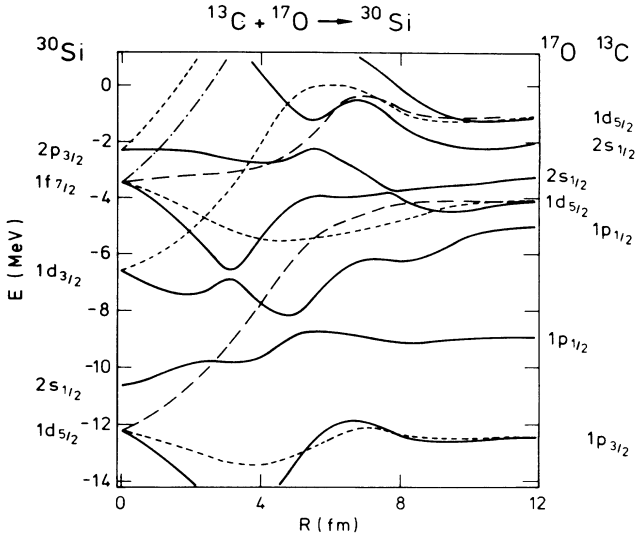

FIG. 3. The neutron level diagram for ^{13}C + ^{17}O→^{30}Si. (See the caption of Fig. 2 for detail).

Present calculations take into account the effects of the turning points in the Landau-Zener formula. In Sec. II calculations and results of the level diagrams in the asymmetric two-center shell model (ATCSM) are given. The model for the Landau-Zener transition including turning point effects is presented in Sec. III. Comparison with the γ-ray yield data are made in Sec. IV.

II. LEVEL DIAGRAMS IN THE ASYMMETRIC TWO-CENTER SHELL MODEL

The TCSM (Refs. 4 and 5) is an appropriate and realistic framework for a dynamical description of the single-particle motion in heavy ion collisions. The

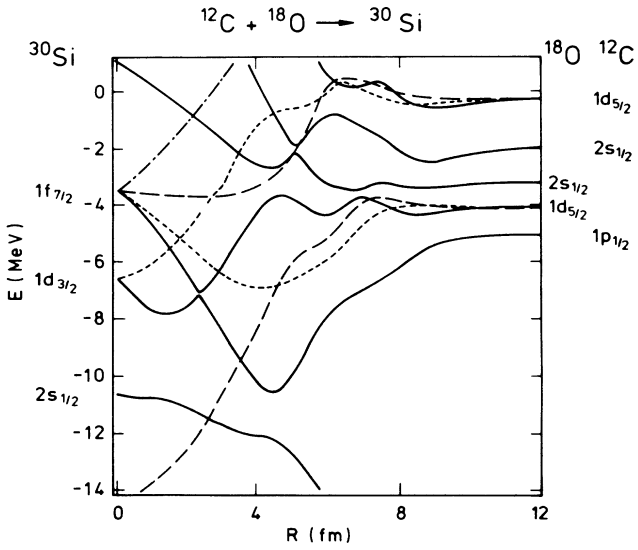

FIG. 4. The neutron level diagram for ^{12}C + ^{18}O→^{30}Si. (See the caption of Fig. 2 for detail).

TABLE I. Experimental neutron single-particle energies (in MeV) used in the fits of the parameters of the ATCSM.

Nucleus	$1p_{1/2}$	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$	Ref.
^{12}C,^{13}C	−4.95	−1.09	−1.86			19,20,21
^{17}O,^{18}C		−4.14	−3.27	0.94		19,22,23
^{29}Si			−8.47	−7.20	−4.85	19,22,24
^{30}Si			−10.61	−6.59	−3.45	19,24

single-particle potential of the asymmetric TCSM and the associated nuclear shape are shown in Fig. 1. The barrier parameter ϵ is defined by the ratio of the actual barrier height to that of the asymmetric two-center oscillator, namely, $\epsilon=E_0/E'$, and the deformation parameters by the ratio of the axes, $\beta_i=a_i/b_i$ $(i=1,2)$. The single-particle energies of the TCSM depend on the internuclear distance and on the frequency of the potential. Realistic two-center level diagrams provide the basis for study of the nuclear Landau-Zener effects in heavy ion reactions and a microscopic understanding of the role of individual molecular nucleonic orbitals in nucleus-nucleus collisions.

We have used the asymmetric TCSM (Ref. 5) to calculate single-particle energies as a function of the internuclear distance for collisions of ^{17}O with ^{12,13}C and collisions of ^{18}O with ^{12}C. The parameters of the two-center shell model potential have been determined by fitting the experimental single-particle energies near the Fermi levels of the separated nuclei ($R\to\infty$) and the corresponding composite nucleus ($R=0$). Experimental neutron single-particle energies used in the determination of the asymmetric TCSM potential are listed in Table I. The resulting parameters which we have applied in the calculation of the level diagrams are given in Table II. In all calculations we used the barrier parameter $\epsilon=0.68$ which was found to give a proper asymptotic convergence of the magnetic sublevels.[6,7]

Calculated single-neutron levels of the reactions $^{12}C+{}^{17}O\to{}^{29}Si$, $^{13}C+{}^{17}O\to{}^{30}Si$, and $^{12}C+{}^{18}O\to{}^{30}Si$ are shown in Figs. 2–4. The solid lines are the $\Omega=\frac{1}{2}$ levels, and dotted, dashed, and dash-dotted lines correspond to the $\Omega=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ levels, respectively, where Ω denotes the quantum number of the z component of angular momentum in the direction of the internuclear axis. Figure 2 shows the neutron level diagram of the asymmetric TCSM for the reaction $^{12}C+{}^{17}O\to{}^{29}Si$. The loosely bound valence neutron of ^{17}O initially occupies the $1d_{5/2}$ level. This level has an avoided crossing with the $2s_{1/2}$ level of the ^{17}O near 7.7 fm where the promotion of the valence neutron from the $1d_{5/2}$ level to the $2s_{1/2}$ level can take place, thus giving rise to the main contribution to the single-particle inelastic scattering, to the first excited state of ^{17}O, namely, $^{17}O+{}^{12}C\to{}^{17}O^*(\frac{1}{2}^+,\ 0.871\ \text{MeV})+{}^{12}C$. The level crossings which are located well inside the interaction region, say $R<5$ fm, are hidden by the centrifugal potentials due to the radial relative motion and by the strong absorption occurring inside and are not expected to make any contributions in the collision.

The neutron level diagram for $^{17}O+{}^{13}C\to{}^{30}Si$ is shown in Fig. 3. The level structure is very similar to the previous case of $^{12}C+{}^{17}O$. Figure 4 shows the neutron level diagram for $^{18}O+{}^{12}C\to{}^{30}Si$. Again the level structure is very similar. However, since we used the ATCSM parameters in this case, which are not similar to the previous ones, it is seen that the avoided crossing between the $1d_{5/2}$ and $2s_{1/2}$ levels of ^{18}O is now shifted towards the inside, namely from $R_c=7.7$ fm to $R_c=6.9$ fm for the $^{17}O+{}^{12}C$ case.

The TCSM level diagrams can be used for the prediction of possible single-particle reactions.[6,7] We can predict which single-particle inelastic excitations and neutron transfer reactions will be enhanced in heavy ion col-

TABLE II. Parameters of ATCSM potentials for $R=0$ and $R=\infty$ (in MeV) and the fitted levels. The single-particle energies are fitted by the formula (Ref. 6). $E(n,l,j)\equiv(N+\frac{3}{2})\hbar\omega-V_0+0.5a[j(j+1)-l(l+1)-\frac{3}{4}]+b[l(l+1)-\frac{1}{2}N(N+3)]$, with $N=2(n-1)+l$. $\hbar\omega=c/A^{1/3}$, $c=30.0$ MeV.

Reaction	Nucleus	$\hbar\omega$	a	b	v_0	Fitted levels		
	^{12}C	13.10	−5.115	0.980	42.82	$1p_{1/2}$	$2s_{1/2}$	$d_{5/2}$
$^{12}C+{}^{17}O\to{}^{29}Si$	^{17}O	11.67	−2.418	0.258	42.82	$1d_{5/2}$	$2s_{1/2}$	
	^{29}Si	9.77	−2.240	−0.348	44.39	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$
	^{13}C	12.76	−4.930	0.948	41.78	$1p_{1/2}$	$1d_{5/2}$	$2s_{1/2}$
$^{13}C+{}^{17}Q\to{}^{30}Si$	^{17}O	11.67	−3.672	0.467	41.78	$1d_{5/2}$	$2s_{1/2}$	
	^{30}Si	9.65	−2.246	0.109	43.86	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$
	^{12}C	17.60	−7.172	1.468	56.13	$1p_{1/2}$	$2s_{1/2}$	
$^{12}C+{}^{18}O\to{}^{30}Si$	^{18}O	15.38	−2.034	0.194	56.13	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$
	^{30}Si	12.97	−3.193	−0.128	56.64	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$

lisions. We can understand, microscopically, the selectivity of specific reaction channels without going into the details of coupled channel calculations which are quite tedious and difficult when a complete molecular Hamiltonian is used. We see here that a systematic study of level diagrams and promotion effects at level crossings is useful in order to understand, microscopically, the sequence of configurations during the course of multistep reactions.

III. THE LANDAU-ZENER MODEL FOR DIABATIC TRANSITIONS, INCLUDING TURNING POINT EFFECTS

As it is well known in atomic collisions, the Landau-Zener promotion from one energy level to another can take place due to a breakdown of adiabatic conditions around an avoided crossing point of adiabatic energy curves. According to Landau[8] and Zener,[9] the transition probability from one adiabatic state to the other by a two-way passage at a crossing point is given by

$$P_{\mathrm{LZ}}=2P_{12}(1-P_{12}) , \tag{1}$$

where,

$$P_{12}=\exp(-2\pi G) , \tag{2}$$

with

$$G=\frac{|H_{12}|^2}{\hbar v\,|\Delta F|} . \tag{3}$$

Here, $|\Delta F|$ is expressed as follows in terms of the derivative of the difference of adiabatic energies,

$$|\Delta F|=\left|\frac{d}{dR}(H_{11}-H_{22})\right|_{R=R_c} . \tag{4}$$

In the derivation of formula (2), it is assumed that the point of avoided level crossing is far from the turning point of the relative motion of the nuclei and hence the relative velocity in the region of level crossing is constant. The relative velocity depends on the incident energy and impact parameter. The impact parameter can be expressed in terms of the angular momentum given by the quantum number. In the following we have used a phenomenological potential for the calculation of the time dependence of the internuclear distance and its velocity v:

$$\begin{aligned}V(R,l,E_{\mathrm{c.m.}})=&V_C(R)\\&-(V_0+V_1E_{\mathrm{c.m.}})/\{1+\exp[(R-R_c)/a]\}\\&+l(l+1)\hbar^2/(2\mu R^2) .\end{aligned} \tag{5}$$

Here, the Coulomb potential is given by

$$V_C(R)=\begin{cases}Z_1Z_2e^2/R & \text{for } R\geq R_1+R_2,\\ \dfrac{Z_1Z_2e^2}{2(R_1+R_2)}\left[3-\left[\dfrac{R}{R_1+R_2}\right]^2\right] & \text{for } R<R_1+R_2,\end{cases} \tag{6}$$

where $R_i=r_0A_i^{1/3}$, $(i=1,2)$.

The condition of constant velocity used by Landau and Zener is not satisfied frequently in low energy heavy-ion reactions. In the present work, we have used an improved Landau-Zener formula which takes into account the effect of an external field on the motion of nuclei. The transition probability for the case where the crossing points are close to the turning point has been investigated by Nikitin[25,26] in the semiclassical approximation. It has been shown later that the semiclassical and the quantum-mechanical treatments are equivalent for the case of linear diabatic potentials connected by a constant interaction matrix element.[27] In the following we review the essential points of the derivation of the formula of Nikitin.[25,26]

By assuming a two-state approximation and the semiclassical approach, the wave function of a loosely bound neutron can be expanded in a basis of two diabatic wave functions $\phi_i(\mathbf{r},R)$;

$$\begin{aligned}&\psi[r,R(t,l)]\\&\quad=\sum_{i=1}^{2}c_i(t)\phi_i[\mathbf{r},R(t,l)]\exp\left[-\frac{i}{\hbar}\int_0^t H_{ii}dt\right] .\end{aligned} \tag{7}$$

The Hamiltonian H is the single-particle Hamiltonian of the two-center shell model. The matrix elements with the states ϕ_i are abbreviated by $H_{ij}=\langle\phi_i|H|\phi_j\rangle$. Inserting ψ into the time-dependent Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t}=H[\mathbf{r},R(t,l)]\psi , \tag{8}$$

one obtains the following coupled equations for the coefficients $c_i(t)$ in the diabatic approximation:

$$\begin{aligned}\dot{c}_1&=\frac{1}{i\hbar}H_{12}\exp(i\alpha_{12})c_2 ,\\ \dot{c}_2&=\frac{1}{i\hbar}H_{21}\exp(-i\alpha_{12})c_1 ,\end{aligned} \tag{9}$$

where

$$\alpha_{12}=\int_0^t(H_{11}-H_{22})dt/\hbar . \tag{10}$$

For the energy difference $H_{11}-H_{22}$ we used the relation at the turning point R_p:

$$\Delta F=-\frac{\partial}{\partial R}(H_{11}-H_{22})\bigg|_{R=R_p} . \tag{11}$$

The expectation values of H coincide at the point of avoided level crossing at $R=R_c$. Equations (9) have to be solved in time with the initial conditions

$$c_1(t\rightarrow-\infty)=1,\ c_2(t\rightarrow-\infty)=0 . \tag{12}$$

The final probability for the inelastic excitation of the neutron is obtained as

$$P_l(E_{\mathrm{c.m.}})=|c_2(t\rightarrow\infty)|^2 . \tag{13}$$

Here, we have indicated the dependence of probability on the incident energy and angular momentum.

In our examples, the interaction matrix element

$H_{12}=H_{21}$ is a small quantity. Therefore, Eqs. (9) can be solved using the first-order perturbation theory for a given dependence of R on time,

$$P_l(E_{\text{c.m.}})=\frac{H_{12}^2}{\hbar^2}\left|\int_{-\infty}^{\infty}\exp(-i\alpha_{12})dt\right|^2 . \tag{14}$$

As shown by Nikitin,[25] the time-dependent integral can be analytically solved for classical trajectories which are obtained for constant effective forces $F_l(E_{\text{c.m.}})$. We have assumed in our calculations that these forces can be approximated by the negative slope of the internuclear potential at the point of level crossing:

$$F_i=-\left.\frac{\partial H_{ii}}{\partial R}\right|_{R=R_c} . \tag{15}$$

Then the classical trajectory for the radial relative motion with a radial velocity $v_l(E_{\text{c.m.}})$ at the point of level crossing is given by

$$R(t,l,E_{\text{c.m.}})=\frac{F_l}{2\mu}t^2-\frac{\mu v_l^2(E_{\text{c.m.}})}{2F_l}+R_c , \tag{16}$$

where

$$\frac{\mu}{2}v_l^2(E_{\text{c.m.}})=E_{\text{c.m.}}-V(R_c,l,E_{\text{c.m.}}),\quad F=|F_1F_2|^{1/2} . \tag{17}$$

Inserting the trajectory (16) into Eq. (14), the transition probability for weak coupling can be obtained in terms of the Airy function as[25,26]

$$P_l(E_{\text{c.m.}})=\pi^2\beta_l^{4/3}Ai^2(-\epsilon_l\beta_l^{2/3}) , \tag{18}$$

where

$$Ai(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\exp[i(xu+\tfrac{1}{3}u^3)]du , \tag{19}$$

$$\beta_l(E_{\text{c.m.}})=\frac{4H_{12}}{\hbar}\left[\frac{\mu H_{12}}{F_l\Delta F}\right]^{1/2} , \tag{20}$$

$$\epsilon_l(E_{\text{c.m.}})=\frac{[E_{\text{c.m.}}-V(R_c,l,E_{\text{c.m.}})]}{2H_{12}}\frac{\Delta F}{F_l} . \tag{21}$$

In terms of β_l and ϵ_l, G_l defined by Eq. (3) can be expressed as

$$G_l=\beta_l/(8\sqrt{\epsilon_l}) . \tag{22}$$

The oscillation of P_l is due to the interference effects occurring at the incident and outgoing trajectories.

In calculating the cross section, one needs to know the crossing point R_c, the interaction matrix element H_{12}, the difference of forces ΔF, and the adiabatic potential V. The former three, namely R_c, H_{12}, and ΔF, can be extracted directly from the energy diagrams calculated with the ATCSM (Figs. 2–4). The angle-integrated cross section for the inelastic excitation is calculated by using the expression

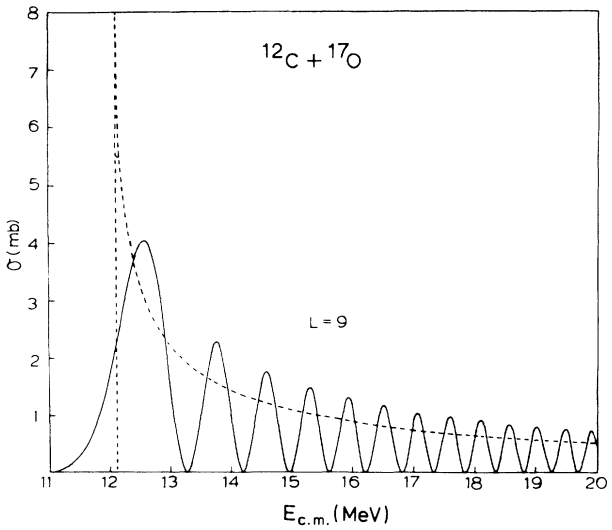

FIG. 5. Partial inelastic cross section $\sigma_{l=9}$ for $^{12}C+^{17}O\rightarrow{}^{12}C+{}^{17}O^*(\frac{1}{2}^+$, 0.87 MeV), illustrating the effect of the turning point. The solid line is obtained by using (18) and includes the turning point effect. The dashed line corresponds to the Landau-Zener formula (1) at small values of G_l or $\epsilon_l\beta_l^{2/3}\gg 1$.

$$\sigma_l=\sum_{l=0}^{l_{\max}}\sigma_l=\frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}}\sum_{l=0}^{l_{\max}}(2l+1)P_l/3 . \tag{23}$$

The factor $\frac{1}{3}$ is due to the fact that only one branch ($\Omega=\frac{1}{2}$) of the three originating levels from the $1d_{5/2}$ state of ^{17}O or ^{18}O has an avoided crossing with the $2s_{1/2}$ state in all three systems we have studied in the present work (see Figs. 2–4).

The effect of the turning point on the transition probability for weak adiabatic coupling can be seen in Fig. 5. The solid and dashed lines represent the partial inelastic cross sections $\sigma_{l=9}$, according to Eq. (23) in terms of the Airy function formula (18) and the Landau-Zener formula (1) at small values of G or $\epsilon_l\beta_l^{2/3}\gg 1$, respectively, for the $^{12}C+{}^{17}O$ reaction.

IV. RESULTS AND DISCUSSION

It has been observed[16,17] in the integrated γ-ray yields for the $^{12}C+{}^{17}O$ reaction that pronounced resonantlike structure appears only in the inelastic channel leading to the first excited $\frac{1}{2}^+$ state (0.87 MeV) of ^{17}O. Similar characteristic resonancelike structures observed[11] earlier for the $^{13}C+{}^{17}O$ reaction were accounted for qualitatively by Abe and Park[12] using the nuclear Landau-Zener promotion mechanism, which were discussed earlier by Glas and Mosel[28] and Park *et al.*[6,7]

By extracting the crossing distance R_c, the interaction matrix element H_{12}, and the classical force ΔF from the energy level diagrams, as shown in Figs. 2–4, we have no free parameter in the calculation. The values of the parameters used in our calculations, including potential parameters, are listed in Table III.

TABLE III. Values used in the calculation of the inelastic cross sections. ($r_0=1.34$ fm, $V_0=7.5$ MeV, $V_1=0.4$ MeV).

Reaction	R_c (fm)	H_{12} (MeV)	F_1 (MeV/fm)	F_2 (MeV/fm)	a (fm)
$^{12}C+^{17}O$	7.74	0.11	−0.92	0.32	0.58
$^{13}C+^{17}O$	7.72	0.06	−0.83	0.15	0.50
$^{12}C+^{18}O$	6.88	0.14	−0.45	0.76	0.40

A calculated inelastic cross section leading to the $2s_{1/2}$ state of ^{17}O in the $^{12}C+^{17}O$ reaction is compared with the observed γ-ray yield curve[16,17] in Fig. 6. The data points are connected by a short-dashed line to aid the eyes. The dashed and solid lines are the calculated cross sections obtained by using the usual Landau-Zener formula (1) and the improved Landau-Zener formula (18) or (23), respectively. It is seen that the solid line, which includes the effect of the turning point, can reproduce better most of the peaks of γ-ray yield curve including the intermediate structure for $^{12}C+^{17}O^*(\frac{1}{2}^+;$ 0.871 MeV) than the usual Landau-Zener formula does.

Figure 7 shows the cross sections for the inelastic excitation of the first $\frac{1}{2}^+$ (871 keV) state of ^{17}O in the $^{13}C+^{17}O$ reaction as a function of the incident energy. Again, it is seen that the cross section calculated with the improved formula gives more structure than the usual Landau-Zener formula (1). In comparing with the experimental data it should be noted that the data are inclusive γ-ray yield measurements and, although the main contribution to the cross section is expected to be a simple inelastic scattering of the first excited state of ^{17}O, other possible, but undetermined, contributions involving the excitation of the 3-55 keV level of ^{17}O which cascades back to the first excited state at 871 keV, for example, or the mutual excitation or breakup of ^{13}C may be included. In addition, the data contain a nonresonant intensity due to the Coulomb excitation of the ^{17}O beam in the gold target backing. This contribution should increase rapidly with energy and is responsible for much of the rise in the intensity of the γ-ray yield with energy. At the highest bombarding energy of $E_{lab}=60$ MeV, the Coulomb excitation was found to account for approximately half of the measured cross section.[11] Calculated cross sections compare well with those of Abe and Park[12] and semiclassical calculations of Milek and Rief[13] and Park *et al.*[14] for the $^{13}C+^{17}O$ reaction.

The $^{18}O+^{12}C$ reaction has been studied by Basrak *et al.*[29] and Chan *et al.*[30] They have measured excitation functions using γ-ray spectroscopy. Observed structure[20] in the inelastic scattering channel leading to the $^{18}O(2^+\rightarrow 0^+)$ 1982 keV transition is compared with our calculation in Fig. 8. In the present calculations the deformation of ^{18}O is not taken into account and the first excited 2^+ state at 1.982 MeV is considered[31,32] to have the neutron configuration of $[(1d_{5/2})^1(2s_{1/2})^1]_{2^+}$. The

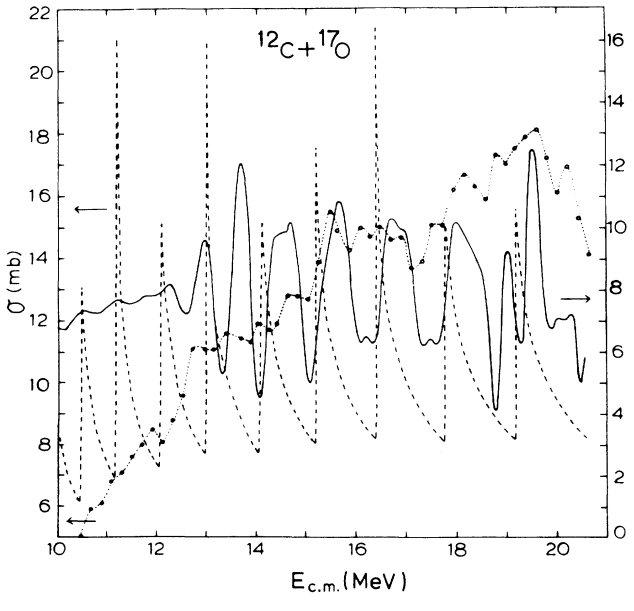

FIG. 6. Inelastic scattering cross section for $^{12}C+^{17}O\rightarrow{}^{12}C+^{17}O^*(\frac{1}{2}^+,$ 0.871 MeV). The short-dashed line connects the data points. The dashed and solid lines represent, respectively, the calculated cross sections with the usual Landau-Zener formula and the improved formula.

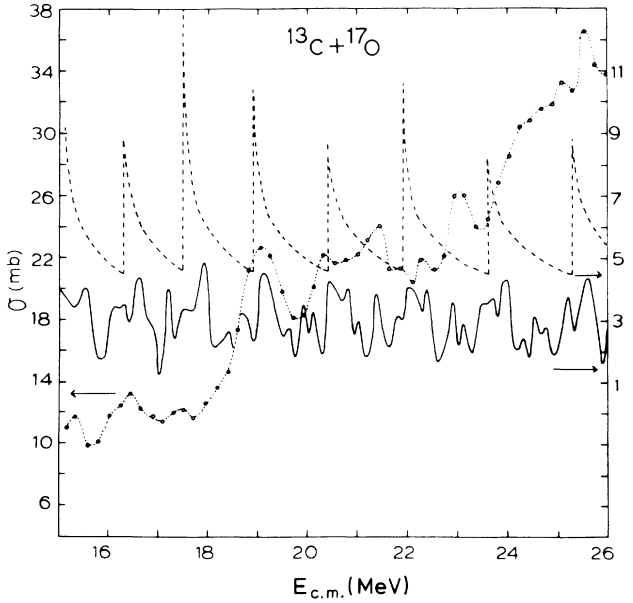

FIG. 7. Inelastic scattering cross section for $^{13}C+^{17}O\rightarrow{}^{13}C+^{17}C^*(\frac{1}{2}^+,$ 0.871 MeV). (See the caption of Fig. 6 for detail.)

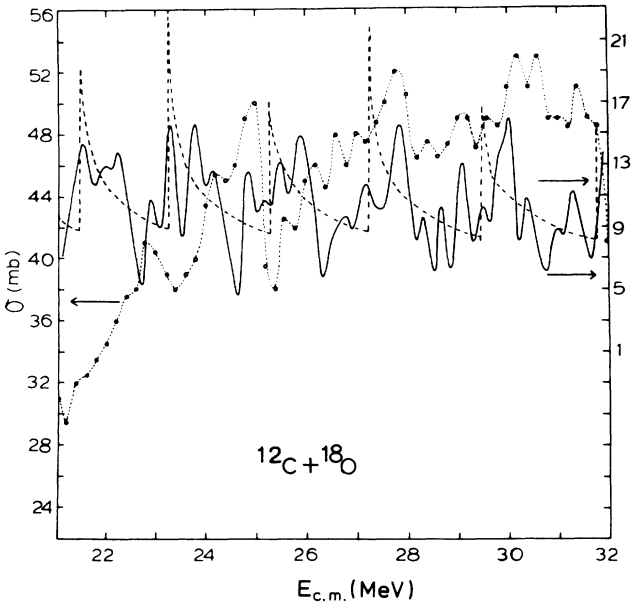

FIG. 8. Inelastic scattering cross section for $^{12}C + ^{18}C \rightarrow ^{12}C + ^{18}O^*(2^+, 1.982\ MeV)$. (See the caption of Fig. 6 for detail.)

γ-ray yield data contain a steeply rising contribution of the Coulomb excitation in the gold backing which amounts to 55% of the total $^{18}O(2^+ \rightarrow 0^+)$ inelastic scattering yield at $E_{lab} = 80$ MeV. It is seen again that the magnitude of the inelastic cross section and most of the peaks in the resonancelike structure are well reproduced by our calculation which includes the effects of turning points (solid line). Simple Landau-Zener formula (1) is not satisfactory in reproducing the observed intermediate structure.

In order to understand the origin of resonance peaks in these reactions, contributions of various partial cross sections to the inelastic cross sections are depicted in Fig. 9. It is seen that the intermediate structures in the cross sections are found to arise due to the energy-dependent oscillatory behavior of several partial cross sections. We note that some peaks can be attributed to a single orbital angular momentum which is nearly equal to the grazing one, while many others arise due to the combined contributions of two or more angular momenta.

V. CONCLUSIONS

The enhanced excitation at level crossing point due to the nuclear Landau-Zener effect is a specific molecular effect.[6,7,12] We have shown that the resonancelike structures in the inelastic excitation to the $^{17}O^*(\frac{1}{2}^+, 0.871$ MeV) in the $^{13}C + ^{17}O$ and $^{12}C + ^{17}O$ systems and to the $^{18}O^*(2^+, 1.982$ MeV) in the $^{12}C + ^{18}O$ reaction, as observed in the γ-ray yield measurements, can be interpreted in terms of the Landau-Zener excitation mechanism at energy level crossings.

Effects of potential barriers on the structure of inelastic excitations of ^{17}O by ^{13}C have been studied recently.[14] Present calculations demonstrate the importance of the effects of turning points in reproducing the intermediate structures observed in γ-ray excitation functions of ^{17}O and ^{18}O as induced by ^{12}C, and those of ^{17}O induced by ^{13}C. The intermediate structures in these reactions are found to arise due to the energy-dependent oscillatory behavior of several partial cross sections. Many of the resonancelike peaks are attributed not due to a single or-

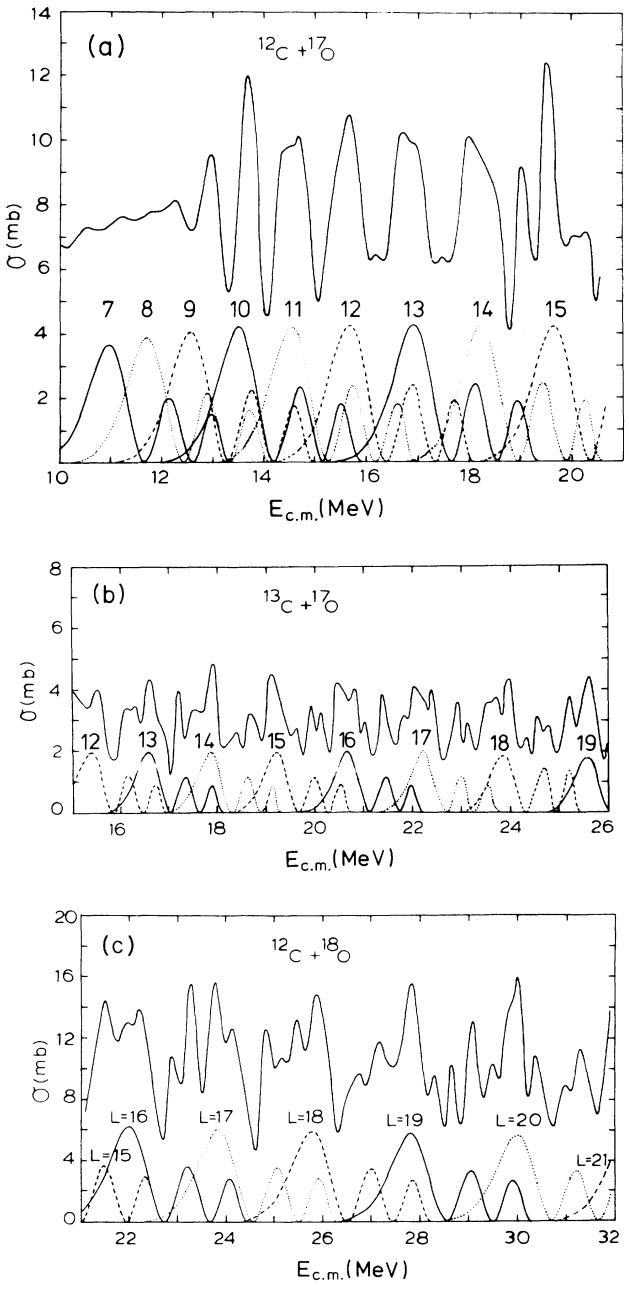

FIG. 9. Contributions of various partial cross sections to the inelastic cross section for (a) $^{12}C + ^{17}O \rightarrow ^{12}C + ^{17}O^*(\frac{1}{2}^+$, 0.87 MeV), (b) $^{13}C + ^{17}O \rightarrow ^{13}C + ^{17}O^*(\frac{1}{2}^+$, 0.87 MeV), and (c) $^{12}C + ^{18}O \rightarrow ^{12}C + ^{18}O^*(2^+, 1.982$ MeV).

bital angular momentum, but to two or more angular momenta. Since the structures in the inelastic cross sections are found to depend strongly on the potential barrier, it is desirable to treat the radial relative motion quantum mechanically. Such calculations[33–35] based on the dynamical particle-core model[36,37] have been performed for the $^{13}C + {}^{13}C$ system and a similar calculation for the $^{12}C + {}^{17}O$ reaction is in progress.[38] Recently, based on characteristic changes of the angular distributions observed as function of the incident energy, Imanishi *et al.*[39] have shown that the Landau-Zener transition also exists in the inelastic scattering of $^{12}C + {}^{13}C \rightarrow {}^{12}C + {}^{13}C^*(\frac{1}{2}^+, 3.086\ \text{MeV})$.

We have shown that a systematic study of two-center level diagrams and promotion effects at level crossings is useful and valuable to study excitation of nucleon degrees of freedom and the role played by individual molecular nucleonic orbitals in heavy ion reactions. Realistic two-center diagrams give us greater microscopic understanding for the selectivity of specific reaction channels and the sequence of configurations during the course of multistep reactions. The present work demonstrates that the valence nucleons and the molecular single-particle motion plays an important role in heavy-ion reactions at low bombarding energies. Present work provides further evidences for the nuclear Landau-Zener effects in heavy-ion reactions and a unique signature for molecular single-particle effects. More experimental works are needed to firmly establish the nuclear Landau-Zener effect and the formation of nuclear molecular single-particle orbits in heavy-ion collisions.

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