Potential barriers and Landau-Zener promotion in the inelastic excitation of ^{17}O by ^{13}C ions

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The inelastic excitation of the $\frac{1}{2}^+$ (871 keV) state of ^{17}O in the reaction of ^{13}C on ^{17}O is described by a time-dependent quantum mechanical model with two diabatic states and a classical treatment of the radial relative motion. The structures in the angle-integrated cross section are interpreted as caused by the barriers of the angular momentum-dependent potentials. The transition strength is enhanced by the Landau-Zener effect between the levels considered.

I. INTRODUCTION

Experimental evidence for a nuclear Landau-Zener effect was found by the Strassburg group in the inelastic excitation of the first $\frac{1}{2}^+$ state of ^{17}O by ^{12}C and ^{13}C ions. Structures in the γ-ray yields of the transition from the $\frac{1}{2}^+$ state to the ground state were the first signatures for this effect (Freeman *et al.*[1]). The analysis of angular distribution measurements of $^{12}C(^{17}O, ^{17}O^*)^{12}C$, made by the same group (Beck *et al.*[2]), support the idea of a nuclear Landau-Zener mechanism (see also Cindro *et al.*[3]).

The observed structures in the inelastic excitation of the first $\frac{1}{2}^+$ state were predicted earlier by Park *et al.*[4] as caused by a nuclear Landau-Zener effect between the ground state and first $\frac{1}{2}^+$ state of ^{17}O. Figure 1 shows the two-center shell model (TCSM) diagram for $^{13}C + {}^{17}O \rightarrow {}^{30}Si$. One recognizes an avoided crossing between the adiabatic energy curves originating from the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ levels of ^{17}O near 8 fm, marked by a circle in Fig. 1. At this relative distance an enhanced promotion of the valence neutron from the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) state to the $2s_{1/2}$ state of ^{17}O can take place.

Abe and Park[5] calculated the inelastic excitation function using the formula of Landau[6] and Zener[7] and the interaction matrix element derived from the TCSM levels at the point of avoided level crossing. Their calculation produced, without any free parameter, a series of resonances which can account for the observed structure qualitatively. The widths of the structures obtained in this calculation are very small, since the formula of Landau and Zener does not take into account the finite reaction time which is of the order of 5×10^{-22} sec for the reactions considered here. Recently, Milek and Reif[8] carried out a semiclassical time-dependent calculation with a set of four adiabatic molecular single-particle states coupled by the radial coupling. Their calculation showed that the transition strength between the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states is not only concentrated at the point of avoided level crossing, but also rather spread over a larger range between 8 and 10 fm. Milek and Reif[8] used a TCSM which is slightly different from that of Abe and Park.[5] Their distance of avoided level crossing between the considered levels is situated inside of the potential barrier.

In the present paper we have studied the effect of the potential barrier on the structures of the inelastic cross section using a semiclassical model which describes the

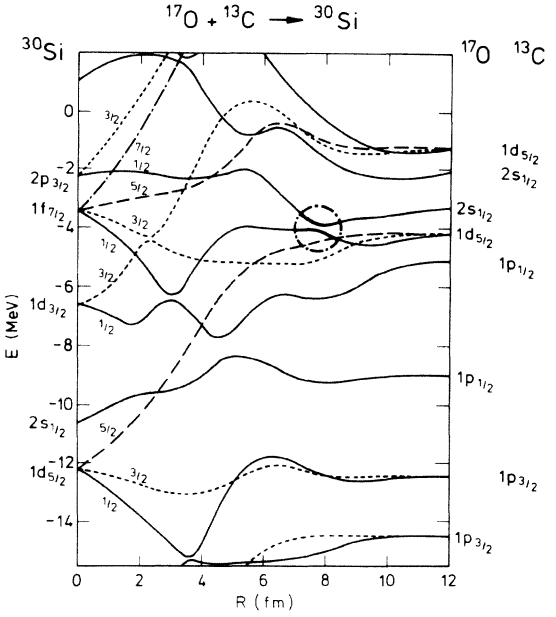

FIG. 1. The neutron level diagram for $^{13}C + {}^{17}O \rightarrow {}^{30}Si$. The avoided crossing of the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states is marked by a circle.

radial relative motion classically and the transition to the inelastic channel quantum mechanically. The $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states are approximated by diabatic states. In Sec. II we present the details of our model and apply it to the calculation of the inelastic cross section in Sec. III. It is found that the positions of the structures are essentially determined by barrier heights of the angular momentum-dependent potentials.

II. MODEL WITH TWO DIABATIC BASIS STATES

We use a semiclassical treatment and describe the radial relative motion of the nuclei for a given quantum number l of the orbital angular momentum with classical trajectories in an effective potential $V(R,l)$, which is chosen as the sum of the Coulomb, nuclear, and centrifugal potentials

$$V(R,l)=V_{\rm Coul}(R)-(V_0+V_1E_{\rm c.m.})/\{1+\exp[(R-R_N)/a]\}+l(l+1)\hbar^2/(2\mu R^2)\ . \tag{1}$$

The internuclear distance $R(t,l)$ depends on the impact parameter via the quantum number l and is obtained by solving the classical equation of motion

$$\mu\ddot{R}(t,l)=-\left.\frac{\partial V}{\partial R}\right|_{R(t,l)}\ . \tag{2}$$

We neglect the energy loss in the radial motion due to the inelastic excitation.

The wave function $\psi(\mathbf{r},t)$ of the weakly bound valence neutron of ^{17}O satisfies the time-dependent Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t}=H(\mathbf{r},R(t,l))\psi\ . \tag{3}$$

Assuming a two-level approach we introduce diabatic molecular wave functions $\phi_1(\mathbf{r},R)$ and $\phi_2(\mathbf{r},R)$, depending slowly on R. Here, ϕ_1 and ϕ_2 represent the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states of ^{17}O, respectively, for $R\to\infty$. The expectation values of H with these functions coincide at $R=R_c$ where the adiabatic levels undergo the avoided crossing. The difference of the expectation values is assumed to depend linearly on R,

$$H_{11}-H_{22}=A(1-R/R_c)\ , \tag{4}$$

where $H_{ij}=\langle\phi_i\,|\,H\,|\,\phi_j\rangle$.

We expand the wave function ψ into the basis of the two states,

$$\psi=\sum_{i=1}^{2}c_i(t)\phi_i(\mathbf{r},R)\exp\left[-\frac{i}{\hbar}\int^t H_{ii}dt\right]\ . \tag{5}$$

Inserting ψ into (3) and projecting with the functions ϕ_j, we obtain the following two coupled equations:

$$\begin{aligned}\dot{c}_1&=-\frac{W}{\hbar}c_1+\frac{H_{12}}{i\hbar}\exp(i\alpha_{12})c_2\ ,\\ \dot{c}_2&=-\frac{W}{\hbar}c_2+\frac{H_{21}}{i\hbar}\exp(-i\alpha_{12})c_1\ ,\end{aligned} \tag{6}$$

where

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

Here, $W(R)$ is the absorptive potential. In deriving these equations we assumed that the radial coupling matrix element $\dot{R}\langle\phi_1\,|\,\partial/\partial R\,|\,\phi_2\rangle$ is negligibly small for diabatic states near the crossing point and that the amplitudes c_i are damped due to the other channels not being treated explicitly. This damping can be related to the absorptive potential $W(R)$ for the elastic scattering of ^{13}C on ^{17}O. For simplicity the absorptive potential $W(R)$ is assumed to have the same R dependence as the nuclear interaction in potential (1),

$$W(R)=W_0/\{1+\exp[(R-R_N)/a]\}\ . \tag{7}$$

At $R=R_c$ the transition matrix element H_{12} can be related to the energy splitting of the adiabatic levels at this point. In our calculations we have used a Gaussian form for $H_{12}=H_{21}$ (real),

$$H_{12}=H_{12}^0\exp[-(R-R_c)^2/(\Delta R)^2]\ . \tag{8}$$

Equations (2) and (6) are solved with the following conditions at the initial time $t=t_i$:

$$\begin{aligned}&R_i=R(t_i,l)=R_c+2\Delta R\ ,\\ &\dot{R}(t_i,l)=-\{2[E_{\rm c.m.}-V(R_i,l)]/\mu\}^{1/2}\ ,\\ &c_1(t_i)=1,\ \ c_2(t_i)=0\ .\end{aligned} \tag{9}$$

The final probability for the inelastic excitation of the $2s_{1/2}$ state of ^{17}O is obtained as

$$P_l=|\,c_2(t_f)\,|^2\ , \tag{10}$$

where t_f is determined by $R(t_f,l)=R_c+2\Delta R$.

The cross section for the inelastic excitation is calculated by[5]

$$\sigma=\sum_{l=0}^{l_{\max}}\sigma_l=\frac{\hbar^2\pi}{2\mu E_{\rm c.m.}}\sum_{l=0}^{l_{\max}}(2l+1)P_l/3\ . \tag{11}$$

The Landau-Zener formula can be derived from Eqs. (6) with the following restrictive assumptions, namely $W=0$, $\dot{R}=$const, $H_{12}=$const, $t_i=-\infty$, and $t_f=\infty$. These assumptions, $\dot{R}=$const and the infinite time interval, are unphysical especially if the crossing point is situated near the potential barrier or if the turning point of the trajectory lies outside of the crossing region. The above equations (6) of the schematic two-level model are realistic and use-

ful in the study of the influence of the potential barriers and the level crossing on the structures in the inelastic cross section.

III. RESULTS FOR THE INELASTIC EXCITATION OF THE $2s_{1/2}$ STATE OF ^{17}O

We have used the following parameter values in the potentials $V(R)$ and $W(R)$: $V_0=7.5$ MeV, $V_1=0.4$, $W_0=2$ MeV, $R_N=6.60$ fm, and $a=0.46$ fm. The parameters of $V(R,l)$ are similar to those given by Malmin *et al.*[9] for the $^{12}C+^{16}O$ system. The parameter W_0 is related to a decay time of the probabilities of $\tau=\hbar/2W_0=1.6\times10^{-22}$ sec, which is somewhat shorter than the scattering time.

Figure 2 shows the potential $V(R,l)$ for $E_{c.m.}=19.4$ MeV and $l=15$. The time dependence of a trajectory is presented in Fig. 3 for the same potential and energy $E_{c.m.}=19.4$ MeV, which is slightly smaller than the barrier height. The figure shows a slow radial relative motion near the barrier which leads to an enhancement of the reaction time.

The values of A and R_c in Eq. (4) are obtained from the TCSM level diagram for $^{13}C+^{17}O$ shown in Fig. 1. We find $A=8.5$ MeV and $R_c=7.7$ fm for the avoided crossing of the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states of ^{17}O. It is seen from Fig. 2 that the crossing distance $R_c=7.7$ fm lies slightly outside the potential barrier. We have taken the interaction strength H_{12}^0 and the width parameter ΔR in Eq. (8) as free parameters and studied their effects on the inelastic cross section (11).

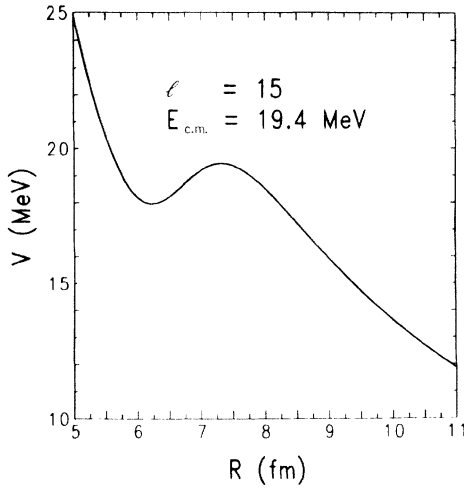

FIG. 2. The potential $V(R,l)$ of the system $^{13}C+^{17}O$ for $E_{c.m.}=19.4$ MeV and $l=15$.

Figure 4 shows the dependence of the partial cross section $\sigma_{l=15}$ for different values of H_{12}^0 indicating that the cross sections σ_l scale with $(H_{12}^0)^2$. This can be shown analytically, because in general the probabilities for the excitation of the $\frac{1}{2}^+$ state remain small, i.e., $|c_2|^2<1$, and, therefore, a first-order solution of Eqs. (6) is already a good approximation.

$$|c_2(t)|^2=\frac{1}{\hbar^2}\left|\int_{t_i}^{t}\exp\left[-\int_{t'}^{t}W(t'')dt''/\hbar\right]H_{12}(t')\exp[-i\alpha_{12}(t')]dt'\right|^2 . \tag{12}$$

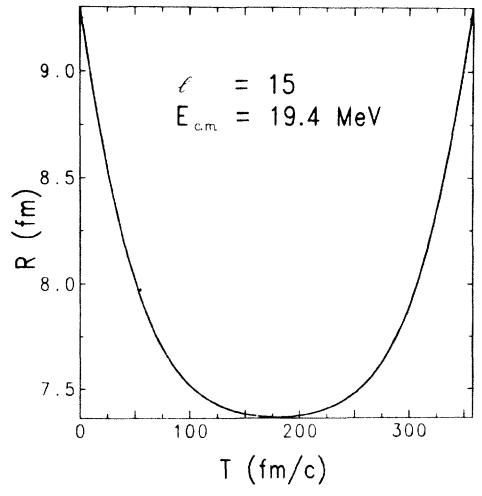

FIG. 3. The internuclear distance R as a function of time for $E_{c.m.}=19.4$ MeV and $l=15$.

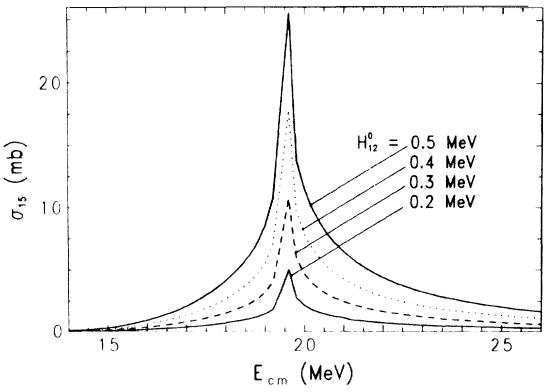

FIG. 4. Partial cross section $\sigma_{l=15}$ for the inelastic excitation of the first $\frac{1}{2}^+$ state of ^{17}O in the $^{13}C+^{17}O$ collision as a function of the incident energy $E_{c.m.}$. The absorptive potential W is set to zero, $\Delta R=1.5$ fm, and H_{12}^0 as indicated in the figure.

This equation shows that the cross sections are in general proportional to $(H_{12}^0)^2$.

Next we consider the position of the maximum of the partial cross sections σ_l. This position is determined by the condition that the incident energy and the barrier height coincide, provided that the distance $R_c - R_B$ between the point of level crossing and the barrier lies within the range ΔR of the transition matrix element. In our case the latter condition is satisfied for $\Delta R \geqq 0.2$ fm. As an example we show in Fig. 4 that the maximum in the partial cross section σ_l for $l=15$ is situated at an incident energy of 19.5 MeV which is the energy of the corresponding barrier. At this energy the time of contact of the system near the crossing point is maximal and, therefore, the excitation is most pronounced. The incident energies $E_{\text{c.m.}}(l)$ coinciding with the barrier heights are approximately given by the condition

$$E_{\text{c.m.}}(l) = V(R = 7.5 \text{ fm}, l) , \tag{13}$$

where the barriers are assumed to be located at $R=7.5$ fm. Equation (13) yields the following approximate expression for these energies:

$$E_{\text{c.m.}}(l) = [7.90 + 0.048 l(l+1)] \text{ MeV} . \tag{14}$$

This formula is a useful approximation for the position of the barriers in the elastic channel. If the radial motion is treated quantum mechanically, the time dilatation of the relative radial motion is generated by the resonances lying slightly above the barriers. These resonances, denoted as virtual resonances, are the doorway states for the molecular configurations. They must be seen as the sources of the structures in our example. Equation (14) yields $E_{\text{c.m.}}(l=15) - E_{\text{c.m.}}(l=14) = 1.4$ MeV for the mean energy difference between two structures. We also note that this result depends only on the potential $V(R,l)$ chosen and not on the level crossing.

In Fig. 5 we show the partial cross section $\sigma_{l=15}$ for $W=0$ and various ranges ΔR. These calculations give shapes which are nearly symmetrical about $E_{\text{c.m.}}(l)$ with widths of $\Gamma_{l=15} \approx 0.4$ and 0.6 MeV for $\Delta R = 0.5$ and 1.5 fm, respectively.

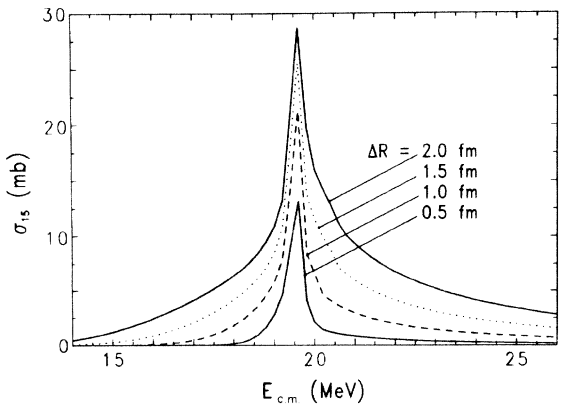

FIG. 5. Similar calculations as in Fig. 4, but H_{12}^0 fixed at $H_{12}^0 = 0.5$ MeV and ΔR varied as shown in the figure. The absorption W is set to zero.

Figure 6 shows the cross section for the inelastic excitation of the first $\frac{1}{2}^+$ (871 keV) state of ^{17}O as a function of the incident energy for a finite absorption $W_0 = 2$ MeV. The partial cross sections σ_l and the experimental data are also presented in Fig. 6. The calculated structures are in reasonable agreement with the data.

As one can recognize from Fig. 6, the shape of the partial cross section is determined for $E_{\text{c.m.}} < E_{\text{c.m.}}(l)$ by the range ΔR of the transition matrix element and for $E_{\text{c.m.}} > E_{\text{c.m.}}(l)$ by the absorptive potential. With larger ΔR the tails of the partial cross sections spread appreciably in energy and add up to an increasing background in the total cross section (see Fig. 6). Since the heights of the maxima of the partial cross sections are less influenced by ΔR, the structures of the total cross section built on the background are approximately independent of ΔR ($\Delta R \geqq 0.5$ fm).

In Fig. 7 we compare the cross section obtained with the Landau-Zener formula with that of the time-dependent calculation. In the Landau-Zener formula we have set $H_{12} = H_{12}^0$. We find that the Landau-Zener formula yields larger transition probabilities since it is derived on the assumption of an infinite reaction time between the two levels. The difference between the Landau-Zener result and our model can be seen by considering the form of the partial cross sections as functions of $E_{\text{c.m.}}$. The Landau-Zener formula gives partial cross sections which rise steeply to a maximum and drop slowly down for energies larger than the energy of the maximum. This slow falloff is responsible for the large background in the cross section.

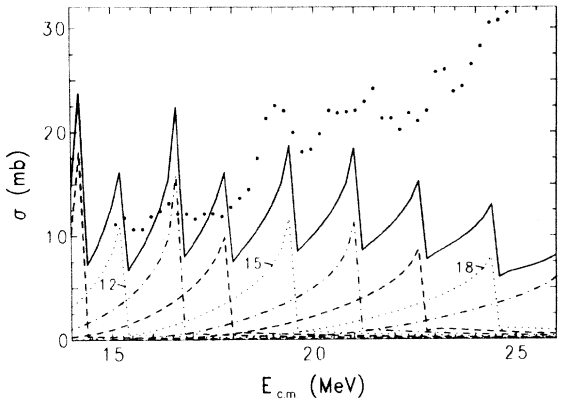

FIG. 6. The cross section for the inelastic excitation of the first $\frac{1}{2}^+$ state of ^{17}O in the collision of ^{13}C on ^{17}O as a function of the incident energy $E_{\text{c.m.}}$. The full curve is the cross section obtained by adding up the partial cross sections shown by broken curves and denoted with the numbers of the corresponding angular momenta. The dotted points are the experimental data of the 871 keV γ-ray yield of ^{17}O measured by Freeman *et al.* (Ref. 1). The parameters of the transition matrix element are set as $H_{12}^0 = 0.5$ MeV and $\Delta R = 1.5$ fm, and the absorption is taken as $W_0 = 2$ MeV.

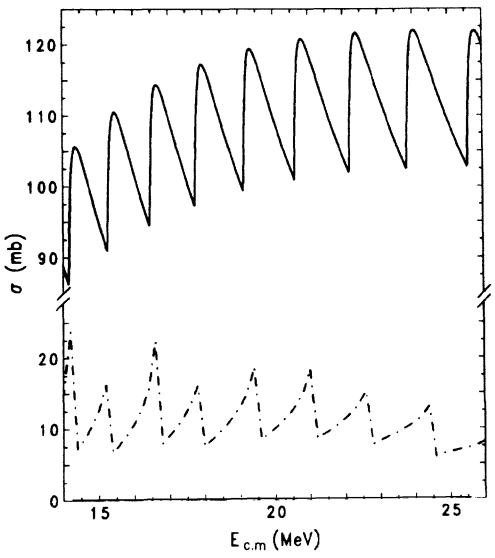

FIG. 7. Comparison of the cross section for the inelastic excitation of the first $\frac{1}{2}^+$ state of ^{17}O calculated with the Landau-Zener formula (full curve) and the time-dependent semiclassical model (dotted-dashed curve). The parameters are $W_0=2$ MeV, $H_{12}^0=0.5$ MeV, and $\Delta R=1.5$ fm. All partial cross sections are added.

IV. CONCLUSIONS

In this paper we have assumed that the structures observed in the 871 keV γ-ray yield of ^{17}O arise from the decay of the directly excited first $\frac{1}{2}^+$ state of ^{17}O in the $^{13}C+^{17}O$ collision. The basic ingredient of the model is the avoided level crossing between the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) and $2s_{1/2}$ states near $R=7.7$ fm. In this case the transition strength between the two states is strongly enhanced about the point of avoided level crossing. It is, therefore, possible to consider at first the application of the Landau-Zener formula for the calculation of the transition probability. However, since this formula was derived under restrictions, which are not fulfilled in the present example, it leads to larger cross sections compared with those of the time-dependent semiclassical treatment of the reaction.

We have shown that the effective potential barriers, including the centrifugal potential, are responsible for the structures in the considered inelastic cross section of the $^{13}C+^{17}O$ reaction. Since the avoided crossing of the two states lies near the barriers ($R_B\cong 7.5$ fm, $R_c=7.7$ fm), the transition matrix element is large also at the barrier. At this point the system sticks together for a longer time, even when the radial relative motion is treated quantum mechanically, and, therefore, a structure appears in the inelastic cross section for each angular momentum. The heights of the structures are essentially determined by the transition matrix element near the avoided crossing of the two states. Therefore, the Landau-Zener mechanism also plays an important role in the transition considered here.

Further measurements are needed to determine the portion of the 871 keV γ-ray yield of ^{17}O which is due to the direct inelastic excitation of the ^{17}O nucleus. Therefore, the transition strength H_{12}^0 in our schematic model cannot yet be fixed. As shown in Fig. 6 the value of 0.5 MeV is chosen for H_{12}^0 in connection with $\Delta R=1.5$ fm. If a larger part of the experimental 871 keV γ-ray yield originates from the sequential decay through the $\frac{1}{2}^+$ state, the transition strength H_{12}^0 could be taken smaller which is more in agreement with the situation at the point of avoided level crossing. The larger values of H_{12}^0 and ΔR used in the calculations could also give an effective description of the transition strength over a larger interval of R.

Similar calculations, which include the effects of the turning point in the Landau-Zener formula and use a somewhat different approach, are being carried out by Cha[10] for the systems $^{12}C+^{17}O$ and $^{12}C+^{18}O$. Preliminary results show remarkable improvements over the usual Landau-Zener formula in fitting experimental data, indicating the importance of the potential barrier effects as discussed in the present paper.

Since the structures depend strongly on the potential barriers, a more realistic quantum mechanical treatment of the radial relative motion is desirable. A model for this purpose is the dynamical particle-core model[11,12] describing the $^{13}C+^{17}O$ reaction by the ^{12}C and ^{16}O cores with two loosely bound neutrons. Work in this direction is in progress.

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