Evidence for nuclear Landau-Zener effect: New resonance mechanism in heavy-ion reactions

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Characteristic resonancelike peaks recently observed in the angle-integrated inelastic cross sections for the ^{13}C-^{17}O system are understood in terms of the Landau-Zener excitation mechanism at energy level crossings. Angle-integrated inelastic cross sections estimated with the Landau-Zener formula show a series of resonancelike peaks as a function of incident energy, each of which is associated with a grazing angular momentum of the relative motion between nuclei. Simple expressions are given for resonance energies and "widths" of new "resonances." This resonance mechanism is a new one, which has not been known in nuclear reactions nor in atomic collisions, although it is based on the well-known Landau-Zener promotion mechanism.

[NUCLEAR REACTIONS ^{13}C-^{17}O inelastic scattering. New heavy-ion resonance mechanism. Nuclear Landau-Zener excitation mechanism at level crossings. Molecular single-particle effects.]

Since the discovery of the sub-Coulomb resonances in the $^{12}C+^{12}C$ system by Bromley *et al.*[1] in 1960, resonant structures have been observed in various combinations of lighter heavy ions. Resonances prominently observed in angle-integrated inelastic cross sections at higher energies[2] have been found to be systematically explained in terms of nuclear molecular viewpoints,[3] which indicates an existence of coupled molecular configurations in high excitation of light nuclei. The study provides a gross understanding of characteristic features of heavy ion interactions such as surface transparency, combined with systematics of fusion reactions induced by heavy ions.[4] All of these resonances, including sub-Coulomb ones, have been observed correlatingly among various exit channels, at least suggesting a formation of a particular compound state. In contrast to them, a new type of resonancelike structure has recently been observed by the Strasbourg group[5] in the $^{13}C+^{17}O$ system. The structure is evident in the yield curve for the 871-keV γ rays of ^{17}O but absent for other observable transitions, as shown in Fig. 1. Structureless features in other reaction channels are consistent with a strong absorptive nature of the system suggested by a general understanding of absorption with a number of available open channels.[6] Hence, this resonancelike inelastic scattering suggests a specific transition mechanism which dominates in competition among many reaction channels.

Recently, realistic two-center level diagrams for several heavy ion systems have been calculated,[7] and it has been expected that level crossings found in several reaction channels should cause enhancement in experimental cross sections. Using the asymmetric two-center shell model (TCSM),[8] we have calculated single-particle energies for the $^{13}C+^{17}O\rightarrow^{30}Si$ system as a function of the internuclear distance. The parameters of the TCSM potential used in the calculations have been determined by fitting the experimental neutron single-particle energies of ^{13}C, ^{17}O, and ^{29}Si, and are given in Table I. The two-center level structure for $^{13}C+^{17}O\rightarrow^{30}Si$ is shown in Fig. 2. As expected, the level structure is very similar to those calcu-

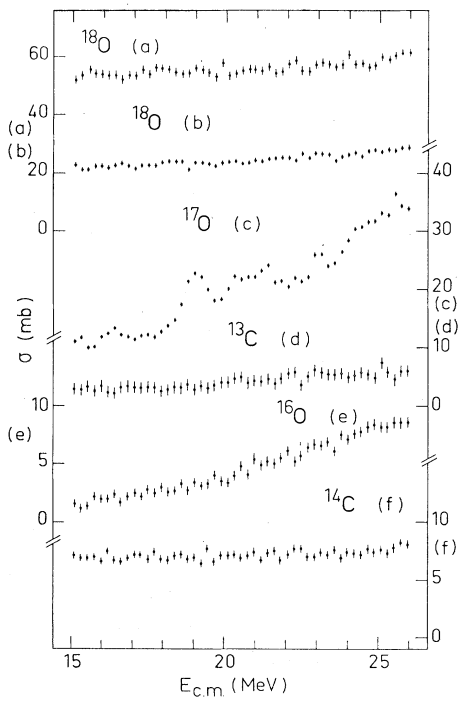

FIG. 1. γ-ray yield excitation functions of the $^{13}C+^{17}O$ system for the following transitions: (a) 1982 keV ($2^+\rightarrow0^+$) ^{18}O; (b) 1573 keV ($4^+\rightarrow2^+$) ^{18}O; (c) 871 keV ($\frac{1}{2}^+\rightarrow\frac{5}{2}^+$) ^{17}O; (d) 3853 keV ($\frac{5}{2}^+\rightarrow\frac{1}{2}^-$) ^{13}C; (e) 6129 keV ($3^-\rightarrow0^+$) ^{16}O; and (f) 6726 keV ($3^-\rightarrow0^+$) ^{14}C.

TABLE I. Parameters of the asymmetric TCSM potential for $R=0$ and $R=\infty$ (in MeV's) and the levels fitted ($C=\hbar\omega A^{1/3}=30.0$).

Nucleus	$\hbar\omega$	a	b	V_0	Fitted levels
^{13}C	12.76	−4.930	0.948	41.78	$1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$
^{17}O	11.67	−3.672	0.467	41.78	$1d_{5/2}$, $2s_{1/2}$
^{30}Si	9.65	−1.936	−0.359	42.91	$2s_{1/2}$, $1d_{3/2}$, $1f_{1/2}$

lated in the previous work[7] for $^{13}C+^{16}O\rightarrow^{29}Si$ and $^{12}C+^{17}O\rightarrow^{29}Si$. 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 occurs near 7.7—8.0 fm, where the promotion of the valence neutron in the $1d_{5/2}$ state of ^{17}O to the $2s_{1/2}$ state can take place. The internuclear distance where avoided crossings occur is found to be fairly independent of the large variations in the parameter sets of the asymmetric TCSM, as in previous works.[7,8] The large crossing distance makes it more favorable for the Landau-Zener (L-Z) promotion mechanism[9] since it is not disturbed by other competing reaction processes. It is, therefore, physically real and should play an important role in the reaction. In atomic scattering, the L-Z electron promotion at an avoided crossing point is well known as an important mechanism for inelastic and charge exchange collisions at low incident energies.[10] Characteristic features of the mechanism are manifested as oscillations in angular distributions and in excitation functions at a single scattering angle. Analogous microscopic treatments based on the adiabatic molecular picture have been developed in nucleus-nucleus collisions. An elastic transfer is a good example.[11] It should be noted here, however, that no resonances have been discussed or observed in angle-integrated excitation functions owing to the L-Z promotion mechanism in atomic and nuclear collisions. Oscillations of excitation functions usually disappear after integration over scattering angles. (There are two exceptional cases in atomic scattering, called Smith and Rosenthal oscillations, where special additional conditions are necessary concerning energy curves.[12]) The angle-integrated cross section with the L-Z model is given as a function of incident energy E by[13]

$$\sigma_{21}(E)=4\pi^2R_C^2\frac{\sqrt{2\mu}}{\hbar}\frac{|H'_{12}|^2}{\Delta F^0}\frac{\sqrt{E-\bar{V}}}{E}, \tag{1}$$

where R_C is the crossing distance of diabatic energy curves ϵ_2^0 and ϵ_1^0, as shown in Fig. 3, and $|H'_{12}|$ is a coupling matrix element between the diabatic states at R_C and is equal to half of the separation between the adiabatic energies. ΔF^0 is a difference of forces along the diabatic curves, i.e.,

$$\Delta F^0=|d\epsilon_2^0/dR-d\epsilon_1^0/dR|_{R=R_C}.$$

μ and $\bar{V}$ are, respectively, the reduced mass of the incident channel and the adiabatic potential depth at R_C. The expression apparently depends smoothly on the energy, with a sharp rise at the threshold $\bar{V}$. It is shown in the dash-dot line in Fig. 4 for comparison with the present result. The L-Z promotion mechanism seems not to bring about a series of resonancelike peaks such as those observed in the $^{13}C+^{17}O$ system. Expression (1), however, is obtained by an integration over impact parameter, as given later. According to a general understanding of heavy ion interactions briefly mentioned above, a possible reaction mecha-

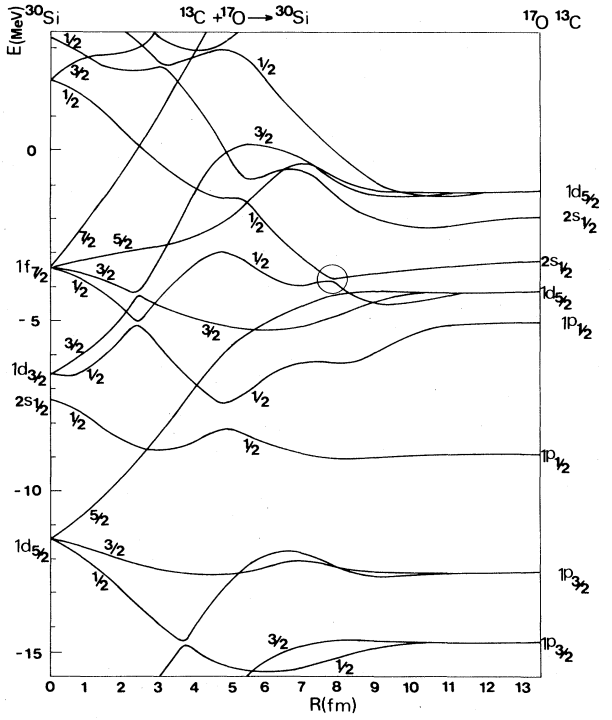

FIG. 2. Correlation diagram for $^{13}C+^{17}O\rightarrow^{30}Si$. An avoided crossing inside the circle is discussed in the text.

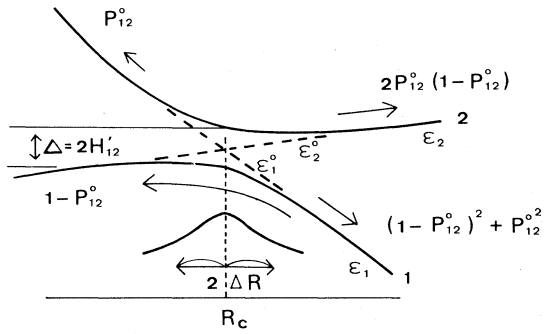

FIG. 3. Schematic diagram of level crossing. Solid and dashed lines denote adiabatic and diabatic energy curves.

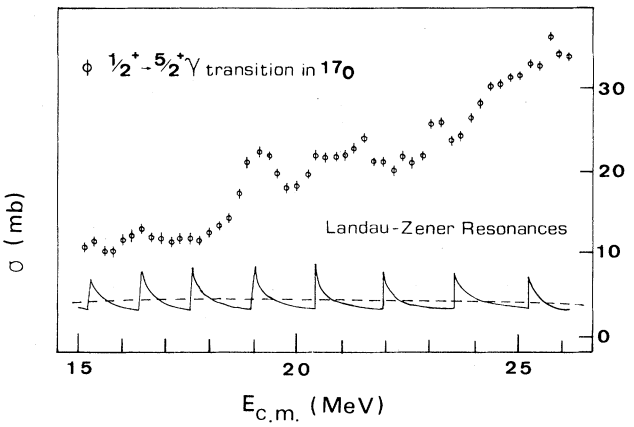

FIG. 4. Landau-Zener inelastic cross sections are compared with the inclusive γ-ray yield curve which is shown as (c) in Fig. 1. Solid and dashed lines denote the present calculation with expression (5) and that with the usual expression (1) with a factor $\frac{1}{3}$, respectively.

nism for each resonancelike peak should be attributed to a grazing partial wave, which requires a careful investigation of the mechanism.

The purpose of the present paper is to show a possibility that the L-Z promotion mechanism produces a series of resonances with a width which is comparable to the observed one.

As is well known in atomic scattering and little discussed in nuclear reactions,[14] the L-Z promotion is due to a breakdown of adiabatic conditions around an avoided crossing point of adiabatic energy curves, where the Born-Oppenheimer approximation of separating a relative motion of force centers and a motion of a valence particle becomes worse. Actually, nonadiabatic coupling is simply given by[13]

$$i\hbar\,|H'_{12}|\,\Delta F^0 v^0/\{[\Delta F^0(R-R_c)]^2+4\,|H'_{12}|^2\}$$

in the two-state model, where v^0 is a radial velocity at $R=R_C$. A transition probability from one adiabatic state to the other by a single passage of the crossing point with a finite radial velocity v^0 is given by[9]

$$P^0_{12}=e^{-2\pi G^0}\,,\quad G^0=\frac{1}{\hbar}\frac{|H'_{12}|^2}{v^0\Delta F^0}\,, \tag{2}$$

where all the physical quantities are those in the diabatic basis.[13] A transition probability $\mathscr{P}$ in the scattering process is expressed by P^0_{12} as follows:

$$\mathscr{P}=2P^0_{12}(1-P^0_{12})\,, \tag{3}$$

since the system passes through the crossing point twice, first in entering into the interaction region, and second in leaving from there. The radial velocity v^0, which is the only quantity concerning relative motion in the above expressions, is calculated by the following classical relation, because the relative motion is not solved in the present treatment:

$$E=\tfrac{1}{2}\mu v^{0^2}+\frac{l(l+1)\hbar^2}{2\mu R_C^2}+\bar{V}\,,$$
$$\bar{V}=\epsilon^0(R_C)+V_c(R_C)\,, \tag{4}$$

where $V_c(R_C)$ is an adiabatic interaction potential between force centers. The orbital angular momentum quantum number l is used instead of a classical impact parameter in order to see partial wave contributions separately. Thus, the velocity v^0 actually depends on the orbital angular momentum l. P^0_{12}, and hence $\mathscr{P}$, depend also on l. The angle-integrated cross section is expressed as usual[15] by

$$\sigma_{21}(E)=\frac{\pi}{k^2}\sum_{l}^{l_{\max}}(2l+1)\mathscr{P}_l(E)/3\,, \tag{5}$$

where k denotes a wave number of the incident channel and $l_{\max}$ is a maximum orbital angular momentum which can reach the crossing point at incident energy E. The factor $\frac{1}{3}$ comes from the fact that only one branch ($\Omega=\frac{1}{2}$) of the three originating from the $1d_{5/2}$ state pseudocrosses with that from the $2s_{1/2}$ state. Angular momentum and energy dependences of $\mathscr{P}_l$ are explicit in the expression. If the summation in (5) is replaced by the integration over the impact parameter, we obtain

$$\sigma_{21}(E)=4\pi R_C^2\left[1-\frac{\bar{V}}{E}\right][f(\gamma)-f(2\gamma)]/3\,,$$
$$f(\gamma)=e^{-\gamma}(1-\gamma)/2-Ei(-\gamma)\gamma^2/2\,,$$
$$\gamma=2\pi g\Big/\left[1-\frac{\bar{V}}{E}\right]^{1/2},\quad g=\frac{1}{\hbar}\frac{1}{v}\frac{|H'_{12}|^2}{\Delta F^0}\,, \tag{6}$$
$$v=\left[\frac{2}{\mu}E\right]^{1/2},$$

where $Ei(-\gamma)$ is the exponential integral. In the case of small γ, expression (6) reduces to expression (1) with the factor $\frac{1}{3}$.

In calculating the cross section, one needs to know the crossing point R_C, the interaction matrix element $|H'_{12}|$, the difference of the classical forces ΔF^0, and the total adiabatic potential depth $\bar{V}$. The former two, R_C and $|H'_{12}|$, can be extracted directly from the energy diagram calculated by the TCSM, assuming that the model provides an adiabatic basis. They are 7.9 fm and 0.05 MeV, respectively. The third one, ΔF^0, could be obtained as well, but is simply expressed by an intuitive parameter ΔR, where the nonadiabatic coupling is effective,

$$\Delta F^0\simeq\frac{2\,|H'_{12}|}{\Delta R}\,.$$

The ΔR is taken to be 0.1 fm. The last one, $\bar{V}$, could also be obtained from the TCSM calculation, but in the present estimation a phenomenological potential[16] for the $^{12}C+^{16}O$ system is employed, which is expected to be little different from the adiabatic one at such a large distance of the crossing point under discussion. The varia-

tions of $\bar{V}$ still do not change the essential feature of the results.

Calculated inelastic cross sections to $^{17}O^*$ ($\frac{1}{2}^+$, 0.87 MeV) are compared in Fig. 4 with the yields of the 871 keV γ ray. A remarkable thing is that expression (5) (solid line) reproduces the series of resonancelike peaks observed, in contrast to the usual expression (1) (dashed line). Although the reproduction of the experimental data is not very good, the result is encouraging in view of the simplicity of our evaluation. (Note also that the γ-ray yields are inclusive, and are not exactly equal to the inelastic cross sections.) Each resonancelike peak is attributed to a single orbital angular momentum, which is nearly equal to a grazing one because the crossing point R_C is close to the barrier top radius. Thus, absorption may not so much affect the resonancelike peaks, though it may drastically change the total magnitude, improving the fitting. A delicate problem that still remains is the applicability of the L-Z formula near the turning point. As already studied in atomic scattering, it is unlikely that modifications owing to the dynamics of the relative motion wash out the characteristic enhancement of the L-Z formula. Rather, a quantum-mechanical penetration effect would moderate the steep rise of each peak. Anyhow, it is very interesting to solve the problem completely, including a quantum-mechanical treatment of the relative motion and a rotational coupling between different Ω's.

The essential features of the calculated result can be simply understood by the expressions for resonance energy $E_l^{\rm res}$ and "width Γ," which permit us further qualitative arguments on resonancelike reactions due to the L-Z effect. The former is readily obtained by the condition $\partial \mathscr{P}_l/\partial E = 0$ at $E = E^{\rm res}$;

$$E_l^{\rm res} = \frac{\pi^2}{4}\frac{1}{(\ln 2)^2}\frac{|H'_{12}|^2}{(\hbar^2/2\mu)/(\Delta R)^2} + \bar{V} + \frac{\hbar^2}{2\mu R_C^2} l(l+1) . \tag{7}$$

The latter is obtained by calculating a difference of energies where $\mathscr{P}_l(E) = \mathscr{P}_l(E_l^{\rm res})/2 = \frac{1}{4}$, although the energy dependence of the peaks is not a Lorenzian;

$$\text{"}\Gamma\text{"} = \frac{\pi^2}{4}\left[\frac{1}{(\ln P_+)^2} - \frac{1}{(\ln P_-)^2}\right]\frac{|H'_{12}|^2}{(\hbar^2/2\mu)/(\Delta R)^2} = 97.74\frac{|H'_{12}|^2}{(\hbar^2/2\mu)/(\Delta R)^2} , \tag{8}$$

where $P_\pm = \frac{1}{2} \pm 1/(2\sqrt{2})$. Thus, resonancelike peaks have a rotational sequence with a moment of inertia of μR_C^2. Their width is determined by the matrix element H'_{12} and the nonadiabatic range ΔR, but is independent of energy and angular momentum. By the use of the same parameters as in Fig. 4, we obtain "Γ"$\simeq$3.5 keV. This is much smaller than the spacing of resonancelike peaks, which invalidates the replacement of discrete summation with integration. If one uses larger values of the parameters arbitrarily, for example, $|H'_{12}| \simeq 1$ MeV and $\Delta R \simeq 1$ fm, then "Γ"$\simeq$35 MeV, where a structure would be smeared out and expression (1) is valid. Many curve crossings obtained by the TCSM have parameter values of the same order of magnitude as the above and hence are difficult to observe as resonancelike structures, although the cross sections themselves are large. In atomic scattering, an order of magnitude of the width can be estimated by the use of orders of the parameters, i.e.,

$$|H'_{12}| \sim 10^{-2} E_{\rm el} , \quad \Delta R/R_c \sim 10^{-2}$$

and

$$(\hbar^2/2\mu)/R_c^2 \sim 10^{-3} E_{\rm el} ,$$

where $E_{\rm el}$ is a typical electronic energy; then "Γ"$\sim 10^{-3} E_{\rm el}$. This is extremely small and hence would require a very high resolution for observation of the corresponding resonancelike structure.

We expect that similar structures should be observed also for the inelastic processes, such as

$$^{12}C + ^{17}O \rightarrow ^{12}C_{\rm gr} + ^{17}O^*(\tfrac{1}{2}^+, 0.87\ \text{MeV})$$

and

$$^{14}C + ^{17}O \rightarrow ^{14}C_{\rm gr} + ^{17}O^*(\tfrac{1}{2}^+, 0.87\ \text{MeV}) ,$$

owing to the L-Z mechanism, since the TCSM diagrams are almost the same as that of the $^{13}C + ^{17}O$ system. Preliminary data[17] on the former by the Strasbourg group seem to indicate such a structure, though weaker, at lower energies below 21.0 MeV. At higher energies above 21.0 MeV, the data points are too few and too spread out in energy at present to detect any structure. Although the system is a little unfavorable owing to the competing strong inelastic channel, additional measurements for the inelastic process above 21 MeV are highly desirable, as are those for the latter system. It is extremely meaningful and valuable to find a curve crossing in various projectile-target systems, whose energy splitting is small and whose range dominated by nonadiabatic coupling is small as well. An additional implicit condition for a prominent observation which should be taken into account is that an initial and a final state are to be of single particle nature.

In conclusion, we investigated how the Landau-Zener mechanism plays a role in an angle-integrated excitation function in nucleus-nucleus collisions. The mechanism has been found to reproduce a resonancelike structure in the inelastic excitation to the $^{17}O^*$ ($\frac{1}{2}^+$, 0.87 MeV) which was observed in the γ-ray yield measurements. The predicted resonancelike peaks are in the rotational sequence with the moment of inertia determined by the avoided crossing distance R_C. Their "width" is given by the other two parameters which characterize an avoided crossing of adiabatic energy curves, i.e., the energy separation at the crossing and the effective range ΔR of nonadiabaticity. The resonance mechanism discussed in the present paper is a new one, which has not been known in nucleus-nucleus collisions nor in atomic and molecular scattering. Quantitative treatments of the present mechanism would provide a way to establish the formation of nuclear molecular orbitals during nucleus-nucleus col-

lisions. According to the mechanism, reactions proceed with an angular momentum projection to the radial direction Ω being conserved. Polarization-type measurements, therefore, are expected to confirm the present prediction.

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