Experimental evidence and the Landau-Zener promotion in nucleus-nucleus collisions

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Recent data from C+O collisions are analyzed in terms of the Landau-Zener promotion in nuclei. Evidence for the presence of this mechanism in nuclear collisions is of considerable interest, since it provides a signature of single-particle orbitals in molecular-type potentials and, at the same time, paves the way to a microscopic understanding of the collision dynamics, in particular of the energy dissipation rate. The analyzed data are of two types: integrated cross sections and angular distributions of inelastically scattered particles. The first set of data shows structure qualitatively consistent with recent calculations of the Landau-Zener effect; for this set of data no other reasonable explanation is presently available. The second set of data, while consistent with the presence of the Landau-Zener promotion, is examined in terms of other possible explanations too. The combined data show evidence favoring the presence of the Landau-Zener promotion in nucleus-nucleus collisions.

I. INTRODUCTION

The process of nucleon promotion from nonintersecting adiabatic levels—the nuclear analog of the atomic Landau-Zener effect[1,2]—was introduced into nuclear physics as early as 1953, in the classic article by Hill and Wheeler on the collective model and fission.[3] In this article Hill and Wheeler consider the process of "slippage" which "... evidently constitutes the elementary act in a viscous phenomenon" and accompany this discussion with a figure (Fig. 33 in Ref. 3) to which Fig. 2 of this paper is essentially identical. The "probability per second of slippage" and the "energy change per slippage" were the principal ingredients of the "damping coefficient" calculated for the fission process, a quantity which will again become fashionable in heavy-ion physics many years later. In the meantime, and for reasons easy to understand, the interest for the nuclear analog of the Landau-Zener promotion faded out. One had to wait for the advent of heavy-ion beams for a concept, basic to the application of this effect to nuclear processes, the concept of classical trajectories, to become commonly accepted in the description of nucleus-nucleus collisions at low and intermediate energies. In fact, it is only in the last 5–6 years that experimental evidence for single-nucleon orbitals in quasimolecular potentials has actually become available.[4,5] With it, renewed interest in studying the nuclear Landau-Zener promotion mechanism—i.e., the promotion of nucleons from nonintersecting adiabatic levels—has emerged[6–10] and data relevant to this mechanism have become available. These data comprise γ-ray yield excitation functions and charged-particle angular distributions from collisions of carbon and oxygen isotopes. The γ-ray data have been published[11,12] and some of the charged particles data have also been presented at various conferences;[13] the bulk of the latter is, however, given in the preceding paper.[14] In the present paper all of these data are collected together for the first time and critically reviewed in terms of its bearing to the nuclear Landau-Zener promotion.

II. THE MECHANISM OF THE LANDAU-ZENER PROMOTION

The subsequent discussion of the mechanism of the Landau-Zener promotion and its applications to heavy-ion collisions follows Refs. 3 and 15. While this mechanism should be present in all processes involving the damping of energy and momentum in nuclear collisions, it should be most readily observed in cases which bear the maximum analogy to diatomic molecules. Such cases are collisions of nuclei consisting of a hard core plus a valence nucleon, like, e.g., $^{12}C+^{13}C$, $^{12}C+^{17}O$, $^{25}Mg+^{16}O$, etc.; many such cases have been discussed in the literature.[7–9] Because of the difference in masses, the relative velocity of the cores is small in comparison with the velocity of the nucleons. This makes it possible to consider the motion of nucleons as taking place about fixed centers (cores) placed at given distances from one another. The two-center shell model (TCSM) of Maruhn and Greiner[16] is a fitting description of these processes. When determining the energy levels of such systems (analogs of the electron terms in a molecule), one finds that they are not single numbers like in nuclei (or atoms), but functions of given parameters. For heavy-ion collisions they are functions of the distance between the two nuclei (in fact, the two nuclear cores). Consequently, we cannot classify these terms according to the values of the total orbital angular momentum L since this quantity is not conserved for nucleons moving in a noncentral "molecular" field.

However, for diatomic molecules and their nuclear analogs the field has axial symmetry about an axis passing through the two cores. Hence the projection of the orbital angular momentum on this axis is conserved and we can use this quantity to classify the nucleon terms in a "molecular" potential.

The intersection and nonintersection of nucleon energy terms in a "molecular" potential, i.e., in a potential generated by two heavy cores separated by a slowly varying distance R, play a foremost role in the nucleon promotion mechanism. We shall discuss this point in some detail. Let $U_1(R)$ and $U_2(R)$ be two different nucleon energy terms. If they intersect at some point, the functions U_1 and U_2 will have neighboring values near this point. To decide whether such an intersection will actually occur, we shall consider a point R_0 where these functions have very close but not equal values (which we denote by E_1 and E_2) and examine the consequences of a small displacement δR. The energies E_1 and E_2 are eigenvalues of the Hamiltonian $\hat{H}_0$ of the system with the cores at the distance R_0; if we change this distance by a small amount δR, the Hamiltonian will change to $\hat{H}_0+\hat{V}$, where $\hat{V}=\delta R(\partial \hat{H}_0/\partial R)$ is a small correction. Applying perturbation theory, we assume Ψ_1 and Ψ_2 to be eigenfunctions of the unperturbed Hamiltonian H_0 which correspond to energies E_1 and E_2. As an initial zero-order approximation for the perturbed wave function we take

$$\Psi=C_1\Psi_1+C_2\Psi_2 . \tag{1}$$

Substituting this in the perturbed equation

$$(\hat{H}_0+\hat{V})\Psi=E\Psi , \tag{2}$$

we obtain the following expression for the perturbed energy in the first approximation

$$E^{\mathrm{up}}_{\mathrm{down}}=\tfrac{1}{2}(E_1+E_2+V_{11}+V_{22}) \pm[\tfrac{1}{4}(E_1-E_2+V_{11}-V_{22})^2+|V_{12}|^2]^{1/2} \tag{3}$$

with $V_{ik}=\int \Psi_i^* V \Psi_k dR$ the coupling matrix element.

If the values of the two energy terms $U_1(R)$ and $U_2(R)$ are to become equal at the point $R_0+\delta R$ (i.e., if the terms intersect), the two values of E given by expression (3) must be equal at that point. This means that the radical in the above expression must vanish. Since it is the sum of two squares, both must vanish simultaneously, i.e., we must have

$$E_1-E_2+V_{11}-V_{22}=0, \quad V_{12}=0 \tag{4}$$

(we assume Ψ_1 and Ψ_2 hence V_{12} real). However, in a "molecular" field generated by two heavy cores we dispose of only one arbitrary parameter governing the perturbation $\hat{V}$, namely the displacement δR. This means that the two Eqs. (4) cannot, in general, be satisfied simultaneously. If however, the matrix element V_{12} vanishes identically, then only one equation remains and can be satisfied with a suitable choice of δR. This happens in all cases when the two terms considered are of different symmetry character. In our case (axially symmetric "molecular" potential) this means that only terms with different projection Ω of the total angular momentum I on the system axis can intersect; terms with the same projections cannot intersect and will accordingly display avoided crossings, as shown in a two-center shell-model diagram for colliding $^{12}C+^{17}O$ nuclei [Fig. 1, taken from Ref. 7(b)]. This general result was derived first by Wigner and von Neumann in 1929; it has since been widely known as the Wigner repulsion law.

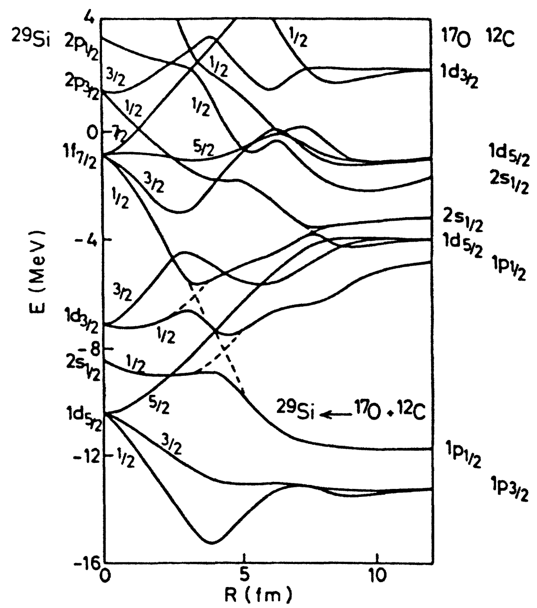

FIG. 1. The two-center shell-model level diagram of $^{12}C+^{17}O$ [taken from Ref. 7(b)].

From the above we see that different symmetries of the single-particle states lead to crossing or noncrossing of the corresponding energy terms (lines in the diagram on Fig. 1). A blowup of the levels near a crossing point is shown in Fig. 2. The crossing levels of different symmetry (here: levels with different values of Ω) are called *diabatic* levels (from the Greek $\delta\iota\alpha$ = through, across). A perturbation in the potential gives rise in general to a coupling $V_{12}\neq 0$ between the diabatic states [Ψ_1 and Ψ_2 in Eq. (1) are diabatic wave functions]. The resulting *adiabatic* (i.e., noncrossing) states have wave functions which drastically change their character at the point of avoided crossing. For relatively large collective velocities (in our case relative veloci-

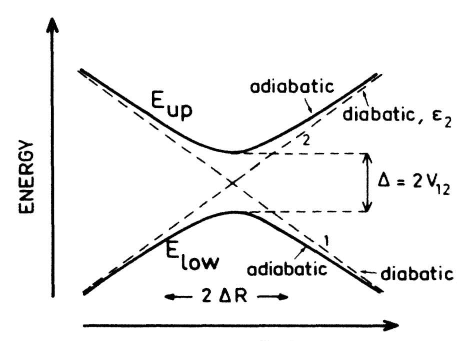

FIG. 2. Blowup of the avoided crossing region.

ties of the two colliding nuclei) the nucleons are not able to adjust their wave functions to the slow adiabatic motion and follow the adiabatic paths. Instead, a nucleon occupying the lower level before the crossing with an unoccupied level, will persevere on the diabatic path, preserving in this way its symmetry character and end up in the upper adiabatic level after the crossing.[10] This diabatic motion is equivalent to the promotion discussed long ago by Landau and Zener for electrons and constitutes the nuclear Landau-Zener effect.

The probability of nucleon promotion is governed by the magnitude of the coupling V_{12} and the rate of change of the collective variable, in our case the relative velocity of the two nuclei. Defining the dimensionless interaction parameter

$$G=\frac{2\,|V_{12}|^2}{\hbar\dot{R}\,\partial(\epsilon_2-\epsilon_1)/\partial R} \tag{5}$$

with $\dot{R}$ the relative velocity of the nuclei (cores) and $\epsilon_i=E_i+V_{ii}$, it is possible to express the probability of a nucleon to be promoted from one adiabatic level to the other[17]

$$P_{12}=e^{-\pi G}\ . \tag{6}$$

For $G \ll 1$, i.e., small coupling $|V_{12}|^2$ or large relative velocity $\dot{R}$ or both, we have $P_{12}=1$, i.e., the diabatic limit. In a concrete scattering process the system passes through the crossing point twice, first entering and then exiting the interaction region. Hence the transition probability is given as

$$\mathscr{P}=2P_{12}(1-P_{12})\ . \tag{7}$$

Maximum probability $\mathscr{P}$ is obtained for $P_{12}=0.5$, which for reasonably chosen values of the slope difference $\partial(\epsilon_2-\epsilon_1)/\partial R$ and $|V_{12}|^2$ limits the range of relative velocities $v_0=\dot{R}$. One should note that the expression (6) has been derived by treating the nucleonic motion in appropriate quantum mechanical terms (wave functions and probability amplitudes). However, the relevant collective variable, i.e., the relative distance has been treated classically as $R=\dot{R}t=v_0t$ with v_0 fixed throughout the passage across the interaction region. This procedure is justifiable if the masses of the cores are much larger than the masses of the single nucleons. Abe and Park[8] have taken v_0 from the classical equations

$$E=\tfrac{1}{2}\mu v_0^2+\frac{L(L+1)\hbar^2}{2\mu R_c^2}+\bar{V}\ ,$$
$$\bar{V}=\epsilon(R_c)+V_c(R_c)\ , \tag{8}$$

with $V_c(R_c)$ an adiabatic potential between the cores (e.g., the phenomenological optical potential) and R_c the crossing distance. In this simplified treatment the orbital quantum number L is used instead of a classical impact parameter in order to separate partial wave contributions. Thus the velocity v_0 and hence P_{12} and $\mathscr{P}$ also depend on L. At each energy where a new partial wave becomes active there will be a sharp variation of $\mathscr{P}$ and, consequently, a sharp variation of the angle-integrated cross section

$$\sigma_{21}(E)=\frac{\pi}{k^2}\sum_{L}^{L_{\max}}(2L+1)\mathscr{P}_L(E)\ . \tag{9}$$

Here k is the wave number of the incident channel and $L_{\max}$ is the maximum orbital angular momentum which can reach the crossing point (R_c) at the incident energy E. Such variations show up as sharp peaks in the calculated energy dependence of σ_{21} (see, e.g., Fig. 4 of Ref. 8) and thus correspond to periodic maxima in the promotion cross section.

III. APPLICATION TO C + O COLLISIONS

Among typical examples of core plus nucleon systems are colliding C + O nuclei: $^{12}C+^{17}O$, $^{13}C+^{16}O$, and $^{13}C+^{17}O$. Level diagrams in a two-center shell-model representation have been calculated for all these systems.[7–9] These various calculations have shown a remarkable stability of results, i.e., a rather weak dependence on not only the potential parameters used in the calculations but also on the type of potential used. In fact, the calculations of Refs. 7 and 8 done with various oscillator potentials and those of Ref. 9 done with a Woods-Saxon potential show pronounced avoided crossings between the same levels and at distances which vary by only about 1 fm or less. As, in addition, TCSM level diagrams for all the C + O isotopic combinations considered are identical within these limits, we shall concentrate on the level diagram for the $^{12}C+^{17}O$ system taken from Ref. 7(b) as representative of all the C + O systems.

Figure 1 shows a narrow avoided crossing between the $\Omega=\frac{1}{2}$ branch of the $1d_{5/2}$ (ground) level of ^{17}O and the $2s_{1/2}$ (first excited) level of the same nucleus. A nucleon promotion at this avoided crossing would, hence, correspond to an enhanced probability of ^{17}O inelastic scattering to its first excited state in the $^{12}C+^{17}O$ collision; the same should be observed in $^{13}C+^{17}O$ but not in $^{13}C+^{16}O$ collisions.

In the semiclassical treatment of Abe and Park,[8] the cross section for the above process is given by dividing expression (9) by 3, since only one branch of the three originating from the $1d_{5/2}$ state is active. The value of the critical radius R_c as well as that of the coupling matrix element V_{12} can be read from the TCSM level diagram in Fig. 1 (see also Fig. 2). They are, respectively, 7.8 fm and about 0.1 MeV.

The value of $\partial\epsilon_2/\partial R-\partial\epsilon_1/\partial R$, i.e., the difference of the forces along the diabatic paths, is a fundamental quantity in these calculations. In fact, its derivation from, say, the measurement of the promotion cross section would give a direct handle on calculating from first principles the energy dissipation rate in nuclei. In Ref. 8 this quantity is simulated by the intuitive parameter

$$\Delta F^0\simeq\frac{2\,|V_{12}|}{\Delta R} \tag{10}$$

with 2 ΔR the length of the interaction region. From Fig. 1 one takes $\Delta R\simeq0.1$ fm.

Recently Milek and Reif[9] have used a dynamical treatment to calculate the transition rates T_{ij} at the various avoided crossings for the $^{13}C+^{17}O$ system. These calculations show that the transition amplitude between the $1d_{5/2}$, $\Omega=\frac{1}{2}$, and the $2s_{1/2}$ levels discussed above displays a sharp peak at the avoided crossing at $R_c \simeq 7$ fm; however, a considerable fraction of the transition amplitude extends also far outside the touching distance of the two nuclei (region of 7—10 fm). This result indicates that nuclear promotion is not necessarily localized in space so that the picture consisting of an adiabatic motion of the system interrupted by sudden transitions between adiabatic levels at avoided crossings may not be valid in the nuclear case.[9] Nevertheless, the general conclusion of Refs. 7 and 8, that nuclear promotion enhances the rate of particular nucleon transitions is upheld in Ref. 9 too.

It should be mentioned that enhanced transitions at avoided crossings of the C + O collisions other than the one leading to ^{17}O inelastic scattering ($d_{5/2}$, $\Omega=\frac{1}{2}$ to $1s_{1/2}$) are also predicted. For instance in both Refs. 7 and 9 avoided crossings of the $1d_{5/2}$, $\Omega=\frac{1}{2}$ level of ^{17}O and the $1p_{1/2}$ level of ^{12,13}C as well as of the $1p_{1/2}$ levels of these nuclei are predicted at, respectively, $R_c \simeq 3.5$ and 4.5 fm (see Fig. 1). The Landau-Zener promotion at the above avoided crossings should lead to enhanced transfer cross sections. The two crossings lay, however, inside the C + O touching distance (6.3 fm for $r_0=1.3$ fm). Thus, especially at the $d_{5/2}$-$1p_{1/2}$ crossing, the C and O nuclei presumably have fused a long time ago and a description in terms of a two-center shell model may not be valid any more.

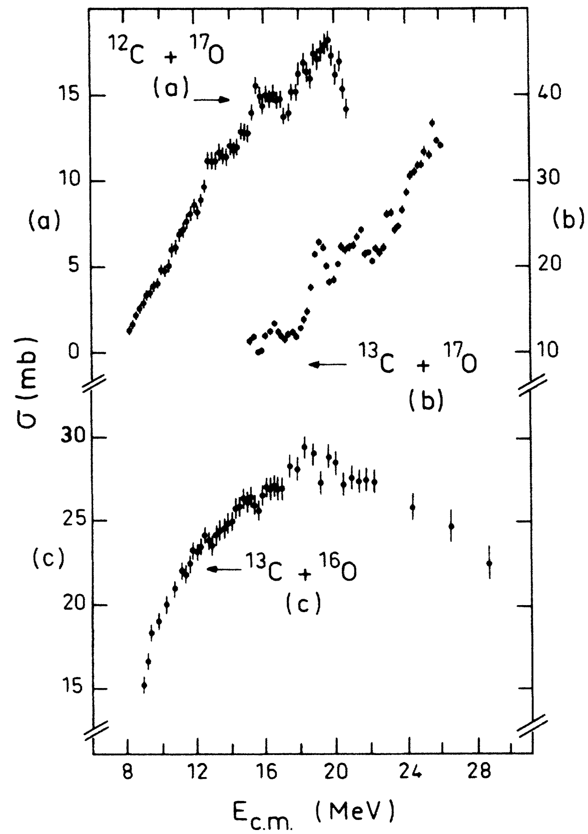

FIG. 3. Excitation functions for the 0.871 MeV γ-ray yield from the 0.871 MeV, $\frac{1}{2}^+$ level of ^{17}O for (a) the ^{12}C+^{17}O reaction and (b) the ^{13}C+^{17}O reaction. For comparison, the excitation function of the 0.871 MeV γ-ray yield from the reaction ^{13}C+^{16}O→^{12}C+^{17}O* (0.871 MeV) is shown (c). Data are from Refs. 11 and 12.

IV. DISCUSSION

In this section we shall discuss the relevance of the experimental results presented in Refs. 11—14 to the nuclear Landau-Zener effect. We shall thus compare these results with predictions for nucleon promotion in the C + O colliding systems.

A. Gamma yield measurements

The first indication[8] of the possible presence of the Landau-Zener promotion in C + O collisions came from the results of Ref. 11 on the gamma yield from the ^{13}C+^{17}O colliding system. The striking aspect of these results was that only the yield of the 0.871 MeV gamma ray from the decay of the first excited $\frac{1}{2}^+$ level of ^{17}O showed structure in its excitation function; none of the other channels showed anything comparable. In fact, gamma yields from all other reaction channels from ^{13}C+^{17}O showed a flat dependence on the collision energy from $E_{c.m.} \simeq 15$ to 25 MeV. (See Fig. 1 of Ref. 11.) A subsequent measurement of the ^{12}C+^{17}O system showed again structure in the yield of the 0.871 MeV γ ray with no structure observed in the γ yield from other reaction channels; the observed structure, however, was less pronounced than for the ^{13}C+^{17}O system. The two 0.871 MeV γ yields are compared in Fig. 3. For comparison we show in the same figure the essentially structureless excitation function of the γ yield from the neutron transfer reaction ^{13}C+^{16}O→^{12}C+^{17}O* (Ref. 12).

The structure in the 0.871 MeV γ-yield excitation functions shown in Fig. 3 supports the presence of a common mechanism specific to the inelastic scattering of ^{17}O, active in both the ^{12}C+^{17}O and ^{13}C+^{17}O collisions. Now, the Landau-Zener promotion in the C + O colliding systems is expected to be the strongest and most easily observable just for the ^{17}O*, 0.871 MeV inelastic channel while it should not be present in the transfer reaction ^{13}C+^{16}O→^{12}C+^{17}O* leading to the same 0.871 MeV level in ^{17}O. Hence the statement that the Landau-Zener promotion is the mechanism responsible for the structure in the 0.871 MeV inelastic γ yield seems to be based on reasonably self-consistent experimental grounds. The presently available calculations of the Landau-Zener promotion probabilities, however, cannot quantitatively account for the above data. In fact, the comparison of the ^{13}C+^{17}O, 0.871 MeV γ yield with two recent calculations[8,9] shows that while both of them provide considerable structure in the calculated excitation functions, the agreement with the data is far from quantitative (Fig. 4). A recent calculation of the enhanced Landau-Zener yield for the ^{12}C+^{17}O 0.871 MeV γ yield[18] shows similar features: calculated values display structure considerably more pronounced than that observed in the data.

There is no obvious reason why the structure observed

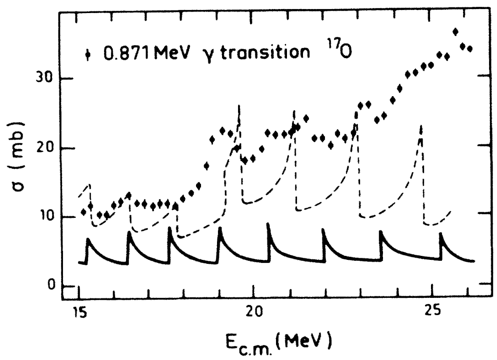

FIG. 4. The 0.871 MeV γ-ray yield from the $^{13}C+^{17}O$ collision compared to the Landau-Zener–type calculations of Refs. 8 (solid line) and 9 (dotted line). Notice that data comprise, together with the yield proper to the inelastic excitation of ^{17}O to its first excited state, also all the feeding through this level; see the discussion in Sec. IV B.

in the inelastic channels should show up in the studied energy range only. Thus we should expect it to persevere at higher incident energies too. It would, thus, be of utmost importance to extend this type of measurement to higher energies. Unfortunately, as discussed in the preceding paper (Sec. V) γ-yield measurements become more difficult and less reliable at these energies.

B. Charged particle measurements

Angle integrated data. An obvious shortcoming in interpreting the γ-yield data is the fact that the measured yield includes all the feeding through a specific level. Thus, e.g., for the $^{12}C+^{17}O$ case, the 0.871 MeV γ-ray data contain, in addition to the γ rays stemming from the inelastic excitation of the 0.871 MeV level of ^{17}O, also the feeding from the 3.055 MeV level as well as the 0.871 MeV γ ray from the mutual $^{12}C^*+^{17}O^*$ excitation. However, as seen from Fig. 1 of the preceding paper, the feeding from the higher levels does not seem to be of overwhelming importance; in fact, the excitation of the two bound levels at 3.055 and 3.841 MeV in ^{17}O seems to be rather small and the combined yield of these two levels together with that of the mutual $^{12}C^*+^{17}O^*$ excitation does not exceed the yield of the first excited level at 0.871 MeV. Nevertheless, and in order to make sure that the observed structure in the γ yield comes from the 0.871 MeV inelastic excitation only, we have undertaken the charged-particle yield measurements described in the preceding paper. Figure 5 of this paper shows the angle integrated data of $^{12}C+^{17}O$ elastic, inelastic to the 0.871 MeV level of ^{17}O and neutron transfer to the $^{13}C+^{16}O$ (g.s.) channels. Only the inelastic data [Fig. 5(b)] show structure similar to the 0.871 MeV γ-yield data. As to comparing peak energies, due to the different measured energy ranges, only the $E_{c.m.}=19.5$ MeV peak permits a comparison: it is, in fact, present in both the γ yield and the angle integrated charged-particle measurements. There is no correlation between the inelastic data and the irregular structure in the forward-angle transfer data [Fig. 5(c)]. However, the origin of the structure observed in backward-angle elastic data [Fig. 5(a)] and its possible correlation with the inelastic data are not at all clear and require further study.

Angular distributions. An interesting consequence of the semiclassical calculations of Ref. 8 is that, at incident energies corresponding to a new partial wave becoming active in the process, the angular distribution of a transition which is due to the enhanced Landau-Zener promotion will be essentially governed by this particular partial wave. The value of this critical partial wave is given in a semiclassical approximation as

$$L_{cr}=kR_{cr}=\frac{1}{\hbar}\sqrt{2\mu(E_{c.m.}-V_{CB})}R_{cr} \qquad (11)$$

with V_{CB} the Coulomb barrier and R_{cr} the critical distance at which the adiabatic transition (promotion) occurs. For C + O collisions this means that at periodic values of the incident energy, corresponding to the onset

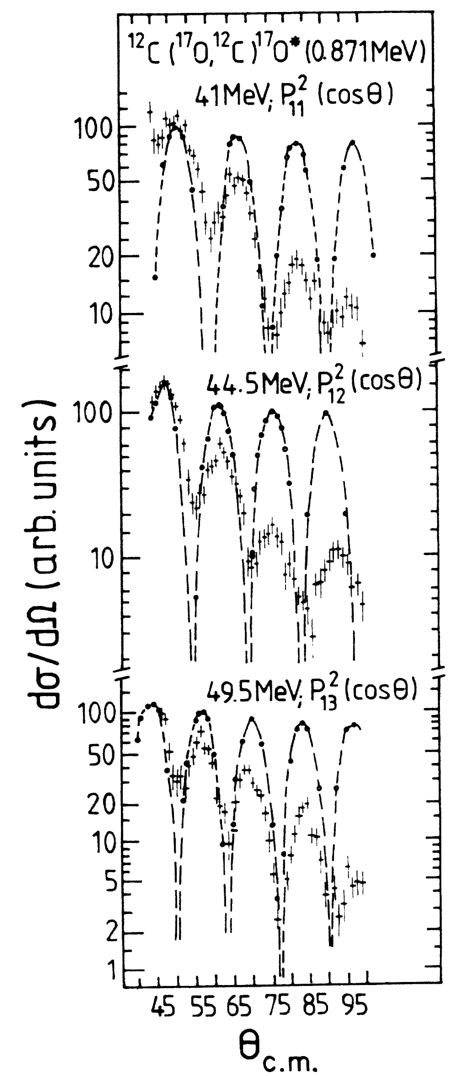

FIG. 5. Angular distributions of $^{12}C(^{17}O,^{12}C)^{17}O^*$ (0.871 MeV) at 41, 44.5, and 49.5 MeV (laboratory) and the corresponding squared Legendre polynomial forms $P_L^2(\cos\theta)$ with $L=11$, 12, and 13, respectively.

of new partial waves, the angular distributions of the inelastic scattering transitions $^{12}C(^{17}O,^{12}C)^{17}O^*$ (0.871 MeV) and $^{13}C(^{17}O,^{13}C)^{17}O^*$ (0.871 MeV) should display $P_L^2(\cos\theta)$-like shapes with L, the order of the Legendre polynomial, being related in a simple way to L_{cr}.

The composite experimental results for the $^{12}C(^{17}O,^{12}C)^{17}O^*$ (0.871 MeV) inelastic scattering angular distributions are shown in Fig. 4 of the preceding paper. While essentially all the measured angular distributions showed a more-or-less pronounced oscillatory pattern, it is only for three of them that this pattern could be assimilated to $P_L^2(\cos\theta)$-like shapes. These three angular distributions at $E_{lab}=41$, 44.5, and 49.5 MeV ($E_{c.m.}=17$, 18.4, and 20.5 MeV) and the corresponding Legendre polynomial shapes of P_{11}^2, P_{12}^2, and P_{13}^2, respectively, are shown in Fig. 5. The maxima and the minima of the measured angular distributions at the above energies are well fitted by the maxima and minima in the associated $P_L^2(\cos\theta)$ shapes; the ratios of magnitudes of the peaks are, however, rather poorly reproduced. One should note that all other measured inelastic angular distributions required a combination of several polynomials to reproduce even the positions of the peaks and valleys.[19]

Estimating the critical value L_{cr} from Eq. (11), one obtains for $E=41$, 44.5, and 49.5 MeV (laboratory), respectively,

$$L_{cr}=kR_{cr}\approx 13,\ 14,\ \text{and}\ 15$$

for $R_{cr}=7.8$ fm (Ref. 7) and

$$L_{cr}\approx 11,\ 12,\ \text{and}\ 13$$

for $R_{cr}=6.7$ fm.[9] The comparison of the angular distributions in Fig. 5 and the corresponding fitting Legendre polynomial shapes yield

$$L_{eff}=11,\ 12,\ \text{and}\ 13$$

for $E=41$, 44.5, and 49.5 MeV (laboratory), in excellent agreement with calculated values of L_{cr}.

In view of the expected closeness of L_{cr} and the grazing angular momentum L_{gr}, it is conceivable to associate the periodicity of the inelastic angular distributions with a simple grazing partial wave effect. To calculate the values of L_{gr} and compare them with L_{eff} we have used the code PTOLEMY (Ref. 20) and two sets of parameters. These parameters are given in Table I. The parameter set A is the one used in the preceding paper at 50 MeV; the set B is an independent set of parameters giving an equivalent fit to the elastic scattering data. The obtained values of grazing partial waves are $L_{gr}=14$, 15, and 16 for parameter set A and $L_{gr}=13$, 14, and 15 for parameter set B at $E_{lab}=41$, 44.5, and 49.5 MeV, respectively. The experimentally obtained values of L_{eff} at the above energies were 11, 12, and 13. The small but systematic difference of $2\hbar$–$3\hbar$ between the calculated L_{gr} and the observed L_{eff} could probably not be taken as significant in view of the uncertainties involved in calculating L_{gr} and the fact that the studied transition being a $\Delta L=2$ transition ($1d_{5/2}\rightarrow 2s_{1/2}$), the allowed values of the angular momentum in the outgoing channel are

$$L_{eff}(\text{obs})=L_{in},\quad L_{in}\pm 2$$

whatever L_{in} is (L_{gr},L_{cr}).

In order to elucidate this point further, angular distributions of the transfer reaction $^{13}C(^{16}O,^{12}C)^{17}O^*$ (0.871 MeV) were measured. This reaction leads to the same exit channel as the inelastic $^{12}C(^{17}O,^{12}C)^{17}O^*$ (0.871 MeV) scattering. At incident energy $E_{lab}=46.2$ MeV the former (transfer) reaction has approximately the same grazing partial wave as the latter (inelastic) reaction at $E_{lab}=50$ MeV and—if the angular distributions are governed by grazing wave effects only—the two measured angular distributions should display the same form. Figure 6 shows that this is not so. A similar, but less striking difference is observed in comparing transfer angular distributions measured at other energies with the inelastic scattering ones measured at the same center-of-mass energies. Again the periodicity differs considerably and the peak-to-valley ratio is flattened out in the transfer distributions. There are, thus, good grounds to believe that the observed angular periodicity in the inelastic angular distributions is related to the effect of the partial wave active in a Landau-Zener promotion, rather than to a simple grazing partial wave effect. Strictly speaking, however, the above argument holds only if one assumes a sharply surface peaked interaction causing both transitions.

It is interesting to compare the observed energies and spacings of the "resonant" angular distributions to the energies and spacings of the peaks observed in the $^{12}C+^{17}O$ inelastic charged particle data and the 0.871 MeV γ yield. The semiclassical calculations of Ref. 8 predict that a "resonant," i.e., $P_L^2(\cos\theta)$-like behavior of the angular distributions, should correspond to enhanced promotion probabilities, hence to maxima in the cross sections for the given transition. The "resonant" angular distributions are found at $E_{c.m.}\approx 17$, 18.4, and 20.5 MeV (and possibly at 22.8 and 25.2 MeV, see note under Ref. 19) with an average spacing $\Delta E^{res}\sim 2$ MeV, in reasonable agreement with the spacing

$$\left[\sim\frac{\hbar^2}{2\mu R_{cr}^2}(2L+1)\right]$$

predicted in Ref. 8. However, peaks in the combined in-

TABLE I. Potential parameters for a Woods-Saxon—type potential used in the calculation of the grazing partial waves for the $^{12}C+^{17}O$ colliding system.[a]

	r_0^R	V	a^R	r_0^I	W	a^I	r_0^C
Set A	1.35	14.26	0.589	1.445	6.17	0.346	1.35
Set B	1.35	17.2	0.509	1.417	6.0	0.265	1.35

[a]Units: r_0 in fm, V and W in MeV.

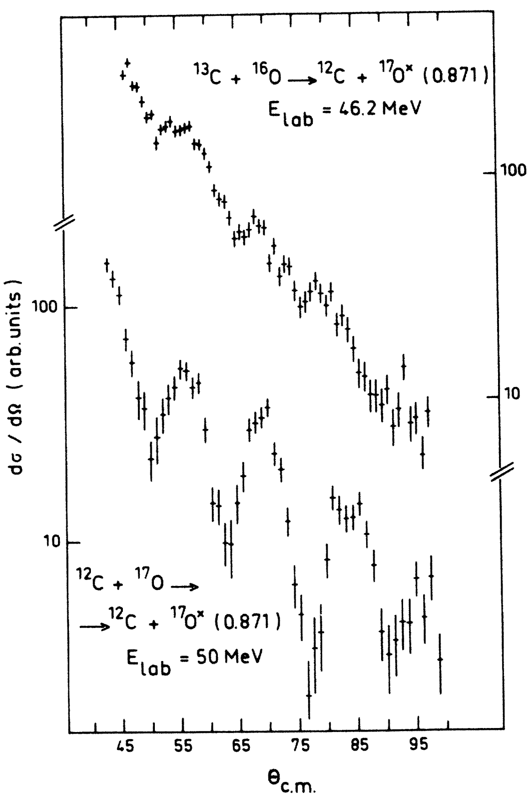

FIG. 6. Angular distributions of the transfer reaction $^{13}C(^{16}O,^{12}C)^{17}O^{*}$ (0.871 MeV) at 46.2 MeV (laboratory) and of the inelastic scattering $^{12}C(^{17}O,^{12}C)^{17}O^{*}$ (0.871 MeV) at 50 MeV (laboratory), see the text.

tegrated data are observed at about 16, 19.5, and 23 MeV, i.e., they display an almost double spacing of about 3.5 MeV. It is not possible to explain this discrepancy in terms of the simple theory.

C. DWBA analysis

We shall now discuss the relevance of the DWBA analysis presented in the preceding paper (Sec. IV) to the evidence for the Landau-Zener promotion mechanism in nuclei. The relevant results are summarized in Fig. 6 of the preceding paper. No coupled-channel effects are included in this DWBA analysis which is one reason which could account for any failure of the calculations to reproduce the experimental data. In spite of this at the two incident energies (50 and 62 MeV laboratory) reasonable fit is easily obtained for the $^{12}C+^{17}O$ reaction leading to the elastic, 2^{+} inelastic of ^{12}C and g.s. neutron transfer exit channels. On the other hand, using the same DWBA code and the same parameters, the calculated values of the inelastic scattering to the 0.871-MeV level of ^{17}O both are not in phase and a whole order of magnitude lower than the experimental data. An extraordinary large $B(E2)$ value for the decay of the 0.871 level to the ground state of ^{17}O would be necessary to raise the calculated angular distribution near its experimental value; even then, however, the calculated cross sections would not be in phase with the measured ones. In fact, as seen from the figure, the DWBA-calculated angular distributions for the ^{17}O inelastic scattering and the $^{13}C+^{16}O$ (g.s.) transfer reaction from $^{12}C+^{17}O$ are in phase, as expected from a surface-peaked transition mechanism; the experimental values for the two transitions are clearly not in phase.

While the above fact could possibly be explained in a variety of ways, it is certainly consistent with the assumption of the existence of a process particularly active in the inelastic scattering to ^{17}O. The enhanced Landau-Zener promotion, expected for this channel, is such a process.

V. SUMMARY OF CONCLUSIONS

The discussion of the data relevant to the possible presence of the nuclear Landau-Zener promotion in C + O collisions has shown two types of evidence: evidence from integrated cross-section measurements (γ yield and angle-integrated charged particle data) and evidence from angular distribution shapes.

The interpretation of the first type of data—structure in the excitation functions of integrated cross sections—is essentially model independent and based solely on the assumption that the Landau-Zener promotion exists and is active in specific reaction channels only; these channels are determined by avoided crossings between levels of the colliding system. The fact that structure in the γ-yield curves of $^{13}C+^{17}O$ is observed only in the $2s_{1/2}\rightarrow 1d_{5/2}$, 0.871 MeV γ transition in ^{17}O and in no other exit channel[11] is a striking piece of evidence that, to our knowledge, has not been explained in any other way but that of the presence of a Landau-Zener promotion. A similar, although less striking behavior of the γ yields measured for the $^{12}C+^{17}O$ system points out in the same direction. The angle-integrated particle data for this latter system, shown in Fig. 5 of the preceding paper, deserve special attention since they permit comparison between transitions to specific final levels; this comparison may have been hindered by the feeding present in the γ-yield data. Structure is present where expected, i.e., in the angle integrated data for the inelastic scattering to the ^{17}O, 0.871 MeV level. The periodicity of the observed structure ($\sim$3.5 MeV c.m.) is, however, roughly the double of that predicted by the semiclassical calculation of Ref. 8 ($\sim$2 MeV c.m.). The origin of the structure observed in the backward angle-integrated data for the $^{17}O+^{12}C$ elastic channel and its relation to the structure observed in the inelastic scattering to ^{17}O is not clear and further investigation will be necessary.

The second type of evidence, that from the inelastic angular distribution shapes, appears to be more model dependent. It is, in fact, based on the assumption that the promotion is localized in space—hence the existence of a critical radius and a critical partial wave. This we expect to be the case for narrow avoided crossings as, e.g., for the $2s_{1/2}$ and the $1d_{5/2}$ ($\Omega=\frac{1}{2}$) levels in the C + O colliding systems. Even in such cases, however, considerable fractions of the transition amplitude may be spread over a large region in space, as suggested by Ref. 9. Hence, one should not expect that the simple critical partial wave rule—translated into squared Legendre polynomial shapes of angular distributions at periodic energies—holds strictly and in all cases. The fact that one sees such regularities is, under these considerations, the more significant, provided that such regularities do not stem from other origins. One of such origins, the possibility that the $P_L^2(\cos\theta)$ regularities come from a simple grazing partial wave effect, seems to be ruled out. In fact, no such regularities have been observed in the inverse $^{13}C(^{16}O,^{12}C)^{17}O^*$ (0.871 MeV) transfer reaction where such an effect of surface peaked interaction should be clearly visible. Last but not least, the failure of the DWBA to reproduce either the phase or the magnitude of the inelastic scattering to $^{17}O(\frac{1}{2}^+)$ while reproducing data for the elastic, inelastic to $^{12}C(2^+)$ and the g.s. neutron transfer for the $^{12}C+^{17}O$ colliding system, is another indication pointing to the presence of a particular mechanism in the inelastic scattering to $^{17}O(\frac{1}{2}^+)$. In view of concurring evidence and in qualitative agreement with the data, we surmise once again that this mechanism is the Landau-Zener promotion.

To summarize, a number of experimental facts, pertaining to data from C + O collisions, seems to relate to the presence of the Landau-Zener nucleon promotion in this colliding system. Some of these data, in the first place the integrated cross section data, have been, to our knowledge, qualitatively explained only in terms of the Landau-Zener promotion. Some other data, while consistent with an explanation in terms of this effect, would allow for concurrent qualitative explanations. The Landau-Zener promotion, however, allows for the largest set of data to be explained within a single frame, at least qualitatively. One should be nevertheless aware of experimental facts like, e.g., the relation of the energy of the "resonant" inelastic angular distributions to the energy of the peaks in the integrated yield curves; such data do not fit into the relatively simple pictures of the promotion mechanisms so far available.

Independent evidence for the Landau-Zener promotion in nuclei, based on the energy behavior of the $^{12}C+^{13}C$ inelastic scattering angular distribution shapes, was reported recently by Imanishi and von Oertzen.[21] The conclusions of these authors point out in the same direction as those of the present paper.

It is clear that the C + O system, although the first to be extensively investigated, is neither the only nor necessarily the best case to be studied. Predictions of signatures of the Landau-Zener effect in systems such as $^{25}Mg+^{16}O$, $^{24}Mg+^{17}O$ and others can be found in the literature;[7] such systems represent obvious areas of future research.

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