EXPERIMENTAL EVIDENCE FOR THE NUCLEAR LANDAU-ZENER EFFECT

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In the description of atomic collisions it is generally valid to assume that the electrons move so rapidly compared to the atoms that they form molecular configurations about the two nuclei during the scattering process. As the system evolves the molecular orbits will pass through points of real or avoided crossings where the electrons can transit from one orbit to another. These so-called Landau-Zener effects are well known in atomic physics. This adiabatic assumption is less justifiable in the case of nuclear collisions as typical collision times are of the same order of magnitude as the rearrangement times and there are few cases where the role of such molecular configurations appears clear. We will discuss experiments which were performed for bombarding energies in the vicinity of 3 MeV/nucleon, which is smaller than the fermi energy and where effects due to molecular configurations may be observable. Evidence will be presented that the results of the experiments can be interpreted in the framework of the Landau-Zener theory [1].

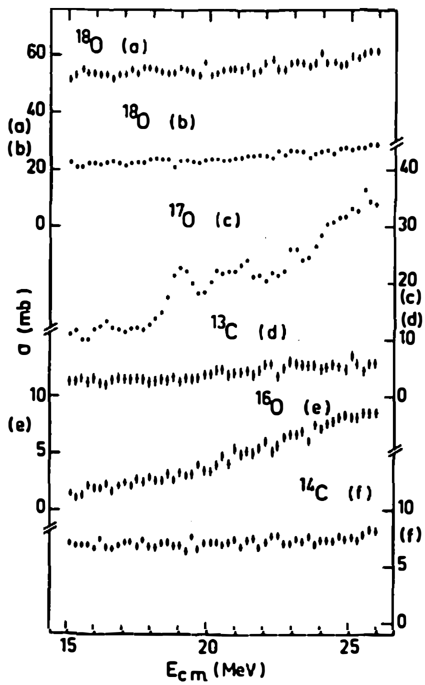

Fig. 1. Some γ-ray yield functions for the $^{13}C + ^{17}O$ reaction including the data for the 871-keV transition of ^{17}O.

The first indications from our data that we had observed nuclear excitations due to the Landau-Zener effect occurred for our studies of the γ-ray yields from the $^{13}C + ^{17}O$ reaction. In similar studies for reactions of the same compound system we had observed resonances in some channels of $^{14}C + ^{16}O$, to a lesser extent for $^{12}C + ^{18}O$, but for the $^{13}C + ^{17}O$ reaction expected to find only structureless yield curves. These expectations were largely borne out by the experimental data, a sample of which is shown in fig. 1. The excitations functions were all smooth except for the yield curve for the 871-keV γ-rays of ^{17}O (fig. 1(c)) where there was quite marked structure. The excitation of the 871-keV level of ^{17}O corresponds to the promotion of the $d_{5/2}$ valence neutron to the $s_{1/2}$ state. It is this type of excitation which can be enhanced by the Landau-Zener effect. There is no apparent reason, however, why this effect would generate structure similar to that observed in the yield curves.

Abe and Park[2] have provided an explanation how the observed structures could arise. Their two-center shell model (TCSM) diagram is shown in fig. 2 illustrating how the single-particule states merge into molecular orbitals as the two nuclei approach each other. The avoided crossing, $\Omega = 1/2$, between the $1d_{5/2}$ and $2s_{1/2}$ orbitals (encircled) is located at approximately the touching distance for these two nuclei. This crossing can therefore be reached without necessarily a strong interpenetration of the two nuclei. Based on this TCSM diagram and the Landau-Zener formalism their explanation for the structures in the excitation functions runs essentially as follows. As the incident energy increases each new partial wave will penetrate to the region of the crossing point and the probability P_{12} for the $d_{5/2}$ nucleon of ^{17}O to be promoted to the $s_{1/2}$ state will increase rapidly. However the total probability P for the transition is given by

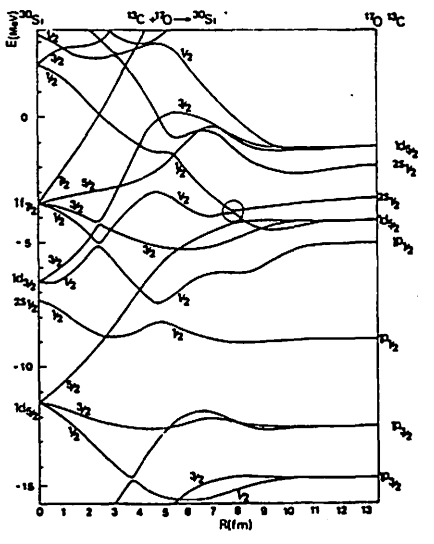

Fig. 2. Two-center shell model diagram for $^{13}C + ^{17}O$.

$$P = 2P_{12}(1 - P_{12})$$

as the crossing point is passed twice during the scattering process, once on the way in and once on the way out. This probability has a maximum of 0.5 for $P_{12} = 0.5$. For larger values of P_{12} the value of P will then decrease as the nucleon will increasingly tend to revert to its initial orbit. It is this behaviour which gives the resonance-like form to the energy dependence of the mechanism.

Abe and Park have estimated the energy position and width of these structures. The resonant energies are given by a function dominated by the term $L(L + 1)\hbar^2/2\mu R_c^2$ i.e. a rotational sequence with moment of inertia μR_c^2 where R_c is the distance of the avoided crossing in the TCSM diagram. There should be approximately 8 of these regularily spaced structures in the energy range covered by the $^{13}C + ^{17}O$ experiment. This is roughly the number of structures which we observed experimentally though they are not as regular as expected from the model. The calculated widths are narrow consistent with the observations but depend sensitively on the details of the crossing points in the TCSM diagram. These predicted structures are not resonances in the usual sense of the term and do not have a Lorenzian shape.

Our next step was to measure the angular distribution of the inelastically scattered ^{17}O nuclei. As far as the Landau-Zener mechanism is concerned the situation should not be very different whether the ^{17}O is inelastically scattered from ^{12}C or from ^{13}C. The TCSM diagrams are schematically similar in both cases. Experimentally however we found important differences between the γ-ray yield curves for the two reactions. For the inelastic scattering of ^{17}O on ^{12}C no structure as pronounced as that in fig. 1(c) was observed. The reason for this is unknown but a possible explanation which could be advanced is that the widths of these structures, being very sensitive to the details of the TCSM diagrams, are wider and more smeared out in the case of $^{12}C + ^{17}O$ reaction. However for the angular distribution measurements the $^{12}C + ^{17}O$ reaction was chosen being the simpler of the two reactions experimentally ; for $^{13}C + ^{17}O$ there are a larger number of competing open channels.

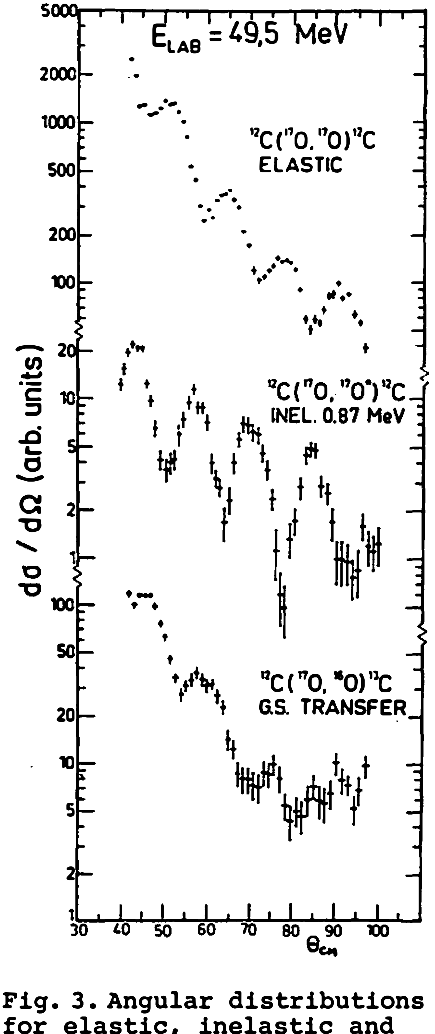

Fig. 3. Angular distributions for elastic, inelastic and transfer channels of $^{12}C + ^{17}O$.

The $^{12}C + ^{17}O$ experiment was performed with ^{17}O beams ranging in incident energy from 40 to 51 MeV in steps of 0.5 MeV. A 20 μg/cm² natural carbon target was used and the scattered particles were detected in kinematic coincidence in two position-sensitive silicon detectors. One detector was placed at lab. angles covering 18° to 48° and the other from 38° to 68°.

In the sum energy spectrum ($E_3 + E_4 = E_{in} + Q$) the elastic peak was flanked by the transfer channel to the ground states of ^{16}O and ^{13}C (Q = 802-keV) and the inelastic channel (Q = -871-keV). The angular distributions for these three channels at an incident energy of 49.5 MeV are shown in fig. 3. The inelastiç angular distributions were strongly structured at all energies and out-of-phase with the elastic, consistent with the Austern-Blair phase rule. They were particularily strong around 49.5 MeV where over the experimental range of angles the distribution could be approximately fitted with a $P_L^2(\cos\theta)$ shape with L = 13. At 46.5 MeV the angular distribution was mainly L = 12. These results could be anticipated from the Landau-Zener effect as the enhancement of the inelastic cross section is due preferencially to a single partial wave. The L value of these partial waves will be given by

$$L = kR_c = \frac{1}{h}\sqrt{2\mu(E-V_{CB})}\cdot R_c$$

From a TCSM calculation for the $^{12}C + ^{17}O$ system a value R_C = 7.8 fm is obtained giving L = 14 and 15 for bombarding energies 46.5 and 49.5 MeV respectively. The difference between these values and those deduced from the angular distributions could reflect the change in J of ^{17}O by two units during the scattering, depending on a more detailed understanding of how the angular momenta couple.

Our evidence for the Landau-Zener effect is based on the rather unusual energy dependence of the inelastic excitation of ^{17}O in its interaction with ^{13}C and on the strongly structured angular distributions of the same inelastic excitation of ^{17}O on ^{12}C. Our studies are continuing. On one hand we plan to investigate the extent to which DWBA calculations can reproduce our experimental data. Such calculations will not reproduce the structures of the excitation functions but will reproduce some of the features of the particle angular distributions. On the other hand the $^{12}C + ^{17}O$ experiment has been extended over a larger range of incident energy and we have also studied the $^{13}C + ^{16}O$ reaction leading by transfer to the same excited state of ^{17}O. These experiments are in the course of analysis.

1. J.Y. Park, W. Greiner and W. Scheid, Phys. Rev. C21 (1980) 958.

2. Y. Abe and J.Y. Park, Phys. Rev. C28 (1983) 2316.