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Final Remarks on the Material Presented in the Circus Session

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As stated at the beginning the survival of the cluster structure of two colliding nuclei is both influenced by the internal structure of the nuclei and by the relative kinetic energy. Concerning this last quantity the really relevant order parameter determining the evolution of Di-Nuclear systems is the angular momentum. We would like to have answers to the question, what is the lifetime of the Di – Nuclear complex? The answer could be expressed in seconds, or for given angular momentum by a rotation angle.

Inspecting the data shown in the first talk by D. Shapira we notice that, simultaneously to the low lying inelastic states of the individual clusters, a broad continuum of states is observed, generally addressed to as deeply inelastic scattering. The energy is dissipated to the lowest possible value compatible with two nuclear (deformed) shapes separating by the Coulomb repulsion. The physical notion of orbiting as suggested by Wilczynski's diagram is applicable to these events and the angle of rotation can be read from the Wilczynski diagram. In this case the interaction time is long and for these impact parameters with large overlap (smaller angular momenta) very fast dissipation of energy occurs. For slightly larger angular momenta excitation of low lying collective states of two nuclei is observed. The inclusive energy spectra shows the whole energy range of excitation, up to values where both of the nuclei are excited up to states above the α-particle emission threshold.

The transition from low lying inelastic excitations to the break-up channels is determined by the strong clustering aspects in the structure of the two nuclei. The lowest thresholds for break-up are in particularly relevant for the sequential break-up into α-particles. However, also the direct break-up is determined by the cluster structure, namely by the probability of a certain substructure in the wave function of the ground state. The distinction of the two processes is experimentally a quite difficult task as explained by Wilczynski.

For the Di-Nuclear resonances connected to the inelastic excitations, the angular momentum balance of the surface partial waves coupled to the spins of the excited states gives rise to favoured situations, when the spins of the intrinsic states align in a particular way. The most direct access to the spin structure of the resonances is obtained by the measurement of spin variables (polarization and alignment). It is possible, as shown by Konnerth, that the energetically favoured Di-Nuclear complex for deformed nuclei can be singled out from the spin alignment measurements. The spin alignment of the two clusters suggests that a rather longlived Di-Nuclear complex is formed, which could be interpreted as a super-deformed nucleus (ratio of the axes being 3:1) consisting of two deformed clusters. Similarly in the model of Uegaki and Abe the Di-Nuclear complex is considered as an entity. They introduce variables for the rotation of the system as a whole, as well as for intrinsic excitation of the Di-Nuclear molecule. In this way a very rich spectrum of vibrational and rotational states of the total system can be calculated. This approach will possibly be able to account for the large number of "states" observed in the excitation function of the systems like $^{24}Mg+^{24}Mg$ or $^{28}Si+^{28}Si$. The role of the Coriolis interaction still has not been considered in these cases. However, we notice a strong evolution towards concepts used in super-deformed nuclei at high spin, which can be viewed as a particular case of a Di-Nuclear complex. This points to the important role of angular momentum and Coriolis coupling will play in the final description of these processes.

Considering single particle motion, we find that adiabaticity can be expected as long as the total angular momentum and thus Coriolis-coupling is small. For energies close to the Coulomb barrier rotating molecular orbitals (defined again in the rotating frame of the Di-Nuclear complex) can be formed. As a particular signature of molecular orbital formation for valence particles the transitions between orbitals at avoided crossings has been discussed quite often. It turns out that they may be possibly observed as fast changes in particular angular distributions close to the Coulomb barrier (systems $^{12}C+^{13}C$, $^{13}C+^{14}C$, discussed by von Oertzen). With increasing energy and increasing relative angular mometnum Coriolis coupling causes the break-down of the adiabatic scheme (similar to rotational dealignment in odd-mass-deformed nuclei) and the experimentally observed cross sections can be well described by DWBA calculations up to second order. Nucleon promotion is found to give a smooth energy dependence for integrated cross sections mainly for two reasons, i) the fast evolution of the correlation diagrams with angular momentum, in such a way that avoided crossings are not spatially fixed, ii) quantal effects and interference effects give an overall width in energy, which does not allow the observation of structures in excitation functions (this is in contrast to the originally claimed observations of the Landau-Zener process which were shown to be incorrect). Transitions at avoided crossings must be described by a coupled reaction channel calculation, because the "Landau-Zener"-formula as a first order perturbation expression is generally incorrect (as remarked by Milek).

We may conclude that the experience gained with dynamics of the Di-Nuclear complex with light systems, where detailed studies could be performed, may furnish as the tools and concepts to study similar phenomena in heavier systems. It is my belief that interesting physics lies in front of us in this field.