Proceedings of

BARN 92

Biological Applications of Relativistic Nuclei

Clermont-Ferrand, october 14-15-16, 1992

Edited by J.P. ALARD and J.C. MONTRET

LABORATOIRE DE PHYSIQUE CORPUSCULAIRE

UNIVERSITE BLAISE PASCAL IN2P3 CNRS

63177 AUBIERE CEDEX

PCCF RI 9308

DESCRIPTION OF HEAVY ION REACTIONS[1]

Joseph CUGNON
University of Liège
Institute of Physics B.5
Sart Tilman
B-4000 Liège 1
(Belgium)

The nuclear reactions between nuclei (or heavy ions) play an important role in heavy ion transport in materials, be them of biological or spatial interest : as a matter of fact, the probability of having a nuclear reaction along the total path of an incoming ion is non negligible (~ 0.3 for a ^{12}C ion of 200 MeV/u in water) and the specific ionisation along this path is influenced by these reactions [1,2].

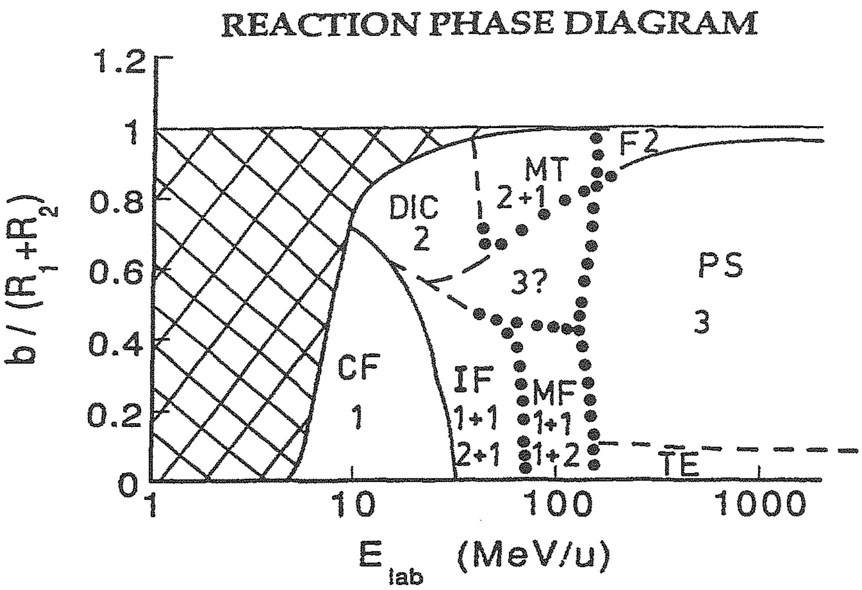
The various reaction mechanisms encountered in the energy domain extending from 10 MeV/u and 2 GeV/u are depicted schematically in fig. 1, where E_{lab} is the energy per nucleon of the incident projectile and b , the impact parameter of the collision. At low energy and in central collisions (small b), a compound nucleus (complete fusion, CF) is formed, which recoils with the momentum of the projectile and evaporates a few slow neutrons. In deep inelastic collisions (DIC) occurring in peripheral collisions (large b), the projectile sticks to the target for a while and eventually escapes, emerging at angles smaller than the grazing angle. The relative motion is considerably damped leading to mass and charge exchange between the two partners and to their internal excitation, which is followed by neutron emission.

At high energy and large b , the projectile barely touches the target but receives sufficient energy (but no momentum) to break into pieces which travel at very small angle, with roughly the incident velocity (this is the fragmentation (F) process). For small b's, there is a geometrical separation of the system. The part of the projectile which is not intercepted by the target continues undisturbed. Similarly, the part of the target which is not intercepted by the projectile remains almost at rest. There is a complete stopping between the two parts that intercept each other, leading to a very excited system which explodes in nucleons and very light particles. This process is referred to as the participant-spectators (PS) regime.

In the intermediate energy regime, at large impact parameters, one goes continuously from the DIC, where nucleons are exchanged between the two partners, to the massive transfer (MT), where a piece of the projectile is transferred to the projectile, while the rest continues almost undisturbed, and to the fragmentation regime. At low impact parameter, one goes continuously from CF, to incomplete fusion (F), in which only one part of the projectile participates to the

[1]Work supported by contract SPPS-IT/SC/29

fusion process, whereas the rest leads to copious light particle emission, to multifragmentation (MF), in which the fused system decays by emission of several intermediate mass ($3 \leq Z \leq 20$) fragments, and finally to the PS regime. In all this series of processes, there is always formation of a fused system, but its decay properties vary with excitation energy, leading to the various kinds of reactions.



Reaction "phase diagram" giving the various reaction mechanisms and their location in the incident projectile energy per nucleon (E_{lab}) - impact parameter (b) plane. Nuclear reactions are absent in the shaded area. The meaning of the abbreviations is given in the text. The figures in each zone indicate the number of primary fragments. The separations indicated by dotted lines are known with some uncertainty. Those indicated by dots correspond to presumably smooth transitions. See text for detail.

These reaction mechanisms are reasonably well understood theoretically in terms of mean field effects, dominant at low energy, and nucleon-nucleon collisions, dominant at high energy [3, 4]. The theoretical models handling these two dynamical aspects predict a smooth variation of the relative importance of these two effects throughout the plane of Fig. 1. What distinguishes the various mechanisms is in fact the number and the relative size of the "primary" fragments, i.e. the clusters present at the end of the collision process itself and prior to any fragmentation or evaporation processes. The numbers of the primary fragment is indicated in Fig. 1. For instance, the CF leads to a single primary fragment and the PS corresponds to three primary fragments. When two numbers are given with a plus sign in between, the first one refers to the number of large fragments and the second to the number of small fragments. For instance, the IF produces sometimes one large and one small, and sometimes two large and one small primary fragments.

More details on the reaction mechanism can be found in refs. [3, 5, 6]. We here want to emphasize the classification based on the number of primary fragments and the continuous aspects of the dynamics : fused system formed at any energy, smooth variation of mean field and collision effects.

Whatever the mechanism is, fragments are basically emitted in the forward direction for energies of biological interest. The study of transport properties inside material thus requires mainly the knowledge of fragment yields. The theory of heavy ion reactions yield predictions which are reasonably reliable for the general flow of nucleons in phase space, but not so much for the production of a specific nuclear species. Briefly speaking, theoretical models can tell that so many nucleons are emitted in a given angle-energy interval, but they cannot tell reliably whether these nucleons are free or whether they form one or two clusters. Absolute measurements are thus eagerly needed. The theoretical models are however useful for neutron production, whose cross section has received so far few attention from the experimental side.

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