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EVIDENCE FOR NUCLEAR MATTER TRANSPARENCY IN CENTRAL HEAVY-ION REACTIONS FOR LIGHT SYMMETRIC SYSTEMS AROUND THE FERMI ENERGY

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Rapport Interne SUBATECH 99-09

Talk presented at the 7th International Conference on Clustering Aspects of Nuclear Structure and Dynamics June 14-19, 1999, Rab, Island of Rab, Croatia

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EVIDENCE FOR NUCLEAR MATTER TRANSPARENCY IN CENTRAL HEAVY-ION REACTIONS FOR LIGHT SYMMETRIC SYSTEMS AROUND THE FERMI ENERGY

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Reaction mechanisms in central heavy-ion collisions around the Fermi energy are investigated within the Landau-Vlasov semiclassical transport model. It is shown that the reaction dynamics precludes the formation of a fusion nucleus: In head-on collisions, a transition from fusion process to binary mechanisms occurs. A pure nuclear transparency is underlined for light symmetric systems around the Fermi energy. For medium-heavy systems, the memory of the entrance channel still exists but, in addition, dynamical multifragment production is observed. These predictions are qualitatively consistent with recent experimental observations.

1 Introduction

In the Fermi energy domain, the main mechanism observed in heavy-ion reactions around the Fermi energy is of binary nature. [1,2] However, the classical fusion process still contributes by a small part of the reaction cross section and it is restricted to the most central collisions. [3] By classical fusion we refer to a process leading to the formation of a single cold residue at the end of the reaction. At low incident energies (below 15 MeV/nucleon), the fusion mechanism is complete and fusion nucleus decays by the standard evaporation process. With increasing incident energy, the fusion becomes more and more incomplete owing to pre-equilibrium emission. Moreover, the classical fusion cross section decreases and vanishes around 50 MeV/nucleon. This trend has been observed in various experimental studies [3] and confirmed by very recent data for the symmetric Ar+KCl system at incident energies ranging from 32 to 74 MeV/nucleon. [4,5] It has been found that the classical fusion cross section is about 40 mb at 32 MeV/nucleon and decreases rapidly to zero for incident energies higher than 50 MeV/nucleon. Similar results have been obtained for the slightly asymmetric system Ar+Ni. [6]

Two interpretations are propound to explain the vanishing of classical fusion: *i*) Opening of new decay channels for the fusion nucleus, such as the evaporation of intermediate mass fragments (IMF) or the so-called multifragmentation process; the fusion process still exists and the vanishing of fusion is an exit channel effect. *ii*) The reaction dynamics precludes the formation of the fusion nucleus; the fusion disappears owing to an entrance channel effect. In this work we are going to show that in the frame of the Landau-Vlasov (LV) dynamical model, [7] a transition from the classical fusion process to the binary mechanism (BM) is predicted in head-on collisions around the Fermi energy. Obviously, in such a scenario, the fusion process really disappears.

The LV model [7] is based on the quantum Boltzmann equation which is solved for a nonlocal effective force (Gogny D1-G1) [8] by projecting the one-body nuclear phase space onto a continuous basis of thousands (here 60 to 100 per nucleon) of coherent states taken as elementary Gaussian functions. One of the main ingredients of the model is the residual nucleon-nucleon (NN) cross section $\sigma_{\rm NN}$ that acts through the collision term. In the simulations presented in this work, the free nucleon-nucleon cross section with its usual energy and isospin dependence was chosen. In-medium effects are studied in [9]. Several symmetric systems with a total mass ranging from 32 up to 250 were investigated for incident energies ranging from 10 MeV/nucleon up to 50 MeV/nucleon. In this paper we focus mainly on the light Ar+Ar system as it has recently been studied by the INDRA collaboration. Preliminary results are also shown for the medium-heavy systems Ag+Ag and Xe+Sn.

2 Transition from fusion to the binary mechanism: the case of light symmetric systems

Figure 1 shows the simulation results for the Ar+Ar head-on collisions at two incident energies: 29 MeV/nucleon (left column) and 30 MeV/nucleon (right column). This figure allows to clearly illustrate the transition from fusion to BM predicted by the model. Indeed, at 29 MeV/nucleon, a single fusion residue is present at the end of the reaction. However, a large deformation of dinuclear type persists for a long period which finally recontracts itself. This deformation has already been observed in calculations carried out at slightly lower incident energies, but it develops with increasing incident energy up to the rupture which occurs at 30 MeV/nucleon (see the bottom panel of the right column). In this case, two spherical nuclei emerge from the reaction around 150 fm/c. Moreover, the grey scale shows a weak mixing between the nucleons of the projectile and the target, proving a strong memory of the entrance channel.

This mechanism implies an important degree of nuclear matter trans-

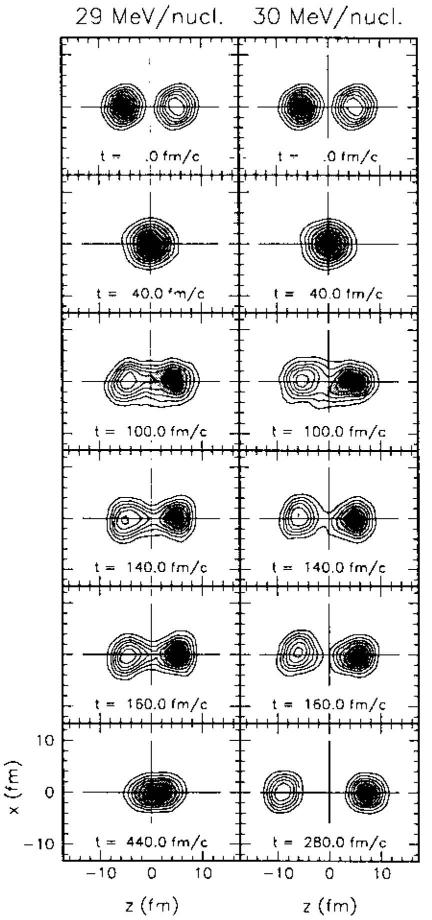

Figure 1. Equidistant density-profile contours in the configuration space at several times of the reaction projected onto the reaction plane for Ar+Ar head-on collisions at 29 MeV/nucleon (left column) and at 30 MeV/nucleon (right column). Curves refer to the whole system, whereas the scale of grey shows the projectile matter density. The z axis is along the projectile direction.

parency, a scenario which has already been mentioned in several works [3] in order to qualitatively explain experimental observations. However, neither experimental quantitative probes nor careful theoretical studies have been performed on this subject yet. A remark concerning the memory of the entrance channel can also be made at 29 MeV/nucleon. Indeed, as shown in the left column of figure 1, there is a slow shape relaxation and a few nucleon mixing over a large period of spatial rearrangement lasting several hundreds of fm/c. Thus, the fusion nucleus, detected at the end of the reaction, can be rigorously considered as a fully thermalized compound nucleus only beyond this period. Such dynamical effects are generally not taken into account, as

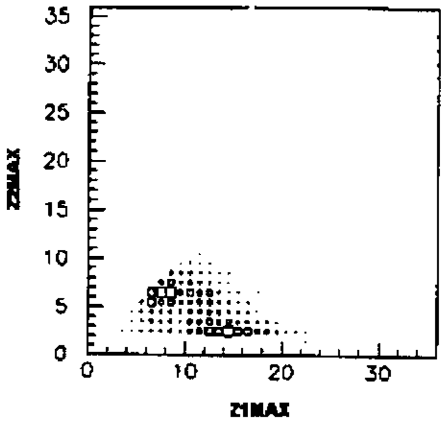

Figure 2. Charge of the second largest fragment Z2MAX versus the charge of the largest fragment Z1MAX for the Ar+KCl system at 32 MeV/nucleon. The analysis is carried out only for the so-called well-measured events [5] and restricted to the most central collisions which are selected by global variable analysis.

the deexcitation of fusion nucleus is described using statistical models in which the equilibration of all degrees of freedom is assumed from the very early instants of a collision. [10] Study of the heavier Ni+Ni system displays the same trend, but the fusion/BM transition occurs at a slightly higher incident energy (between 31 and 32 MeV/nucleon). That is not so surprising since the nuclear matter which has to be passed through is larger in the case of Ni+Ni in comparison with the Ar+Ar system.

The value of the transition energy deserves two comments: *i*) The transition energy is strongly dependent on the nucleon-nucleon cross section. [9] Thus, it could be a right observable to infer on in-medium effects. *ii*) There are no fluctuations in the code; the model is able to provide only an average value for the transition energy between fusion and BM. Obviously, any sharp transition will never be found experimentally: The fusion process is present up to higher incident energies, although with a sharply decreasing weight [4,5] which cannot be predicted within the frame of deterministic calculations such as provided by the LV model.

3 Experimental indications

The recent INDRA experimental results on the Ar+KCl reaction could be in agreement with the above scenario. Figure 2 displays the yields of two largest fragments as a function of fragment charge. [5] In this plot one distinguishes two components. The component with the large values of Z1MAX and the small values of Z2MAX corresponds to events in which a single fusion residue is detected and can be attributed to classical fusion. The other component is characterized by two main fragments with approximately the same charge (Z1MAX≈Z2MAX) and could be attributed to BM such as observed in the model. The latter component was interpreted in [5] in terms of dynamical fission of the fusion residue, a rather surprising mechanism for such a light system. Let us add that at 32 MeV/nucleon, the experimental cross section associated to each component is found to be approximately the same: 43 and 44 mb, respectively. Moreover, from the same plots at 40, 52, and 74 MeV/nucleon one infers that the classical fusion component disappears progressively, while at the same time the BM component is always present but with a diminishing average values of Z1MAX and Z2MAX [5] (probably due to an increasing contribution of dynamical emission [11]). Both the presence of binary processes after selecting very central collisions at 32 MeV/nucleon and the disappearance of classical fusion events with increasing incident energy qualitatively endorses our simulation predictions.

4 Transition from fusion to binary mechanism: the case of medium-heavy systems

It is intriguing to extend this study to heavier systems. Figure 3 shows the simulation results for the Ag+Ag (top) and the Xe+Sn (bottom) systems in head-on collisions. At 45 MeV/nucleon (left top panel), there is still a fusion residue (the comments concerning the slow shape relaxation and the few nucleon mixing remaining valid). At 50 MeV/nucleon (right top panel), there are two main fragments in the exit channel showing that transparency effects still exist for this heavier system (see also the grey scale). However, there is a major difference in comparison with light systems: a multifragment emission occurs in-between the two main fragments. This multifragment production is much clearer for the Xe+Sn system at 50 MeV/nucleon as can be seen in the right bottom panel of the figure. Since our study of heavy systems is at the beginning, one cannot draw any definitive conclusions. However, let us make two comments: *i*) It seems that there is a limit in the system size if the pure transparency with no IMF in-between the two outgoing nuclei is to be observed. *ii*) From the above figures of central collisions, the multifragment production appears as an induced dynamical process rather than a process following the formation of a fully equilibrated fusion nucleus. Let us mention that the dynamical production of fragments in the Xe+Sn system at 50 MeV/nucleon has recently been investigated by the INDRA collaboration. [12]

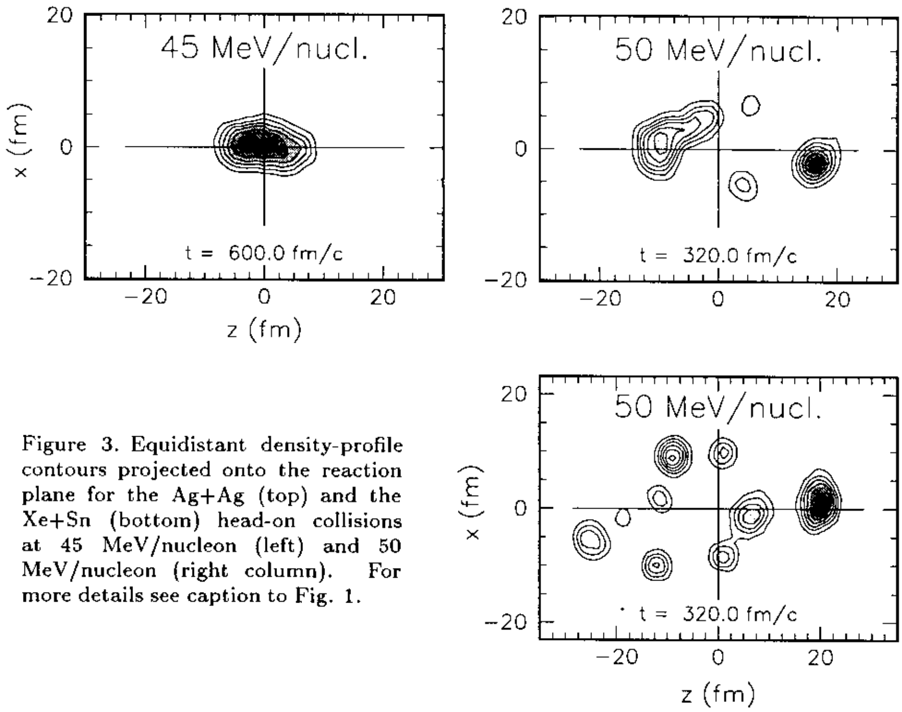

Figure 3. Equidistant density-profile contours projected onto the reaction plane for the Ag+Ag (top) and the Xe+Sn (bottom) head-on collisions at 45 MeV/nucleon (left) and 50 MeV/nucleon (right column). For more details see caption to Fig. 1.

5 Conclusion

We have found that the vanishing of fusion is due to dynamical effects: the binary mechanism becomes the dominant process up to the most central collisions. For light symmetric systems, we observe an effect of pure nuclear transparency which leads to the formation only of two massive fragments in the exit channel of the reaction, a quasiprojectile and a quasitarget. For heavier systems, the transparency is also observed in the sense that two remnants of the projectile and of the target are present. In addition, a number of fragments are also produced in the neck region between the two remnants. This effect is of dynamical origin and the dynamical multifragment production seems to be related to the size of the system. The system-size limit for the onset of the multifragment production has to be precised and a comparison with experiment has to be performed. It will also be interesting to study the same phenomena in asymmetric systems. Let us underline that the above predictions are qualitatively consistent with experimental observations, particularly with the recent results of the INDRA collaboration on the Ar+KCl and Xe+Sn systems. Nevertheless, more quantitative comparisons are needed, especially to experimentally probe the existence of pure nuclear transparency for light systems.

6 Acknowledgments

It is a pleasure to thank Prof. F. Sébille for supplying us with the Gogny version of the Landau-Vlasov computer code.

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