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# DYNAMICAL INSTABILITIES IN HOT EXPANDING NUCLEAR SYSTEMS : A MICROSCOPIC APPROACH TO THE UNDERSTANDING OF MULTIGRAGMENTATION

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DYNAMICAL INSTABILITIES IN HOT EXPANDING NUCLEAR SYSTEMS : A MICROSCOPIC APPROACH TO THE UNDERSTANDING OF MULTIGRAGMENTATION

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ABSTRACT

We present a microscopic study of the quasi-fusion/explosion transition in the framework of Landau-Vlasov simulations and for intermediate energy heavy-ion collisions (beam energy from 10 to 100 MeV/A). After a short presentation of the results of schematic calculations, which furnish a guideline for microscopic investigations, we discuss the relevance of our approach for studying multigragmentation. Once the limitations of this kind of dynamical simulations exhibited, we perform a detailed analysis in terms of the equation of state of the system. In agreement with schematic models we find that the composite nuclear system formed in the collision actually explodes when it stays long enough in the mechanically unstable region (spinodal region). Quantitative estimates of the explosion threshold are given for central symmetric reactions (Ca + Ca and Ar + Ti). The link of the results with transport properties and the equation of state of nuclear matter are briefly discussed.

* This paper covers joint work with D. Cussol, Ch. Grégoire, M. Pi, B. Rémaud, F. Saint-Laurent, P. Schuck and F. Sébille. This work will be published later. The present author is solely responsible for the way it is discussed here.

## I. INTRODUCTION

The disintegration of an excited nuclear system into Intermediate Mass Fragments (IMF) is currently one of the most exciting fields of activity in intermediate energy heavy-ion physics (E/A ~ 10-100 MeV/A) (See Ref. 1) for a recent review). On the experimental side the development of 4 $\pi$ detection should allow for a more exclusive description of IMF's and possibly offer clues on the mechanism responsible for the explosion of the initial system. From a theoretical point of view many approaches have been studied, leading to partial understandings of multifragmentation. In static models a phase space balance allows to reproduce fragment yields but does not give any information on the physical mechanism responsible for the explosion[2)]. On the other hand exploratory dynamical calculations have been performed either in mean-field or extended mean-field frameworks [3,4)], or in molecular dynamics-like models[5)]. These approaches however lack for a clear definition of their theoretical background and it is hence difficult to disentangle between numerical and physical effects. As only microscopic dynamical calculations can presumably allow a deep understanding of multifragmentation it seems useful to try to relate them to the possible scenarios of the break up of the nucleus, which can be figured out from schematic models[6,7)]. This could in particular give a safer basis to the actual links of multigramentation both with the Equation Of State (EOS) and with the transport properties of nuclear matter.

We have investigated the fusion/explosion transition using a numerical simulation of the extended mean-field Landau-Vlasov Equation (LVE) [1,8)] and performing an analysis of the reactions in terms of the spinodal region[6,7)]. We show, in agreement with schematic models that explosion does occur when the excited nuclear composite system stays long enough ($\gtrsim$ 120 fm/c) in the region of mechanical instability (spinodal). Due to our microscopic description we are able to take consistently into account finite size and dynamical effects such as in particular the energetic emission of preequilibrium particles, which strongly influence the energy balance of the reaction.

## II. THE SPINODAL ANALYSIS

Due to the short time scales involved, composite systems formed during heavy-ion collisions presumably explode via dynamical instabilities and a scenario of the transition can be roughly figured out from schematic models[6,7)]. In these models it was shown that, if

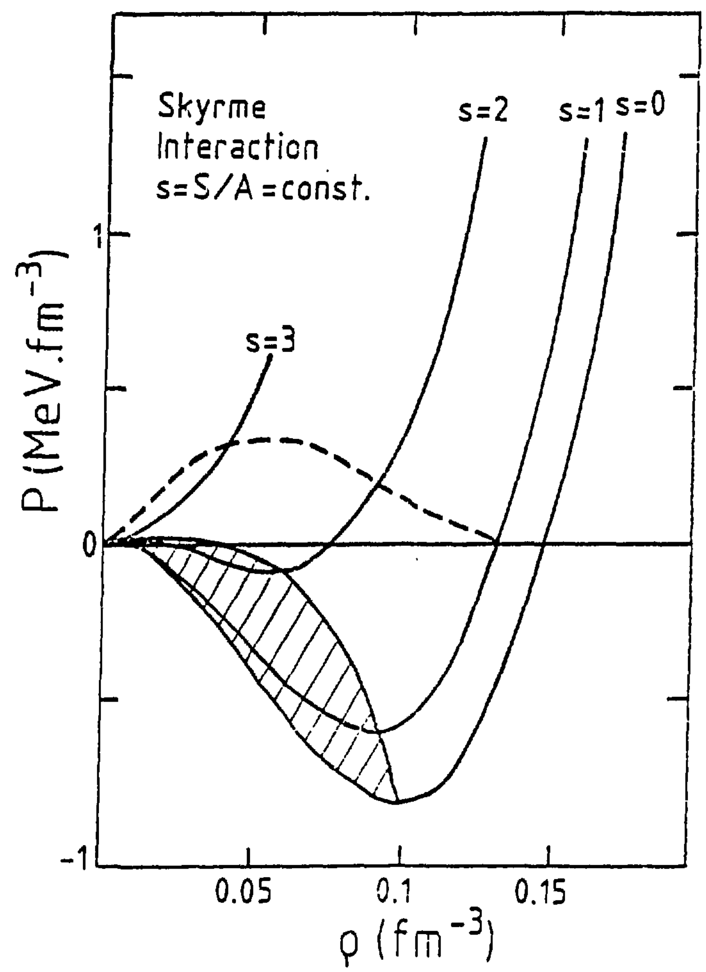


Fig. 1 : Schematic representation of a typical Equation Of State $P(\rho)$ (pressure P (in MeV $fm^{-3}$) versus density $\rho$ (in $fm^{-3}$)) obtained with a Skyrme force. We have indicated 4 isentropic lines (S/A = 0,1,2 and 3 in Boltzmann constant unit) and the isentropic spinodal region (hatched area). Also is shown for completeness the liquid-gas coexistence line (dashed line).

one assumes that the expansion of the initially compressed system is isentropic, the actual explosion occurs when the system crosses the isentropic spinodal line, namely enters a region of mechanical instability (Fig. 1). More precisely as was recently investigated by Pethick and Ravenhall [7)] entering the spinodal region is a necessary but not sufficient condition for the excited nucleus to explode. Indeed the spinodal region is a region of the EOS in which even small fluctuations are able to disrupt the system ; that is, provided the nucleus stays long enough in the unstable region any small density fluctuation may grow up to be comparable in size to the actual nuclear density hence breaking the system into pieces. In this picture two quantities govern the whole phenomenon : the transit time in the spinodal region $\Delta t_s$, which bears a memory of the whole dynamical evolution and the growth rate of instabilities $\Gamma$, directly connected to the sound velocity and hence to the EOS and to transport properties. A criterion of explosion is then given by the value of the integral $I = \int_{\Delta ts} \Gamma \, dt$, as shown in ref. 7).

A quantitative description of the fusion/explosion threshold however requires microscopic simulations of nucleus-nucleus collisions and we now turn to briefly describe them.

## III THE LANDAU-VLASOV EQUATION

For sake of completeness let us recall the framework of the calculation. The Landau-Vlasov equation is an extended mean field kinetic equation (namely in which two body collisions are taken into account) for the one body phase space (Wigner) distribution function $f(\vec{r}, \vec{p}, t)$. It reads

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m} \cdot \vec{\nabla}_r f - \vec{\nabla} U(\vec{r}) \cdot \vec{\nabla}_p f = I_{coll}[f] \qquad (1)$$

in the case of a local mean-field potential $U(\vec{r})$.

We actually use oversimplified Skyrme interactions for this mean-field part. Their parameters $(t_0, t_3)$ have been fitted to reproduce nuclear matter saturation properties ($\rho_0 \simeq 0.15$ fm$^{-3}$, $E/A = -16$ MeV and compressibility $K_\infty \simeq 200$ MeV). In Eq. (1) $I_{coll}[f]$ stands for the collision integral which is expressed in the Uehling-Uhlenbeck approximation[8] :

$$I_{coll}[f(\vec{r},\vec{p},t)] = \frac{1}{2m^2\pi^3 h^3} \int d\vec{p}_2 \, d\vec{p}_3 \, d\vec{p}_4 \, \frac{d\sigma}{d\Omega}$$

$$\delta(\vec{p} + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \; \delta(p^2 + p_2^2 - p_3^2 - p_4^2)$$

$$\{(1-\bar{f})(1-\bar{f}_2)\bar{f}_3\bar{f}_4 - (1-\bar{f}_s)(1-\bar{f}_4)\bar{f}\bar{f}_2\} \qquad (2)$$

where the $\bar{f}$ represent occupation numbers and $f_i$ stands for $f(\vec{r},\vec{p}_i,t)$.

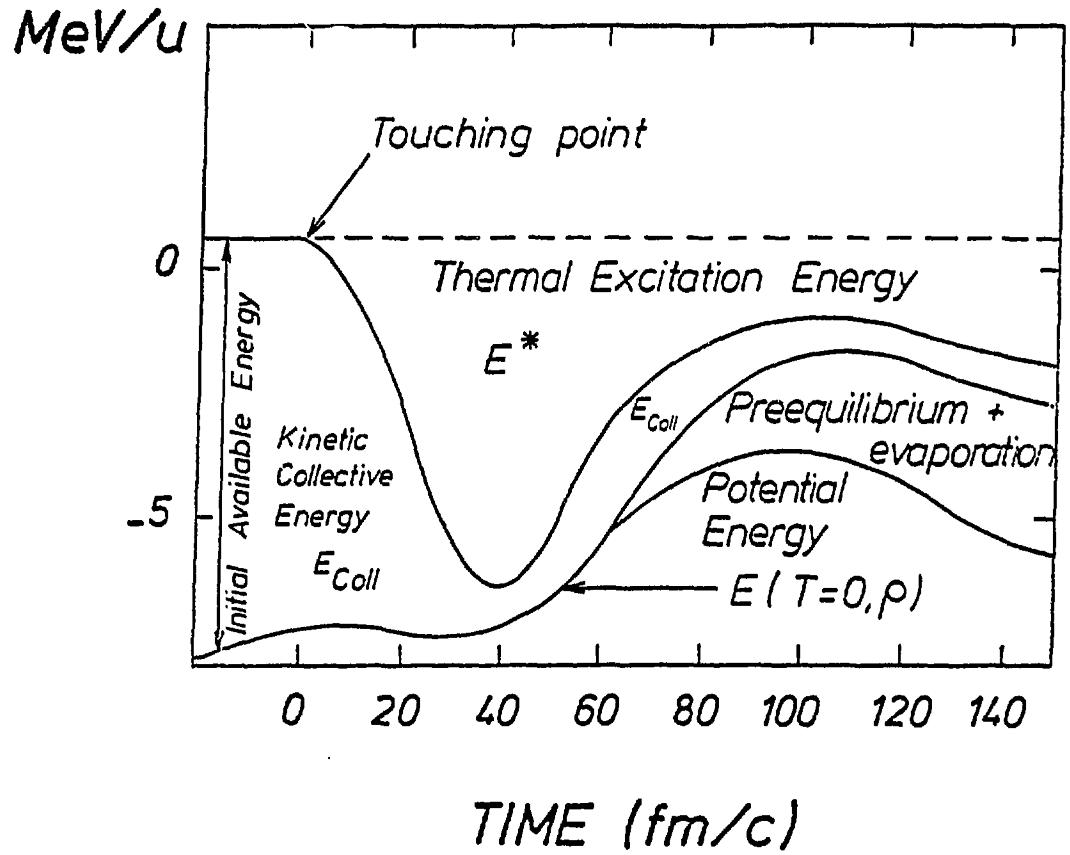


Fig. 2 : Energy transfers in an head on $^{40}Ar$ + $^{197}Au$ collision at 60 MeV/A bombarding energy. The time evolution of the thermal and compressional excitation energies can be seen from this figure (see also section 4). Also is indicated the preequilibrium component which strongly affects the global energy balance.

Equation (1) together with the collision term Eq. (2) has been extensively studied in the past few years by various groups and we refer the reader to their results for more details (9,10 and 11 for a review).

A typical result of Landau Vlasov calculations, showing the crucial importance of dynamical effects in the formation of excited nuclear systems, is presented in figure 2. Note the complex splitting of the initially available energy (namely the kinetic energy of the beam) between thermal and potential excitation energies as well as the strong preequilibrium component. Let us however stress, at that point, that the Landau Vlasov equation has been, up to now, simulated rather than truly solved. These simulations are based on so called particle methods in which the one-body distribution is projected on a swarm of test particles evolving in time according to classical equations of motion. Although some of these approaches actually represent a good approximation to the exact equation, as was recently shown in the case of the Boltzmann equation[12), two body collisions are treated in an Intra Nuclear Cascade way[10), hence introducing a stochastic component not present in the original collision integral (Eq. (2)). Two test particles do indeed collide if they encounter, during a given time step $\Delta t$, a distance of closest approach smaller than $\sqrt{\sigma_{NN}/\pi}$ ; in that case their new momenta are randomly chosen within preserving momentum and energy conservation which amounts to introduce two (free) random angles. As a consequence, this kind of simulations essentially violate the deterministic nature of the Landau-Vlasov equation. While this may be of minor importance in several situations, such as for example the way to equilibrium, it has to be kept in mind when considering phenomena such as multifragmentation, in which the disruption might be connected to a growing of instabilities. Let us hence briefly figure out the possible limitations of our approach.

For sake of clarity we schematically split the expected scenario of explosion (see section II) into 4 steps : i) the "entrance channel" which leads to an excited, compressed nucleus starting to expand ; ii) the presence of fluctuations which could constitute the seed for the growing of an unstable mode once in the spinodal region ; iii) the growing of the instability itself and iv) the clusterization which corresponds to the actual separation of the system into several fragments. Both steps i), iii) and iv) are within the range of applicability of the Landau Vlasov equation as they are essentially related to the mean field Equation of State and to an averagering over 2-body collisions. Steps i) and iii) can be reasonably well described in any test particle method while step iv) can only be achieved in simulations in which no average is performed over parallel simulations. When parallel ensemble calculations[10) are performed the resulting mean field is averaged over a large number of simulations so that it is completely smooth and does not allow for clusterization inside a given run. This in constrast is not the case in the so called full ensemble technique developed by the french group[9,12). Step ii) finally, is not contained in the Boltzmann equation but does exist in nature. Note however that an extension of the Boltzmann equation has recently been proposed for remedying to this problem[13) by adding a fluctuating component to the "average" collision integral (Eq. (2)). In the actual simulations fluctuations however are present and have 2

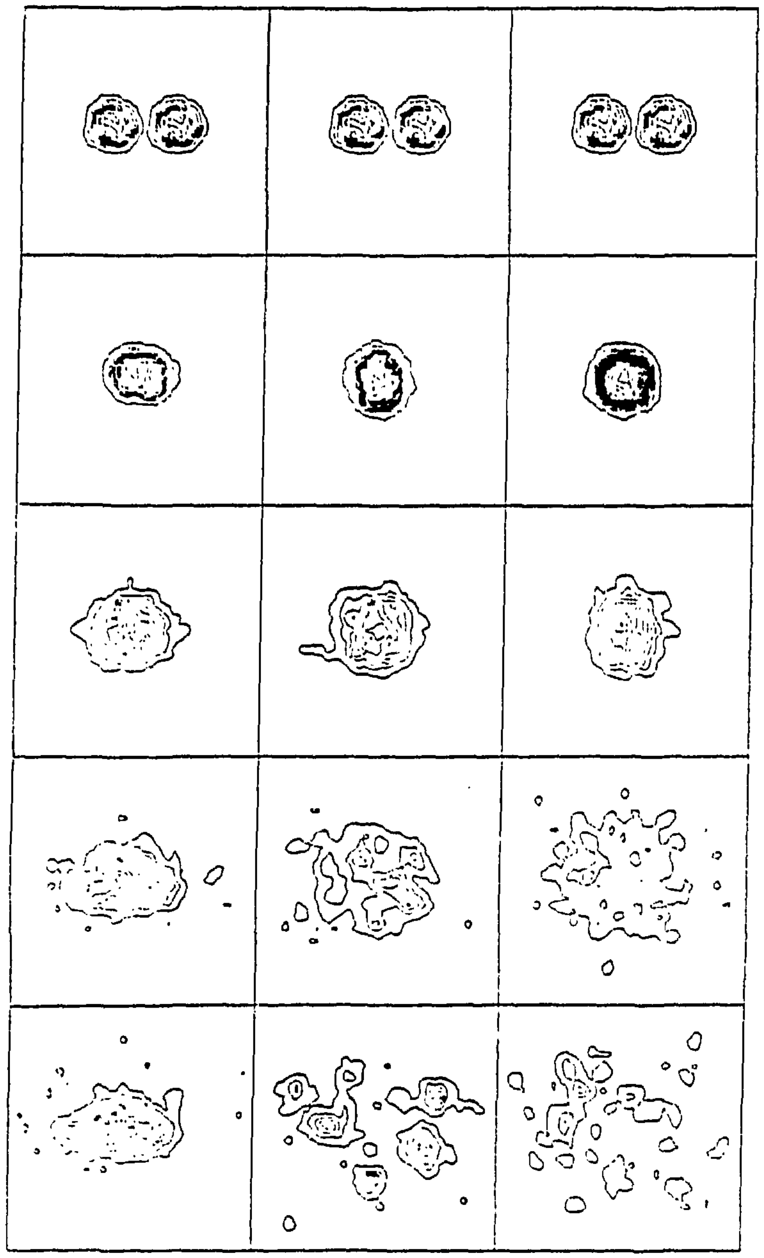

Fig. 3 : Contour plots of the density in 3 head-on Ca + Ca collisions at 20 (left), 50 (middle) and 100 (right) MeV/A lab energies. The 20 MeV/A case is a typical quasi-fusion event, while the 50 MeV/A case would correspond to multifragmentation and the 100 MeV/A case to vaporisation. Restrictions on the interpretation of this kind of results are indicated in the text. Instants are 0,32,48,80 and 128 fm/c for the 20 and 50 MeV/A cases and 0,20,30,60 and 90 fm/c for the 100 MeV/A plot. Each square represents a 40 x 40 $fm^2$ area.

possible origins i) the initial sampling of phase space, the effect of which being presumably washed out by the numerous 2-body collisions in the entrance channel ; and ii) the 2-body collisions themselves as explained above. The practical point of view we shall hence adopt here, is to consider that the fluctuations inserted by an insufficient description of the collision integral (Eq. (2)) may indeed reasonably well mock up the physical ones. This assumption is justified on the one hand by the relative insensitivity of the growing of instabilities, to their initial seed[14] and on the other hand by the thermal nature of the distribution of these fluctuations.

Before leaving this section let us shortly compare our calculations to related dynamical approaches (see section 4-2-4 of Ref. 1) and references quoted therein). It should be stressed that in any dynamical model developed so far, fluctuations were inserted "by hand" through the initial condition and/or through the simulation of the collision integral, similarly to our calculations. The major difference hence lies first in our proper spinodal analysis allowing for a connection with the EOS, second in our mean field allowing a reasonable clusterization as explained above.

## IV THE SPINODAL ANALYSIS IN A REALISTIC REACTION

We can summarize our further strategy as follow : i) consider a reaction at various beam energies (in our case E/A between 20 and 100 MeV/A for the Ca + Ca system and for head on collisions) ; ii) extract from the simulation the relevant variables for constituting an "Equation Of State" of the reaction, namely an average density $< \rho >$ and the "intrinsic" energy which, in our case of isentropic evolutions constitutes the thermodynamical potential ; iii) exhibit the spinodal region ot this particular EOS ; and iv) estimate the transit time in the spinodal region. In figure 3 are shown the density profiles of 3 typical reactions, namely fusion (E/A = 20 MeV/A), multifragmentation (E/A = 50 MeV/A) and vaporisation (E/A = 100 MeV/A).

The average energy is defined as

$$< \rho > = \frac{1}{A} \int \rho^{2}(\vec{r}, t)\, d\vec{r} \qquad (3)$$

where the local density $\rho(\vec{r})$ is simply

$$\rho(\vec{r}) = \int f(\vec{r}, \vec{p}, t)\, d\vec{p} \qquad (4)$$

The time evolution of < $\rho$ > is plotted in figure 4 for the Ca + Ca system. Note the strongly damped large amplitude monopole oscillation present even in the fusion case (E/A = 20 MeV). With increasing beams energy the vibration progressively disappears up to the highest energy case (E/A = 100 MeV) for which only expansion occurs.

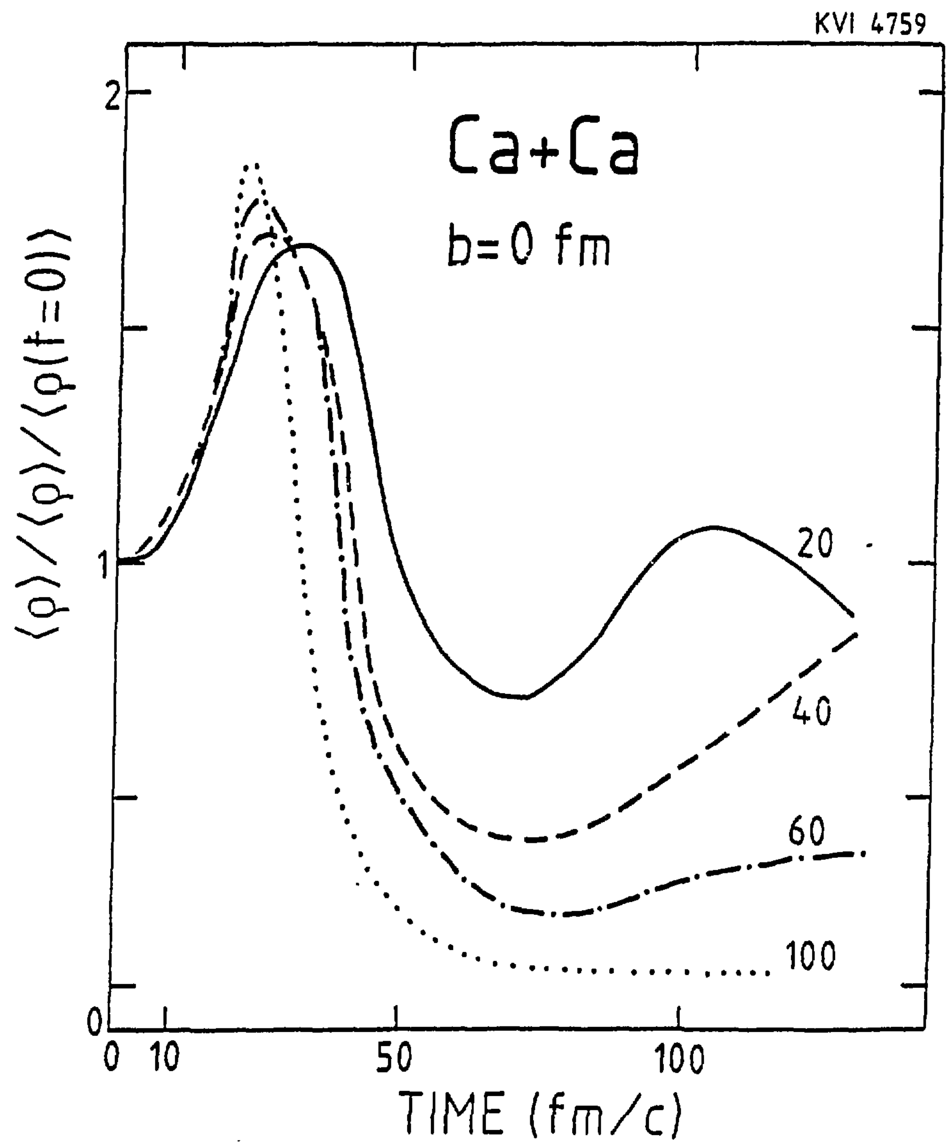


Fig. 4 : Time evolution of the average density $\langle\rho\rangle$ (Eq. (3), in $fm^{-3}$) for the $^{40}Ca$ + $^{40}Ca$ reaction at various bombarding energies. Note the almost saturating maximum compression.

The intrinsic energy $E_{int}$ is obtained by subtracting from the total energy (in the center of mass) the collective kinetic energy $E_{coll}$ defined by

$$E_{coll} = \frac{1}{2} m \int \frac{\vec{j}^{\,2}(\vec{r})}{\rho(\vec{r})} \, d\vec{r} \qquad (5)$$

where the local current vector $\vec{j}(\vec{r})$ is given by

$$\vec{j}(\vec{r}) = \int \frac{\vec{p}}{m} f(\vec{r}, \vec{p}, t) \, d\vec{p} \qquad (6)$$

The intrinsic energy $E_{int}$ may in turn be splitted into two components, namely a compressional one $E^{o}_{int}$ and a thermal one $E^{*}_{th}$. The compressional energy $E^{o}_{int}$ corresponds to the "cold" equation of state. It is calculated as a function of the density of the system by making it, initially in its ground state, expand and explode, within having switched off two body collisions for preventing heat production.

The EOS of the Ca + Ca reaction is plotted in figure 5 where $E_{int}$ is drawn as a function of $1/_{<\rho>}1/3$. At low energies (E/A $\lesssim$ 40 MeV/A) the monopole oscillation (figure 4) corresponds here to explore the vicinity of the "equilibrium" state, namely the point of lowest energy, similarly to the case of a standart, "cold", small amplitude monopole mode. At 60 MeV/A lab energy the system does explode but a potential barrier still exists, while at 100 MeV/A the intrinsic energy monotonically decreases with the size of the system. Assuming that the spinodal line (K = 0) roughly corresponds to 60 % of the "equilibrium" density [15] we see that explosion occurs after the crossing of this line, above 40 MeV/A lab energy. In order to go a step further in our analysis of the onset of the instability we are going to evaluate the transit time in the spinodal region, following the analysis of Pethick and Ravenhall[7].

In their way to characterize the spinodal instability the authors of Ref. (7) show that the first unstable multipole mode is the quadrupole one but the monopole mode merges quite close to the quadrupole, higher multipolarities appearing only when one experiences deeper insights in the spinodal region. This essentially means that if quadrupole modes are presumably the easiest ones to excite at low energy, as soon as energy increases monopole-like instabilities may become of prime importance. In order to estimate the approximate multipolarity of the collective velocity field associated to the

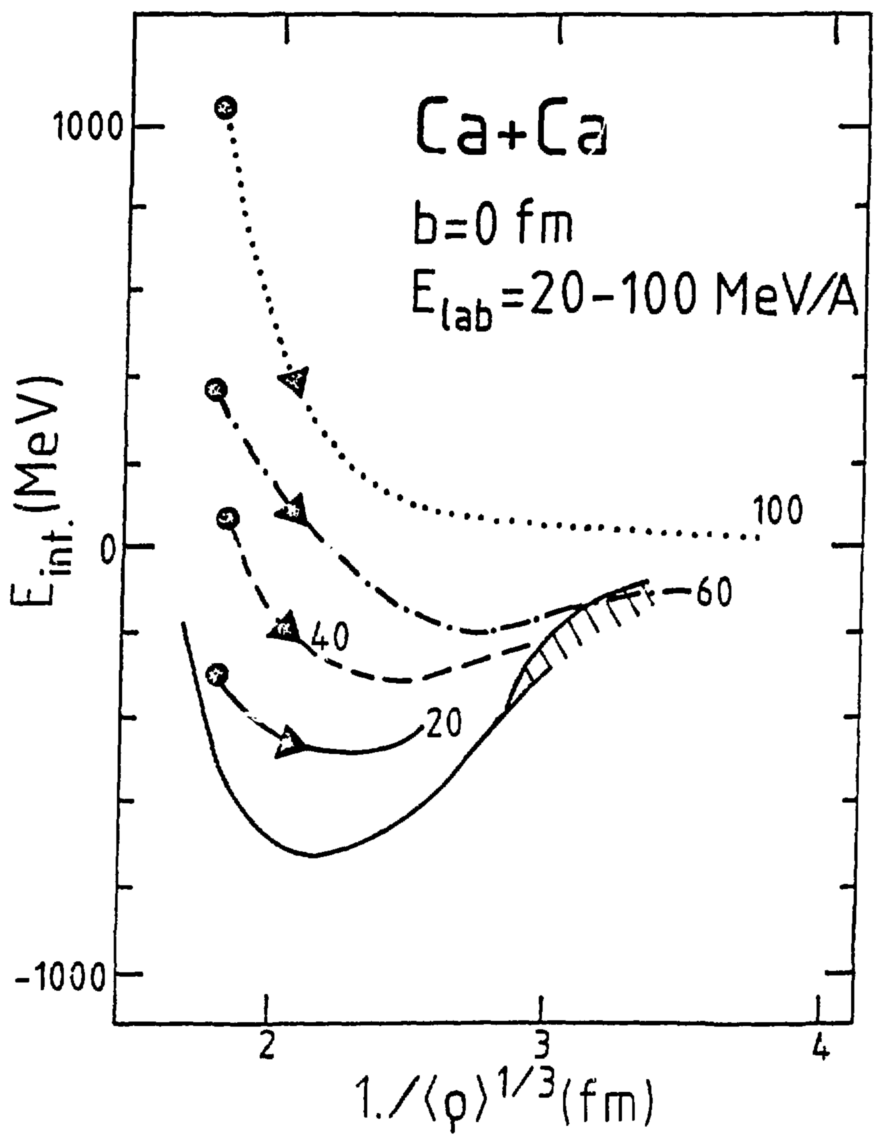


Fig. 5 : "Equation Of State" of the $^{40}Ca + ^{40}Ca$ reaction between $E_{lab}$ = 20 and 100 MeV/A. $E_{int}$ (in MeV) is plotted versus $1/\langle\rho\rangle^{1/3}$ (see Eq. (3), in fm). Also is indicated a rough evaluation of the spinodal region (hatched area) corresponding to this EOS (see text).

expansion we have hence made a comparison between $E_{coll}$ (Eq. 5) and the "monopole-like" collective energy

$$E_{coll}^{monop} = \frac{1}{2} m \int \frac{(\vec{j}.\vec{r})^2}{\rho.\vec{r}^2} d\vec{r} \qquad (7)$$

where we have simply retained the radial projection of the current vector $\vec{j}$. It turns out that, with increasing beam energy most of the total collective energy $E_{coll}$ (Eq. (5)) appears under the form of radial collective energy $E_{coll}^{monop}$ (Eq. (7)). This allows to assimilate, in first approximation, $E_{coll}$ to a monopole mode although it should be kept in mind that the comparison between $E_{coll}$ and $E_{coll}^{monop}$ essentially gives an indication on the nature of the dominating process rather than actual quantitative estimates.

Provided one hence assumes that most of the collective energy is of monopole nature in the transition region (typically 80 % for E/A ≃ 30 MeV) one way to describe the instability is to consider the hydrodynamical frequency associated to the system. By writing the collective energy as

$$E_{coll} = \frac{1}{2} B \quad \frac{d}{dt} < \vec{r}^2 > \qquad (8)$$

(within inserting the inertia parameter B), and expressing the intrinsic energy as

$$E_{int} = \frac{1}{2} k < \vec{r}^2 > \qquad (9)$$

where k defines the stress constant, one can simply estimate the hydrodynamical frequency $\hbar\Omega$ as

$$(\hbar\Omega)^2 \; m \; \frac{k}{B} \qquad (10)$$

The system is hence in the unstable region when $(\hbar\Omega)^2 < 0$ and it is consequently easy to estimate the transit time inside the spinodal line.

In figure 6 $(\hbar\Omega)^2$ is plotted as a function of time for the Ar + Ti reaction at two laboratory energies. At 20 MeV/A $(\hbar\Omega)^2$ essentially stays positive, an excursion into the spinodal region being experienced only over a very small time period. Anyhow one has to keep in mind the assumption of pure monopole mode which can be somewhat questionable for that case. A striking point, clearly independant of this question is the fact that at 44 MeV/A the system stays in the spinodal region for a very long time and indeed explodes. The interesting point is hence the clear transition at around 40 MeV/A lab energy between a regime in which the system, even if it flirts with the instability, does not stay long enough in this region to explode, and a regime in which it stays typically more than 120-150 fm/c and

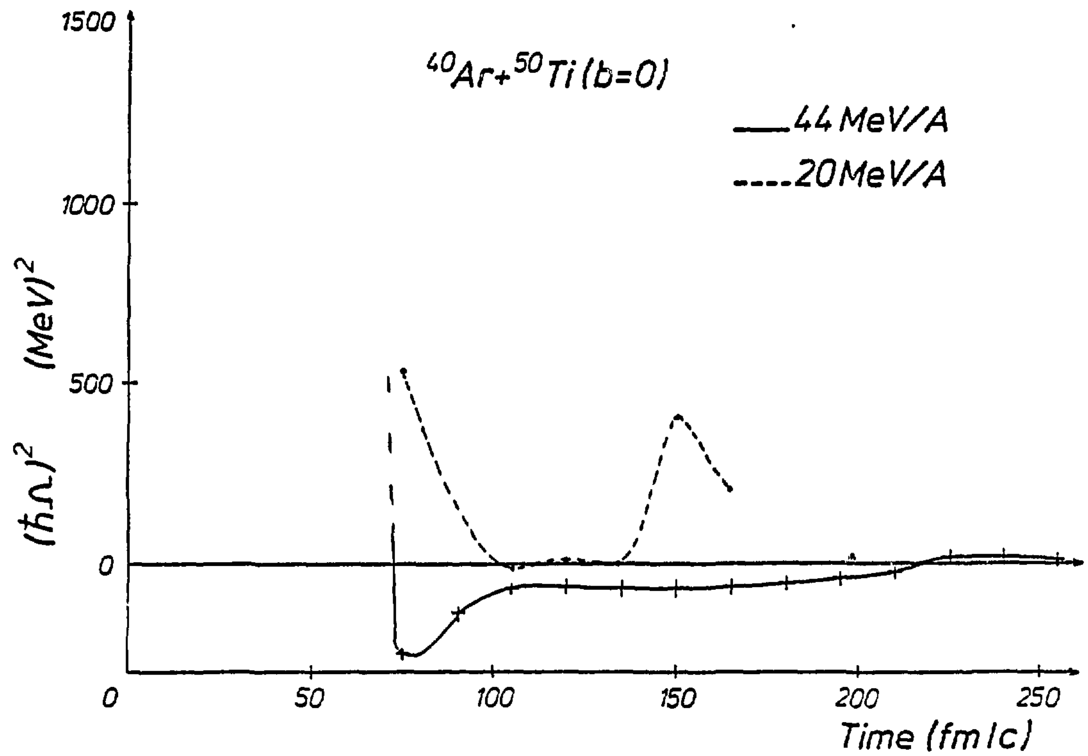


Fig. 6 : Time evolution of the square of the hydrodynamical frequency $(\hbar\Omega)^2$ (Eq. (10), in $(MeV)^2$) for the Ar + Ti central reaction at two bombarding energies. The passage in the spinodal region corresponds to negative values of $(\hbar\Omega)^2$.

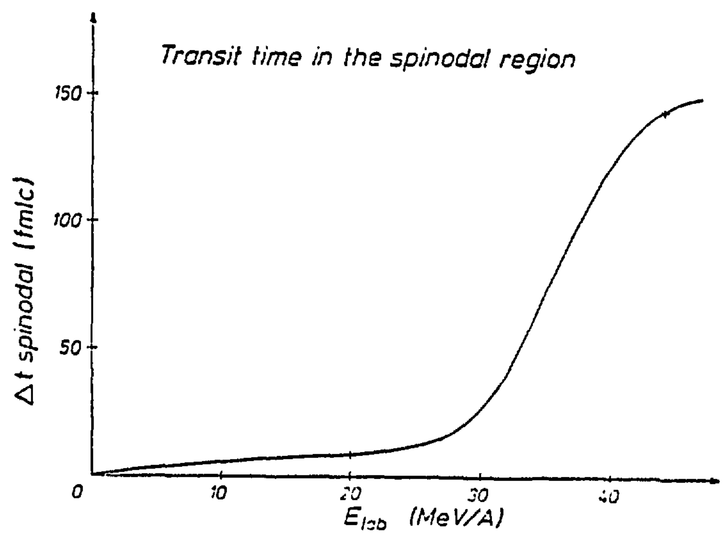


Fig. 7 : Transit time in the spinodal region (cf. also figure 6) versus the bombarding energy ($E_{lab}$ in MeV) for central Ar + Ti reactions. Note the order of magnitude transition around $E_{lab}$ = 40 MeV.

consequently explodes. This transition can be very clearly seen in figure 7 where we have plotted the transit time in the spinodal region versus the bombarding energy for the Ar + Ti reaction. Although the accuracy of the values plotted may be discussed within some percents because of the monopole analysis of the system, the order of magnitude transition around 40 MeV/A bombarding energy is however far beyond possible uncertainties !

Before concluding this analysis let us shortly discuss the influence on our results of the nuclear matter compressibility $K_\infty$ and the possible effects of the transport properties of the system. The calculations presended above have been done with a Skyrme interaction of "standart" compressibility $K_\infty = 200$ MeV. As the kind of reactions we have studied allows to explore an intermediate range of the EOS, namely densities between 0.5 and twice the saturation density, it seems particularly interesting to study the influence of $K_\infty$ on the disappearance of fusion. Calculations for heavy assymetric systems indicate that the deviation from the normal density scales as $1/\sqrt{K_\infty}$, as far as the amplitude is concerned. Keeping in mind that the spinodal region corresponds to densities smaller than 2/3 of the saturation density, it is clear that the softer the EOS, the deeper is the penetration into the spinodal region. In other words, for heavy assymetric systems like Ar + Au, one should expect a multifragmentation cross section increasing with decreasing compressibility modulers. The situation is probably different for light symmetric systems and requires further investigations. In these cases, the spinodal line can be reached easily even for moderate energies like 30 MeV/A, whatever $K_\infty$ is (assumed smaller than 400 MeV). The onset of multifragmentation would be governed by the transit time inside the spinodal region. As a amtter of fact we have also made calculations with an interaction corresponding to a stiff EOS ($K_\infty =$ 350 MeV), for the Ca + Ca system. In that case it seems that fusion actually disappears at a somewhat lower bombarding energy than in the $K_\infty = 200$ calculations. The system undergoes a compression phase up to a maximum compression which strongly depends on the lab energy, contrarily to the case of the soft EOS (see figure 3), but essentially possesses the same collective energy as the "soft" one. It is interesting to try to figure out how these results can be connected to actual transport properties and to the EOS of the expanding system. Following our analysis, and in the spirit of Ref. (7), the crucial quantity is given by the product of the growth rate $\Gamma$ times the transit time in the spinodal region $\Delta t_{trans}$. If one assumes that

$\Delta t_{trans}$ roughly scales as $1/\sqrt{K_\infty}$. The growth rate is directly connected to the sound velocity $c_s$ in the medium. Two "asymptotic" cases can be easily worked out. The first one corresponds to a system without 2-body collisions (a Fermi liquid) and $\Gamma$ is then proportional to $c_s^2$ and hence to $K_\infty$, so that in that case $\Gamma.\Delta t_{trans}$ (which gives a rough estimate of the integral $\int_{\Delta t_{trans}} \Gamma\, dt$) should scale as $\sqrt{K_\infty}$. On the contrary, in the ultra collisional case (hydrodynamical limit) $\Gamma$ is proportional to $c_s$ or $\sqrt{K_\infty}$ so that $\Gamma.\Delta t_{trans}$ should be more or less independent of the compressibility. Our numerical results seem to lie somewhat in between these 2 situations (which once more confirms the relevance of microscopic realistic studies !) which presumably emphasizes the complexity of the mixing between mean-field and 2-body correlation effects. A more systematic study is hence necessary, in order to allow a more complete interpretation of the results and a better understanding of the interplay between mean-field and 2-body correlations.

CONCLUSION

In this note we have presented a microscopic study of the quasi-fusion/explosion transition in intermediate energy heavy-ion reactions (E/A ~ 10-100 MeV/A), within using a simulation of the Landau-Vlasov equation. We have shown the usefulnes of such dynamical approaches as compared to qualitative schematic models. We have discussed the relevance of the present simulations of heavy-ion collisions in multifragmentation and we have indicated the limitations of the various existing models. By extracting the kinetic collective energy we have obtained an "Equation Of State" of the Ca + Ca reaction at various incident energies. The explosion of the composite systems may then be connected, in this equation of state, to the crossing of the isentropic spinodal line. More precisely, by estimating the transit time $\Delta t_{trans}$ during which the system actually stays in the mechanically unstable region ($K \leq 0$) we have been able to map out the explosion threshold to a sudden change in $\Delta t_{trans}$, from some fm/c to more than 100 fm/c, at around 35-40 MeV/A lab energy. This result quantitatively agrees with recent schematic estimates[7)]. The possible links with transport properties and the EOS of nuclear matter have also been indicated. Further investigations along this line presumably constitute a promising task for intermediate energy heavy ion collisions.

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