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Mean Field Instabilities in Dissipative Heavy Ion Collisions

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ABSTRACT

We discuss new reaction mechanisms that may occur in semi-peripheral heavy ion collisions at intermediate energies. In particular we focus on the dynamics of the overlapping zone, showing the development of neck instabilities, coupled with the possibility of an increasing amount of dynamical fluctuations. In a very selected beam energy range between 40 and 70 MeV/u we observe an important interplay between stochastic nucleon exchange and the random nature of nucleon-nucleon collisions. Expected consequences are intermediate mass fragment emissions from the neck region and large variances in the projectile-like and target-like observables. The crucial importance of a time matching between the growth of mean field instabilities and the separation of the interacting system is stressed. Some hints towards the observation of relatively large instability effects in deep inelastic collisions at lower energy are finally suggested.

1. Introduction

In recent years many experimental and theoretical efforts have been concentrated on the mechanisms which develop in heavy ion collisions at intermediate energies. In particular it has been observed that these reactions are often accompanied by a copious production of intermediate mass fragments (IMF). Different theoretical

models have been suggested to understand this feature. It is generally believed that during the more violent collisions a wide region of the nuclear phase diagram can be explored and new states of nuclear matter can be accessed; the nuclear system may enter an instability region and the fragment production may be explained on the basis of the growth of any small fluctuation, leading to a final explosion. Recent work on these topics can be found in the literature [1]. Moreover considerable progress on the study of fragmentation by spinodal decomposition has been made also in other fields as, for example, in the case of classical systems like the binary alloys [2].

However recent experimental results have raised the attention on the possibility to observe IMF production also in semi-peripheral collisions, where the scenario of a violent nuclear explosion cannot apply because of the low degree of centrality. Therefore in this article we will try to shed some light on the mechanisms responsible for the fragment production observed in medium momentum-transfer reactions, corresponding to middle-central impact parameters. We will study the dynamics of the nuclear overlapping zone (the "neck" region) for semi-peripheral heavy ion collisions in the beam energy range 10 to 100 MeV/u. We will show that the occurrence of spinodal instabilities in this zone determines the break-up of the di-nuclear system formed in the earlier stage of the collision. The reaction dynamics discussed here represents the borderline between deep inelastic and fragmentation events. A deep understanding of these intermediate processes will in general improve our knowledge of dissipative collisions, in particular on the leading

dynamical path to multifragmentation.

We will focus on the presence of an extremely interesting reaction mechanism in a transition energy region between 40 and 70 MeV/u due to the coupling between stochastic nucleon-nucleon collisions and the nucleon exchange process already present also at lower energies and extensively studied in deep inelastic collisions and fusion-fission events, from both theoretical and experimental points of view [3,4,5,6,7]. The detectable consequence should be the possibility of IMF formation from the neck region and a clear increase of the variances of all observables (mass, charge, emission angle, velocities, angular momenta...) of projectile-like (PLF) and target-like (TLF) fragments. This novel behaviour of the dynamics in the overlapping zone was actually predicted in an early model of the heavy ion collisions in the Fermi energy domain [8], although the interesting problem of the variances was not addressed at that time. More recent simulations using transport equations are showing similar results [9,10,11]. Some preliminary experimental evidences are already available for neck-IMF production [12,13,14,15,16,17] and for the PLF-TLF variances [13,18].

With increasing energy the effect is disappearing for two main reasons:

- i) locally the nuclear system is going outside the spinodal instability region, in the vaporization phase, and we are moving towards a fireball formation.
- ii) the separation time becomes much shorter and there is not enough time for the fluctuations to grow.

On the other hand, for dissipative collisions at low energy (between 10 and

30 MeV/u) we have longer interaction times and therefore a large coupling among various mean field modes. The mean phase space trajectory will give a good picture of the dynamics and the expected variances will be mostly of statistical type. However in some cases, due to a combined Coulomb and angular momentum effect, some instabilities can show up, as shown later in the paper. The amplitude of fluctuations will be essentially determined by the random nucleon exchange, without any stochasticity from two-body collisions. As a consequence we will not expect to see IMF formations but still quite large effects on the widths of PLF- (TLF-) observables.

In Sect.2 we discuss the physics of mean field instabilities and the importance of dynamical time-scales. A quantitative analysis is performed in Sect.s 3, 4 where a stochastic transport approach is introduced. A detailed study of the expected effects on mass variances can be found in Sect.5. Some conclusions and perspectives are finally exposed in Sect.6.

2. Instabilities and Dynamical Evolution

We focus on semi-peripheral heavy ion collisions at intermediate energies, where two or three primary sources are formed. The main purpose of this paper is to study the mechanisms which occur when the di-nuclear system, formed in the earlier stage of the reaction, breaks up into pieces.

Binary breakings for not central collisions are simply related to Coulomb and rotational effects, which prevent the formation of a fused system. This happens in

deep-inelastic collisions at low energies on relatively long time scales. No dynamical instabilities are involved, the mean trajectory of the one-body distribution function, i.e. the one given by TDHF calculations, will account for the process and the variances will be of statistical type, related to the nucleon exchange dissipation mechanism. Sometimes some shape instabilities, like in fission decays [19], can appear, also leading to three-body breakings [20].

With increasing the energy, the interaction time will decrease while we start to see the building up of higher density regions. Spinodal instabilities can consequently show up in the overlapping zone leading to new effects on the breaking mechanism. The system will split apart if, after the shock and the initial compression, the rarefaction phase leads the density in the overlapping zone (the neck region) below the critical density [21]. The occurrence of volume instabilities can therefore account for the formation of two primary fragments (like in deep-inelastic collisions) or of three primary sources, at higher bombarding energies, where the important nucleon-nucleon collision rate determines the development of an intermediate velocity source.

It is well known that, when instabilities are present, fluctuations become extremely important. In fact, in unstable situations, fluctuations are usually amplified and may lead the considered system towards an evolution pattern very different from the one associated to the mean trajectory behaviour. In particular, the presence of fluctuations is essential to explain the break-up of the system in terms of the occurrence of spinodal instabilities in the overlapping region and therefore

influences the value of the reaction cross section associated, for instance, to incomplete fusion or binary events. In the following we will try to relate the presence of volume instabilities to the possibility, due to the growth of fluctuations, to obtain large variances for all observables associated to projectile-like (PLF) and target-like (TLF) fragments in semi-peripheral reactions within a bombarding energy range 15 to 70 MeV/u, as well as fragment emission from the neck region, starting from beam energies around 40 MeV/u.

A parameter of crucial importance is the time interval during which the dinuclear system remains interacting and exchanging nucleons before its break-up. If this time, which essentially depends on the considered impact parameter and beam energy, is long compared to the characteristic time for the growing of instabilities in nuclear matter, the system will have the possibility to cancel the effect of the enhancement of fluctuations due to the presence of the instability; in this case we expect to observe just the equilibrium fluctuations associated to the stochastic nature of nucleon exchange and/or nucleon-nucleon collisions in stable systems. This is for instance the case of deep-inelastic collisions at low energy, below 10 MeV/u.

On the other hand, if the interaction time is of the same order of magnitude of the instability growing time, these fluctuations will be amplified and will lead to larger variances for all observables related to the primary products of the reaction. This is extremely interesting since recent experimental results have already raised the attention on the possibility to obtain a big variety of masses of PLF and TLF,

as well as intermediate mass fragments (IMF) emission from the neck region in semi-peripheral heavy ion collisions at intermediate energies [13,14,15,18], where the condition on the interaction time discussed before seems to apply.

For instance, in the case of volume instabilities, typical time scales for the growing of fluctuations are around $40 - 60 \text{ fm}/c$ [22], depending on density and temperature reached in the overlapping zone.

Finally, when the interaction time interval is extremely short, there will be no time to build fluctuations and the effects described above will disappear. This is, for example, the case of participant-spectator like reactions [23].

In the following we will try to explore all the possible situations considering nuclear collisions at various energies and impact parameters.

3. Theoretical framework

As introduced before, fluctuations play a fundamental role when unstable situations are taken into account. This is the reason why we will consider stochastic mean field approaches to describe the dynamical evolution of nuclear reactions. In such a kind of theories the nuclear system is still described by its one body density function in phase space $f(\mathbf{r}, \mathbf{p}, \mathbf{t})$, while this function may experience a stochastic evolution in response to the action of a fluctuating source term, in some analogy with the Brownian motion.

Recently kinetic one-body equations of the Boltzmann-Nordheim-Vlasov (BNV) or Boltzmann-Uheling-Uhlenbeck (BUU) type have been implemented by the intro-

duction of a fluctuating term, coming from considerations associated to the random nature of the nucleon-nucleon collision integral [24]. The resulting Boltzmann-Langevin (BL) equation reads:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \cdot \frac{\partial f}{\partial \mathbf{r}} - \frac{\partial U}{\partial \mathbf{r}} \cdot \frac{\partial f}{\partial \mathbf{p}} = \bar{I}[f] + \delta I[f] \quad (1)$$

where U is the mean field potential, $\bar{I}[f(\mathbf{r}, \mathbf{p}, t)]$ represents the average effect of the collisions (the BNV term), while $\delta I[f(\mathbf{r}, \mathbf{p}, t)]$ denotes the fluctuating remainder (the Langevin term).

In the following we will use a simplified approach: we start from the BNV equation and we solve it using the test particle method [25]. Therefore we introduce some fluctuations directly in the one-body density function, by means of a finite mapping of the phase space due to the use of a finite number of test particles in the resolution. The fluctuating term δI of eq.(1) is therefore replaced by a stochastic term of different structure.

We notice that this term introduces fluctuations on all the possible modes of the one-body density function and therefore allows the system to show up any kind of mean field instability in the dynamical evolution. In ref.[26] it has been shown that such stochastic transport approach leads to the amplification of the same most important modes, when compared with the BL method in cases of collisional dynamics. Moreover it has also the important feature of including some mean field fluctuations and so it seems particularly suitable for the dynamics in the Fermi energy domain.

However we stress that, in the present work, the use of the correct amplitude of the related fluctuations is not very relevant since we are interested just on the possibility to reveal unstable situations and not on a precise description of the entire dynamics (for which the correct fluctuation value is needed). More details will be given in the next sections.

4. Results

We have studied the collision between medium mass ions ^{60}Ni on ^{90}Zr at various beam energies, for a reduced impact parameter $\frac{b}{b_{max}}=0.5$, and the reaction ^{58}Ni on ^{58}Ni at 15 MeV/u for different impact parameters. All the calculations are performed using local Skyrme forces corresponding to a mean field of the type

$$U = A \left(\frac{\rho}{\rho_0} \right) + B \left(\frac{\rho}{\rho_0} \right)^\sigma, \quad (2)$$

with $A = -356 \text{ MeV}$, $B = 303 \text{ MeV}$, $\sigma = 7/6$. This parameterization corresponds to a soft equation of state ($K=200 \text{ Mev}$). Finite range effects have been considered in the evaluation of the mean field by means of the use of phase space gaussians for the test particles. The widths are fixed in order to reproduce the correct surface energy term for the ground state. A number of 50 test particles per nucleon is considered, which correctly reproduces the average dynamics in the stable regions [9,10,27].

In order to study the development of fluctuations we build more events (phase space trajectories) with the same macroscopic initial conditions but a different mapping of the phase space. In fig.1 we show the density contour plots on the

reaction plane for three events (each row is a different event) around the separation time for the reaction $Ni + Zr$ respectively at 15 MeV/u (a), 40 MeV/u (b) and 80 MeV/u (c). The different behaviour of the "neck" region is quite evident in the three cases. At low energy we have a binary reaction, like in deep inelastic collisions. At 40 MeV/u we see the development of various patterns in the overlapping zone with an increase of the PLF, TLF variances and the possibility of fragment formation in the neck region. At high energy we get a fireball-type explosion.

We can perform a more accurate study of the involved instabilities just looking at the mean values and variances of various multipole moments of the nuclear matter distribution. We look first at the density behaviour in the neck region. In fig.2 we report the time evolution of the mean density (circles) and the behaviour of the density variance (squares):

$$\sigma_\rho^2 = \frac{1}{N_{events}} \sum_{i=1}^{N_{events}} (\rho_i(t) - \bar{\rho}(t))^2 \quad (3)$$

in a sphere of radius 2 fm around the centre of mass, inside the overlapping region, for the reaction $Ni + Zr$ at 15 MeV/u.

In order to explain the behaviour represented in these curves, we recall the nature of the fluctuations that we have introduced in the dynamics and precisely on the one-body density, because of the finite mapping of the phase space. If the density is calculated in small cells of volume ΔV , as $\rho(\mathbf{r}) = \frac{n(\mathbf{r})}{\Delta V}$, the associated variance will be $\sigma_\rho^2 = \frac{1}{\Delta V^2} \sigma_n^2$. The variance associated to the number n of nucleons contained in the considered cell can be expressed as follows: $\sigma_n^2 = \frac{\bar{n}(\mathbf{r})}{N_{tot}}$, since the discrete mapping introduces the fluctuations associated to classical poissonian distributions,

reduced by the used number of test particles per nucleon N_{test} . Therefore we obtain:

$$\sigma_\rho^2 = \frac{1}{\Delta V} \frac{\rho}{N_{test}}. \quad (4)$$

When instabilities do not occur, we expect just oscillations in the variance behaviour; the amplitude of these oscillations will follow the value of the mean density, according to eq.(4). This can be observed in the figure, up to a time $t = 200 \text{ fm}/c$. Afterwards, when the system starts to separate, the mean density falls down into the spinodal instability region and we correspondingly start to observe a nearly exponential increase of the density variance, as expected in presence of instabilities [27]. This will affect the calculated widths of all observables associated to PLF and TLF fragments in the exit channel, as we will show in the next section.

We have done the same kind of analysis at 40 MeV/u. In fig.3a we plot the behaviour of the mean density (circles) and of the density variance (eq.(3)) (squares) for a sphere of radius 3 fm around the center of mass of the system. We obtain a clear exponential increase of the density variance, starting from $t_{inst} = 100 - 120 \text{ fm}/c$. We remark that the variance seems to saturate before the separation time, showing that there is enough time for the fluctuations to grow.

In order to get an idea also of shape effects we have studied for the same reaction, $Ni + Zr$ at 40 MeV/u, the behaviour of the density octupole moment, computed along the symmetric rotating axis. We consider the quantity $O(t) = \sqrt{\frac{7}{16\pi} \frac{\sum_i (5z_i^3 - 3z_i r_i^2)}{N_{tot}}}$ where the sum runs over the N_{tot} test particles bound to the di-nuclear system. This moment is strictly related to the fluctuations of the ratio between the masses of the two main fragments which are formed (see fig. 1b).

In fig.3b we plot the mean value (circles) and the variance (squares) of $O(t)$. We can observe an exponential increase of the variance starting from $t = 100-120 \text{ fm}/c$ to $t \approx 180 \text{ fm}/c$, while the mean value keeps roughly constant in the same time interval. Therefore this shape instability seems to develop well before the separation and almost exactly in the same time interval of the instabilities associated to the density in the overlapping zone.

As we will see in the next section, large fluctuations are observed in the exit channel. Moreover, in this case, a middle-velocity source at low density is formed, with the possibility to observe IMF emission from the neck region (as we see from some events).

At 80 MeV/u (fig.4) the mean density in the considered sphere soon decreases because of the formation of an intermediate mass region at small density (see fig.1c). Nevertheless fluctuations have not time enough to grow since the dynamics is very fast and therefore the density variance does not grow.

5. Mass variances

One of the most important features concerned in semi-peripheral heavy ion collision experiments is the width of the mass spectra obtained for PLF-TLF like fragments. Now we will try to relate the value of this observable to the possible occurrence of spinodal instabilities in the fragment formation.

In the previous section we have discussed the amplitude of the fluctuations that we introduce in the dynamics and their dependence on the used number of test

particles (see eq.(4)). If no instabilities are encountered, these fluctuations are not amplified but they will build an "equilibrium" variance for all observables associated to the formed primary fragments. In particular for the masses we obtain:

$$\sigma_A^2 = \frac{\bar{n}_{ex}}{N_{test}} \quad (5)$$

where $\bar{n}_{ex}$ is the mean total number of nucleons which are in the cells that participate to the mass exchange between primary fragments. Therefore it should be noticed that the fluctuations that we have introduced give, in the case of stable situations, variances that, suitably rescaled by N_{test} (see eq.(5)), are in agreement with the results predicted by the nucleon exchange model (NEM) and with experimental widths measured at low energy [3]. On the contrary, when instabilities occur, these fluctuations are amplified, the scaling law is not valid anymore and we will obtain larger variances.

Therefore, in order to reveal the presence of instabilities, we will calculate the mass variances, considering many events, for the systems mentioned before and we will compare the obtained result with the value given by eq.(5). As we can see from Tab.I, in the case of the reaction $Ni + Zr$ at 15 MeV/u, the mass variances do not follow eq.(5). Large variances are obtained, indicating that some instabilities have been developed meanwhile the di-nuclear interacting system breaks up. This is well in agreement with the mean density and variance behaviour observed in Fig.2 and already discussed in the previous section. Moreover we notice that, in this case, the time that projectile and target need to pass through each other is of the order of 100 fm/c (which corresponds to a mutual velocity $v/c = 0.12$), i.e. of

the same order of magnitude of the characteristic time for the growing of spinodal instabilities in nuclear matter, which is about 50 fm/c [24]. We remark that the value of the mutual velocity that we obtain here is very near to the minimal mutual velocity v_c , discussed in ref.[21], that is necessary to explain the break-up of the di-nuclear system in terms of the occurrence of spinodal instabilities in the neck. Therefore instabilities grow and build larger fluctuations in the exit channel.

We stress that, at lower energies, we expect smaller velocities and consequently longer interaction times: the system will have the time to destroy the effects of the instability and to restore a statistical equilibrium in the exit channel.

Interaction time of the order of 50-100 fm/c are found for the beam energy $E/A = 40$ MeV/u. Moreover in this case, because of the enhanced available energy and then of the copious nucleon-nucleon collisions, we have larger amplitude fluctuations: a further increase of the mass variances associated to PLF and TLF is observed (see Tab.I), together with the possibility to obtain IMF emission from the neck region.

Finally at 80 MeV/u the mass variances converge to the expected equilibrium value since instabilities have no time to grow. In fact an interacting time $t \approx 30$ fm/c is found in this case, which is short compared to the instability growing time.

It is interesting to notice that the equilibrium value given by eq.(5), suitably rescaled by the used number of test particles per nucleon, can be obtained considering only one single run and constructing many events just by a random choice of the total number A of nucleons among the $N_{test} \cdot A$ test particles.

Fig.5a shows the mass distribution obtained considering only one run, as explained before, for Ni + Zr at 80 MeV/u (full line), just after the the break-up. For each of the two primary fragments, this curve is well in agreement with a gaussian distribution, with the width given by eq.(3), rescaled by the used number of test particles per nucleon (dashed lines). This is a further evidence of the fact that, at this energy, fluctuations remain the statistical equilibrium ones, since instabilities have no time to develop.

On the contrary, when fluctuations are amplified, the mass variances obtained considering many events (eq.(3)) can become much larger than the ones given by eq.(5). Just to illustrate this effect, we can still compare the widths of the mass distribution calculated from one single run with the variances obtained using many events and suitably rescaled. This is presented in Fig.5b, in the case of the reaction Ni + Zr at 15 MeV/u. The fact that the two methods of calculating the mass variances give very different results can be considered as a signature of the occurrence of instabilities. However we stress that the widths of the dashed curves are not to be used directly for a quantitative comparison with experiments since, in unstable situations, the scaling properties of fluctuations with the used number of test particles per nucleon cannot be introduced in such a simple way. A more quantitative study is presently in progress.

A similar analysis can be performed keeping constant the reaction energy and varying the impact parameter, since central collisions induce a greater dissipation of energy and therefore longer times of interaction than peripheral ones. We have

considered the system $Ni + Ni$ at 15 MeV/u for different impact parameters.

Equilibrium fluctuations are obtained for central collisions ($b = 3$ fm), where fusion occurs. In this case we do not have any instabilities and the mass variances are the statistical ones, obtained considering the mean number of evaporated nucleons (see Tab.II). For a semi-peripheral collision ($b = 6,7$ fm), in which the critical velocity is attained ($v/c = 0.12$), we have the expected increase of the mass variances (see Tab.II). This characteristic can be related also to the occurrence of other non-equilibrium processes like, for instance, a non equilibrated partition of the excitation energy and/or of the intrinsic spin between PLF and TLF [28].

However we notice that the variances observed at $b = 6$ fm are smaller than the ones obtained at $b = 7$ fm. That is another nice evidence that the key parameter is the interaction time. All collective effects affecting this time, angular momentum and compression, are then acting in the same way on the observation of instability effects. In this case we have more central collisions that are generally associated to longer interaction times: this allows the system to destroy some of the fluctuations built up from the instability. Finally, for a peripheral collision ($b = 9$ fm), the mass variances go back to the equilibrium ones since in this case instabilities have no time to show up.

6. Conclusions and perspectives

Mean field instabilities can play an important role in the reaction dynamics of heavy ion collisions, with sizable effects on the widths of all physical observ-

ables up to the possibility of direct dynamical breakings of the system. Of crucial importance is the time matching between the growth of mean field instabilities and the separation of the system in interaction. This point can lead to a careful prediction of the best experimental conditions for the observation of such effects. Moreover we would expect to see in the same events other characteristic features of non-equilibrium processes, i.e. in excitation energy partitions and in- and out-of reaction plane asymmetries. The physical region for the best observation of these effects should be in the range of medium energy collisions, between 20 and 70 MeV/u beam energy, a kind of transition zone between deep inelastic and multifragmentation reactions.

In particular we have shown the onset and decay of a novel reaction mechanism for semi-peripheral heavy ion dissipative collisions at medium energies, due to the presence of spinodal instabilities in the neck region. We predict large effects on the variances of properties of PLF and TLF, particularly interesting for the formation of new exotic isotopes. Direct emission of intermediate mass fragments from the neck region is also expected. We actually remark that in our simulations with the test particle approach we are probably underestimating the amount of fluctuations present in the dynamics when the system meets some instability. This means that the fragment formation times are overestimated so the probability of a direct observation of IMF production from the neck region is reduced since meanwhile the system is separating.

We finally stress the nice experimental features of this reaction mechanism since

the PLF and TLF partners could be well observed with a consequent clear detection of the reaction plane and of the event geometry [14]. From a theoretical point of view this study represents a very good test ground for the understanding of collective dynamical effects in the fragmentation process for two main reasons: i) the geometry of the fragmentation region is quite well defined and so it would be enough to analyse the evolution of few unstable modes, ii) the fragment formation times are of the same order of separation times and so we do not expect large recombination effects.

As already stated many times, in order to perform a quantitative comparison between simulations and reaction data, an important parameter in our calculations is N_{test} , the number of test particles per nucleon used for the solution of the stochastic BNV equation. As shown in eq.s(4,5) this parameter rules the amplitude of the fluctuations when the system is in a stable dynamics and the increasing separation of different trajectories in instability regions. We have shown that mean field instabilities occur already at energies as low as $15 - 20 \text{ MeV}/u$, where a large part of the reaction cross section is given by incomplete fusion events. Since the breaking of the compound rotating system is highly sensitive to the amount of fluctuations a careful comparison of the experimental incomplete fusion cross section with the corresponding results of the simulations will give a strong indication on the actual amplitude of fluctuations encountered during the dynamical evolution and therefore on the number of test particles to be used.

The dynamical behaviour discussed here would be indeed a unique feature of

the nuclear many body system, where the mean field picture plays a fundamental role, and will lead to new tight constraints on the understanding of the nuclear interaction in the nuclear medium. In this respect we stress the interest of studying such instabilities in reactions induced by radioactive beams, with large variations of the N/Z ratio in the overlapping zone. We remark that the beam intensity is not a problem for pursuing an event by event analysis.

Finally, as already remarked, experimentally we can foresee a good way to control the production of new isotopes from projectile- and/or target- like fragments. Indeed all the results on projectile fragmentation in the Fermi energy domain should be revisited considering the possibility of a showing up of instabilities. New experiments can be planned [29].

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Figure Captions

Fig. 1. Density plots on the reaction plane for the $b/b_{max} = .5$ $Ni + Zr$ collision for 3 events: 1a) 15 MeV/u at $t = 280, 300, 320$ fm/c ; 1b) 40 MeV/u at $t = 120, 140, 160$ fm/c and 1c) 80 MeV/u at $t = 80, 100, 120$ fm/c .

The side of each box is 36 fm .

Fig. 2. Time evolution of the mean density (circles) and of the density variance (squares) in a sphere of radius 2 fm around the centre of mass for $Ni + Zr$ at 15 MeV/u .

Fig. 3. Time evolution of the mean density (circles) and of the density variance (squares) in a sphere of radius 3 fm around the centre of mass for $Ni + Zr$ at 40 MeV/u (a). Mean value and variance of the octupole moment as a function of time (b).

Fig. 4. Same of Fig. 2 for $Ni + Zr$ at 80 MeV/u .

Fig. 5. Fragment mass distribution calculated, in the case of the reaction $Ni + Zr$ at 80 (a) and 15 MeV/u (b), performing many events and scaling by the used number of test particles per nucleon (dashed line), or considering a random sampling of the test particle distribution obtained in one single event (full line).

TABLE I

PLF mass variances for the reaction $Ni + Zr$ at different energies and for the same impact parameter.

E/A (<i>MeV/u</i>)	σ_A^2	
	Simulation	Equilibrium value
15	15.12	0.408
40	32.06	0.244
80	0.30	0.278

TABLE II
*PLF mass variances for the reaction $Ni + Ni$ at $E/A = 15 \text{ MeV}/n$
for different impact parameters.*

$b \text{ (fm)}$	σ_A^2	
	Simulation	Equilibrium value
3	0.5	0.50
6	9.8	0.37
7	10.8	0.29
8	0.2	0.17

a)

b)

c)

Time

Fig. 1

Fig. 2

Fig. 3