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MEMORY EFFECTS IN NUCLEAR FRAGMENTATION

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Abstract. - *A general procedure to identify instability regions which lead to multifragmentation events is presented. The dominant mode at the instability point is determined from the knowledge of the mean properties (density and temperature) of the system at that point. For spinodal instabilities the dependence of fragment structures on the dynamical conditions is studied changing the beam energy and the considered equation of state. An important competition between two dynamical effects, expansion of the system and growth of fluctuations, is revealed. It is shown that in heavy ion central collisions at medium energies memory effects of the configuration formed at the instability time should be observed in the final fragmentation pattern. Some hints towards a fully dynamical picture of fragmentation processes are finally suggested.*

1. Introduction

Heavy ion collisions at intermediate energies have been widely described through some kinetic approaches (*VUU*, *BUU*, *BNV*) [1,2,3] which are able to correctly reproduce the mean trajectory of the system in phase space. However, when one is interested in processes like, for instance, multifragmentation events, these methods are not valid anymore since they do not contain the dynamics of fluctuations, which is very important in an unstable system [4]. Nevertheless we will show that the use of such kinetic equations, solved within the test particle approach, can still be very useful to extract quite precise information on physical properties of the instability regions.

Actually, since always some numerical noise is present when the system enters an instability region, because of the used numerical algorithm, we see in the solution of these transport equations a fast growing of fluctuations, symmetry breakings and cluster formation [5]. Indeed these geometries should be related to the configuration of the system at the time of instability, to the leading unstable modes, to the time scale for cluster formation and to the expansion time. The possibility of detecting such critical dynamical features of

the nuclear system is extremely stimulating. Aim of this work is to show how to get results not depending on the numerical algorithm and then to extract a physical scenario for the observation of memory effects, of collective dynamics type, in fragmentation events.

We discuss first how some mean properties of the system at the instability point may carry very important information on the structure of the fragmentation mechanism. In fact if the mean dynamics is well described it is possible to reveal the presence of instabilities; for instance, in the case of a volume instability, one can realize that the system lies inside the spinodal region, just looking at the local values of density and temperature [6]. These observables can be used to calculate the dominant unstable mode and the correspondent characteristic growing time τ at the critical point [7].

The next behaviour of the system depends on the amount of fluctuations (*i.e.*, in our case, on the used number of test particles) present at the instability point, because the smaller are fluctuations the longer is the cluster formation time. Of course if there are no fluctuations, clusters will not be formed. Nevertheless, if we believe that actual fluctuations are large enough, we expect the cluster formation time to be short: in this case there is a good chance to keep the memory of the structure formed at the instability time in the fragmentation pattern.

On the other hand long fragment formation times as well as long expansion times will imply a strong coupling between different unstable modes with a consequent developing of a fully chaotic dynamics in the exit channel [8,9]. As expansion time we mean the time needed for the system to reach the freeze-out configuration, with a mean density as $1/8 - 1/10$ the normal nuclear density value.

We will focus our analysis on the spinodal (volume) instabilities. One of the main purposes of this paper is to study memory effects versus the dynamical evolution (the expansion) of the system in some different situations. In particular we will consider the effects of changing the beam energy and the equation of state in a collision.

The effect of a collective dynamical expansion has been already deeply analysed by W.A.Friedman [10]. Aim of our work is to show the possibility of observing directly some

collective dynamical modes in fragmentation events, in competition with the expansion effects.

2. Leading collective modes of nuclear disassembling

As already stressed, the *BNV* equation, used to study heavy ion collisions [3], is suitable to identify the presence of instability regions, even if it is just an one-body approach. The fact that the system enters an instability region is, indeed, a property of the mean dynamics. In a previous paper [11] it has been discussed how to extract informations on the fragmentation mechanism from properties of the system at the instability point. In particular it has been shown that there are a few modes (with the associated characteristic growing time τ) which are dominant. In this paper we will investigate how these modes (and therefore the structure of fragmentation) depend on the dynamical conditions; we will try also to go further and to study the evolution of the fragmentation pattern in order to see if memory effects of the original configuration are kept.

We have performed the same kind of calculations in two dimensions (2D) of ref. [11]. Apart the reduced numerical effort, 2D models can be very pedagogical. However we will show that the main results should be valid also in realistic 3D cases. We consider a two-dimensional collision between two slabs of nuclear matter in a box of lengths $L_x = 63 \text{ fm}$ and $L_y = 21 \text{ fm}$; in order to reduce the computational time, the mean field is averaged on the y direction. The x radius of the two nuclei is equal to 4 fm (the radius of a ^{40}Ca nucleus) while the total number of nucleons is fixed requiring that the density of the two slabs is equal to the normal density, which is 0.55 fm^{-2} in two dimensions. We have simulated a central collision at intermediate energies. As the time increases we see the formation of a nearly uniform zone which lies in the spinodal instability region [8]. Since the effective mean field depends on x only, the same holds for those modes that can be excited and this simplifies the analysis considerably. Indeed, in the present scenario, the eigenmodes of the density are plane waves, characterized by a wave number k . Therefore it is instructive to perform a

Fourier analysis of the density fluctuation $\delta\rho$ by defining the following quantity:

$$\sigma_k^2 = \int_0^{L_x} dx \int_0^{L_x} dx' e^{-ik(x-x')} \langle \delta\rho(x)\delta\rho(x') \rangle. \quad (2.1)$$

The quantity σ_k^2 represents the spectral correlator. When the system enters the instability region (*i.e.* when the time t is equal to t_{inst}) the quantity σ_k^2 exhibits an exponential growing of the type:

$$\sigma_k^2(t) = \sigma_0^2 e^{2t/\tau_k} \quad (2.2)$$

clearly indicating the presence of an unstable mode with associated imaginary energy $E_k = i\hbar/\tau_k$ [12,13]; σ_0^2 represents the amount of fluctuations present at the time of instability and clearly scales with the number of test particles per nucleon N_{TP} [11]. A saturation of the exponential growth is expected when fragments are formed and the system is back in a stable dynamical region.

In order to study the sensitivity of fragment formation (in particular of the instability time and of the number of fragments) to the dynamics of the reaction, we have performed calculations changing the beam energy and the considered equation of state. The e.o.s. can be easily modified using a different value of the parameter σ in the Skyrme-like form of the mean field potential $U = A(\rho/\rho_0) + B(\rho/\rho_0)^\sigma$.

Requiring a binding energy of 16 MeV at $\rho = \rho_0$, *i.e.*

$$E/A(\rho = \rho_0) = \left(\frac{A}{2}(\rho/\rho_0) + \frac{B}{\sigma+1}(\rho/\rho_0)^\sigma + \frac{1}{4m}\hbar^2\pi\rho \right)_{\rho=\rho_0} = -16 \quad (2.3)$$

(in order to simulate three dimensional nuclear matter) and the minimum condition for this point ($(\partial(E/A)/\partial\rho)_{\rho=\rho_0} = 0$), we obtain the following sets of values for the parameters A and B :

$$\sigma = 2 \quad A = -100.3 \text{ MeV} \quad B = 48 \text{ MeV} \quad (I)$$

$$\sigma = 3 \quad A = -84 \text{ MeV} \quad B = 32 \text{ MeV} \quad (II)$$

In the following we will refer to the parameterization (I) as "soft" equation of state (compressibility modulus $K = 288 \text{ MeV}$), while the parameterization (II) will give the "stiff" equation of state ($K = 432 \text{ MeV}$).

Let us discuss first the effects that can be seen in the fragment formation if we change the beam energy. Increasing the beam energy, the system is allowed to perform larger oscillations in density (see fig. 1a). Because of these oscillations, a volume instability region is reached and then the formation of fragments becomes the most likely mechanism of de-excitation. Corresponding to the enhanced beam energy, the value of the density, when the system becomes unstable, is smaller, since the temperature in the participant zone is expected to be larger [1,12]. Consequently the pattern followed by the fragmentation and, in particular, the number of fragments that we obtain in the final state may change. Another effect of the increased energy is an earlier fragment formation due to the faster dynamics.

In our case the most unstable mode at the instability time corresponds to $K = 6$ for $E/A = 40 \text{ MeV}/u$ [11] and to $K = 6 - 7$ for $E/A = 70 \text{ MeV}/u$ when K represents the node number $K = kL_x/2\pi$.

As we can see from fig. 1b, where we plot σ_k^2 for $K = 6$ as a function of time, the instability time (*i.e.* the minimum point of σ_k^2) changes from $t \approx 50 \text{ fm}/c$ to $t \approx 40 \text{ fm}/c$ and correspondingly the saturation is observed earlier, when we pass from $E/A = 40$ to $E/A = 70 \text{ MeV}/u$. It is interesting to remark that the fragment formation time, *i.e.* the time interval between instability and saturation, seems to not depend on the beam energy. This effect can be related to recent results on fragment formation times deduced from velocity correlation measurements in central events [14,15].

Let us consider now the effects of changing the e.o.s. keeping constant the beam energy ($40 \text{ MeV}/u$). Smaller oscillations in the density are observed using a "stiff" equation of state (see fig. 2a) and the number of fragments reduces to 5.

Moreover the dynamics goes faster, giving an effect similar to that one obtained using a larger beam energy; in fact the instability time and the saturation point are reached earlier (see fig. 2b).

The observed effects on the instability time and on the dominant mode at that time are however quite small. This is expected from the presence of a physical finite range in the mean field construction, important in order to reproduce nuclear surface properties [2]. In

fact in the calculations the mean field potential has been folded with a gaussian function $e^{-r^2/2a^2}$ where $a = 0.87 \text{ fm}$. A natural cut-off in the instability wavelenghts is deduced, with the consequence that the most unstable modes will not be noticeably density dependent [16]. This effect is observed also in realistic three dimensional calculations [18].

However the fact of changing the beam energy or the e.o.s. has also the relevant effect of producing a larger radial expansion velocity of the system. This parameter is indeed very important when one wants to reveal memory effects in fragmentation because there is an interplay between the dynamical expansion and the explosion of instabilities.

3. Fluctuation dependence of memory effects

We stress here that all calculations have been done using the same number of test particles N_{TP} (20 per nucleon). It is very important to remind that the fluctuations present in our approach are strictly related to this number. Thus if we increase the value of N_{TP} (i.e. we correspondingly reduce the amplitude of fluctuations), the system may expand before going to fragmentation. Of course, in this case, the number of fragments and the structure of the fragmentation process will depend on this new situation and consequently on the number of test particles we are using. Therefore the observed number of fragments can be different from the one associated to the mode which is dominant at $t = t_{inst}$. We mean that, because of the dynamical expansion, no prediction can be made about the fragmentation pattern, since it depends on the amplitude of fluctuations and, in our case, on the number of test particles. In fig.3 we show the fragmentation pattern, in the case of the reaction $Ca + Ca$ at $40 \text{ MeV}/u$ ("soft" e.o.s.), changing the used number of test particles. It is possible to observe that the dominant mode at $t = t_{inst}$ ($K = 6$) fully fixes the behaviour of the system when 20 or 80 test particles per nucleon are used (fig.s 3a, 3b); indeed at the later time ($t = 150 \text{ fm}/c$) six fragments are obtained. On the other hand, the number of formed fragments changes from 6 to 7-8 going to $N_{TP} = 200$ (fig. 3c) just because in this case the system may expand before exploding, since fluctuations are small. This can be seen also in the behaviour of the density variance σ_p^2 as a function of time [11].

We have to remark that the first unstable mode ($K = 6$) is not depending on the number of test particles (see fig.3 of ref.[11]). This is a nice indication that the initial distribution (at $t = t_{inst}$) of the strength of fluctuations in phase space, i.e. the seeding of initial state fluctuations, is not related to an arbitrary choice of N_{TP} , provided the mean trajectory up to that point is well described. However our analysis shows that this first unstable mode will not fix the final structure of fragmentation if fluctuations are small and therefore we have time for a symmetric expansion. These density effects on the final pattern will be more and more important going to higher beam energies or considering a "stiff" equation of state, since in both cases we have a higher velocity of expansion.

Memory effects of the dominant mode at the instability time are therefore lost when fluctuations are small, the fragment formation time is long and the spherical symmetric expansion is dominant. In this sense, in order to correctly describe the behaviour of the system, the right physical amount of fluctuations that the system contains must be known. However, we expect the actual value of fluctuations to be quite large at the critical point, in order to get a corresponding short fragmentation time, of the order of 100 fm/c, (see fig.s 1b,2b) in agreement with some first experimental evaluations [14,15]. Therefore we believe that there is a good chance to keep the memory of the collective dynamical effects observed at the instability point in the pattern of fragmentation events.

We can evaluate the dependence of the fragment formation time t_{fragm} on the amount of fluctuations present when the system enters the instability region and then on the number of test particles per nucleon. Since the variance (eq.(2.2)) should reach a fixed saturation value when the fragments are formed, while σ_0^2 is scaling with N_{TP} , we finally get an increase of fragmentation times with increasing the number of test particles per nucleon from N_1 to N_2 :

$$t_{fragm}(N_2) - t_{fragm}(N_1) = \frac{\tau}{2} \ln \left(\frac{N_2}{N_1} \right) \quad (3.1)$$

Because of the logarithmic behaviour and since τ is of the order of 50 fm/c, see fig.1 and ref.s[11,13], we expect a slow dependence of t_{fragm} on N_{TP} . We will get the same value of

the time necessary for fragment formation, around $100 fm/c$, for a wide range of the used N_{TP} . However it is also clear that a very large number of test particles will increase t_{fragm} to values of the same order of the time needed for the expansion of the system and consequent loss of the memory of the first unstable mode is expected. This is what we start to see in fig.3c where $N_{TP} = 200$ was used.

The same argument is valid in a 3D world since very similar times are deduced for the growth of fluctuations and for the expansion. Indeed in various calculations for central collisions around $50 MeV/u$ a fragment formation has been seen [5,17]. The nuclear system enters the spinodal zone at higher beam energy with respect to the 2D case because of pre-equilibrium emission. The instability develops with times τ around $40 fm/c$, as expected from microscopic results solving dispersion relations for nuclear matter [18], while the expansion velocity remains of the order of $1/20 c$ [13,17].

4. Conclusions

We have shown that, when one is interested in the dynamics of critical situations, it is possible to extract very important informations just solving the BNV equation within the test particle approach, provided that the dynamical evolution is correctly described until the system becomes unstable. The dependence of the dominant mode, at that critical point, on the dynamical conditions has been investigated in a simplified model, considering different beam energies and changing the e.o.s. The corresponding effects seem to be not relevant for the structure of the system at the instability time.

However the enhanced expansion velocity can strongly affect the final fragmentation pattern, depending on the amplitude of fluctuations. Intermediate mass fragments are formed from spinodal (volume) instability regions in a competition between two dynamical effects: i) expansion of the system over times t_{exp} and ii) growth of the initial fluctuations to form nuclear clusters over times t_{fragm} . The condition for the possibility of observation of

"memory" effects in the phase space structure of the produced primary *IMF*'s will be

$$t_{exp} \geq t_{fragm} \quad (4.1)$$

which seems well satisfied in central collisions between heavy ions at medium energies ($40 - 70 \text{ MeV}/u$), where a moderate radial flow is present [19]. For central events at higher energies we expect much larger expansion velocities and the system will have no time to enter the spinodal instability region. Opposite scenario will hold in events with very small radial collective flow: a strong coupling among different collective unstable modes is expected with a possible eventual thermalization of the system. A statistical multifragment decay will follow with no direct dynamical effects. This corresponds to the physics of peripheral fragmentation at higher energies [20], to the breaking of projectile- like and target-like fragments recently observed in deep-inelastic collisions at lower energies [21] and to the fragmentation induced by high energy small hadronic projectiles [22].

The expansion characteristic time is certainly changing with the compressibility and with beam energy. On the other hand the fragment formation time is mostly depending on the amount of fluctuations present in the system when entering the instability region and on the growing time of the variances of the leading unstable modes. In a two dimensional reaction model we have shown that for central collisions of symmetric systems at medium energies, $40 - 70 \text{ MeV}/u$, where we expect to deeply enter the nuclear matter spinodal zone [6,8,11]:

i) t_{fragm} is very weakly dependent on the used equation of state and on beam energy, provided a suitable amount of fluctuations are present at the instability time. This implies that essentially always the same collective unstable modes are ruling the fragment production mechanism;

ii) the condition eq.(4.1) is satisfied in actual cases, which means the possibility of observing a strong memory of such dominant modes in fragmentation events;

iii) a purely statistical picture, including a collective expansion, will not be adequate to describe fragmentation events.

The observed effects on fragmentation pattern are general and the method can be certainly extended to realistic 3-dimensional simulations, not only to study spinodal (volume) instabilities. The problem is that in a 3D case one should follow several multipole moments of the density distribution, depending also on the impact parameter.

However the fact that t_{fragm} has a logarithmic dependence on the number of test particles, see eq.(3.1), seems to suggest that realistic dynamical simulations of fragmentation events can be obtained just using the minimum number of test particles which assures a good picture of the mean phase space trajectory in the stable region. Of course a more accurate approach would imply the use of the right physical value of fluctuations. Concerning this subject, work is presently in progress.

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FIGURE CAPTIONS

Fig.1 Time evolution, for the two slabs collision, of the mean density in the participant zone (a) and of the variance of the most unstable mode (b) for $E/A = 40 \text{ MeV}/u$ (circles) and $E/A = 70 \text{ MeV}/u$ (squares).

Fig.2 Time evolution, for the two slabs collision, of the mean density in the participant zone (a) and of the variance of the monopole mode (b) for a "soft" e.o.s. (circles) and a "stiff" e.o.s. (crosses).

Fig.3 Time evolution of density plots of slab-slab collisions for $N_{TP} = 20$ (a), 80 (b) and 200 (c). The first column is at $t = 0$, the second at $t = 100$ and the third at $t = 150 \text{ fm}/c$.

Fig. 1

Fig. 2

x (arb. units)

Fig. 3