Vol. B18 (1987) ACTA PHYSICA POLONICA No 10

CONDENSATION PHENOMENA IN THE FAST EXPANSION OF HOT NUCLEAR SYSTEMS*

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(Received November 26, 1986)

Within a field theoretical model it is shown that a series of numerical experiments with random initial conditions corresponding to hot nuclear systems leads to final stable fragments in a quite natural way. Besides it is expected that this time-dependent break-up description could give a stimulation on future calculations for mass spectra and at least some hints concerning the questions of a quasi-critical behaviour of a finite system.

PACS numbers: 25.70.Np

1. Introduction

Two nulei with a relative velocity close to the speed of light collide. On a time scale of about 10 fm/c a highly excited and compressed nuclear system is formed at a considerably high entropy. How does such a system expand and finally disassemble when passing through a regime of dynamical instabilities? While earlier disregarded, the interest in this question has grown recently. Quite a variety of models have been developed to discuss this question. Most of them, however, by-pass the dynamical evolution of the process and discuss the fragment formation in terms of a quasi-static concept: the freeze-out. These models range from the simple picture of coalescence in phase-space [1], percolation models [2], the thermo-chemical chemical equilibrium among nuclei [3] or nuclear droplets (condensation model [4]) up to the discussion of nuclear matter at strained densities discussing the phase coexistence of a nuclear fluid and a vapor phase [5]. Only few attemps have been undertaken to study the implications of the dynamics of the fragmentation process. They range from a quantum one-body evolution picture [6], over a description by means of a classical Vlasov equation [7], a Vlasov equation supplemented with collision term [8],

* Presented by J. Knoll at the XXVI Cracow School of Theoretical Physics, Zakopane Poland June 1–13, 1986.

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up to an entirely classical model in the frame work of a molecular dynamics approach [9]. I like to report upon the first kind of model which was actually the first one discussing these questions.

2. *One-body evolution at finite entropies*

It was important to realize that mean-field approaches in the sense of treating the whole statistical ensemble by one mean field are principly not capable to treat the phenomenon of multifragmentation. Rather, the individual fluctuations of a certain state out of the statistical ensemble together with the instabilities implied by the saturating nature of the nuclear forces are the decisive factor for fragmentation.

As nuclear binding is of genuine wave mechanical nature (the Pauli-pressure determines the nuclear sizes, not the range of the forces) we consider a quasi-quantum mechanical model. It comprises three ingredients: *a*) the definition of the initial configuration at the onset of the expansion phase, *b*) the dynamics that cranks this configuration through the instability region, and *c*) a definition of the final stable fragments:

a: We assume that up to a certain time ($t = 0$) which may be the moment of the highest compression the reaction can be described by a macrodynamical approach like the cascade or the hydrodynamical models. This may provide sufficient information as to determine the initial state of the expansion phase, e.g. in form of the one-body density matrix $f^0(r, p)$ at time $t = 0$. In line with the high entropy at this time we represent the system by a statistical ensemble of pure states (product wave functions), such that the ensemble average reproduces f^0.

b: Given a Skyrme type of interaction with proper saturation properties each of these pure states (here to after called event) is then propagated by self consistent one-body dynamics. The one-body field which governs the evolution of the event is deduced from the time-dependent one-body density of this product wave function. In this way the dynamics has the knowledge on its proper one-body density and is capable to form fragments which ultimately remain stable due to the nonlinearity of the dynamical equations.

c: A fragment is defined as the connected area in space where the density exceeds a certain threshold value (at present taken as 0.1 of the saturation value of ϱ^0).

So far the study is confined to a 2+1 dimensional model world (two space and one time dimension), and anti-symmetrization is neglegted. We calculated the evolution of a mass 40 system (40 single particle wave functions per event) on a physical theatre of 60 fm by 60 fm size. No additional symmetry is used. A two parameter Skyrme force with saturation at a Fermi-momentum of $k = 1.2$/fm (with the saturation density $\varrho^0 = k^2/\pi$) and binding energy of 16 MeV has been used. We also discuss results with a spin-isospin dependent force.

For our initial study we by-pass the compression phase and assume the initial phase--space distribution f^0 to be of a Gaussian form both in coordinate and momentum space with an initial compression of $\kappa = 2.5$. The momentum parts is parametrised by a Maxwell distribution of 'temperature' T. The single particle wave functions are taken as Gaussian wave functions with random centroids in position and momenta (boost) in accordance with the distribution f^0. Each event of the statistical ensemble corresponds to one random set of positions and momenta for the 40 single particle wave functions.

A few comments are in order: We recall that anti-symmetrization is neglected so far; the study of genuine Fermion systems is in progress [10]. The problems are at the side of formulating appropriate stochastic initial conditions while the dynamical evolution is the same due to the Skyrme nature of the effective interaction. As compared to ordinary mean field theories at finite temperature which treat the whole statistical ensemble in a single common (i.e. ensemble averaged) mean field, here each individual state evolves in its proper one-body field. Thus we account for fluctuations in the one-body field, which in turn generate the various ways the system can granulate. Our picture implies that the evolution for $t \geqslant 0$ is isentropic.

3. *Time development of a hot and compressed mass 40-system*

Let us first consider the developement of one pure state in time as displayed by Fig. 1. The sequence shows the density distribution $\varrho(r, t)$ at four different time steps $t = 0$, 24, 48, 72 fm/c, for an initial value of $T = 50$ MeV. Due to the internal stress caused by the large momentum spread the events immediately expand and overstress around $t = 24$ fm/c, i.e. the density falls below ϱ^0 throughout. One recognizes density depressions (bubbles) in the interior and some areas of higher density at this time initiating the disassembly of the system. At a later stage these density islands are capable to recover back to saturation density sucking in the matter of their local envirement. It turns out that all islands which have at least a mass of two nucleons remain stable and therefore form ultimately stable soliton-like fragments. Indeed, this performance cannot be regarded as a surface evaporation process. It is a boiling dynamics, with bubble formation in the interior while first fragments fly away from the surface.

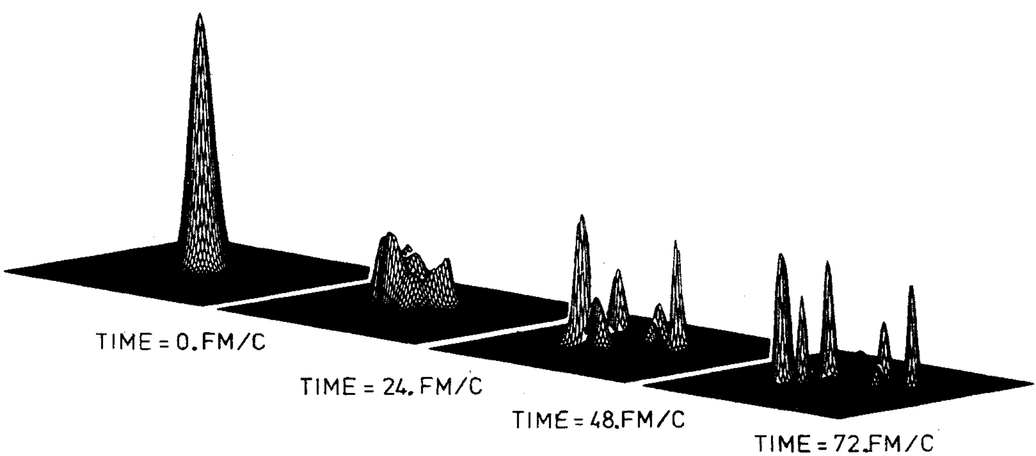

Fig. 1. Disassembly dynamics of a hot and compressed nuclear system from model calculations in a configuration space of two dimensions. The figure displays the time evolution of the density $\varrho(r, t)$ of a certain event at four different time steps. The perspective plot shows vertically the density which initially exceeds the saturation value by a factor 2.5, at a temperature of $T = 50$ MeV

4. *Mass spectra and multiplicity distributions*

Let us finally come to the results not of one arbitrarily and randomly choosen pure state but of the full ensembles. Computing a series of events pertaining to a specific ensemble (T) one can compile multiplicity and mass distributions, Fig. 2.

For the moment we study the dependence on T as well as the dependence on both the initial state correlations and the nature of the binding forces. In detail the following scenarios are discussed:

a: the initial state is spin-isospin correlated, i.e. always the four different spin-isospin wave functions are identical to one another, and the binding force has no spin-isospin dependence.

b: the initial state is not spin-isospin correlated, and the force has no spin-isospin dependence.

c: the initial state is not spin-isospin correlated as in (b), however the force has a spin--isospin dependence, which focusses into the valley of stability ($N = Z$).

The case (c) relative to case (b) clarifies that the nature of the binding force has strong implications on the final mass spectra. An attraction toward equal spin and isospin is incorporated in the force of case (c). Clearly this force focusses nucleons which emerged as free nucleons in case (b) to bound fragments up to mass 4 in case (c). Note that the initial conditions in case (c) and (b) are taken precisely identical from event to event. In case (a) we see that the initial correlations are carried over into the distribution of final fiagments, favouring mass 4-type fragments.

Besides the spin-isospin dependence discussed so far, a quite general behaviour of the resulting mass spectra as a function of the excitation energy (comprised in T) can be obser-

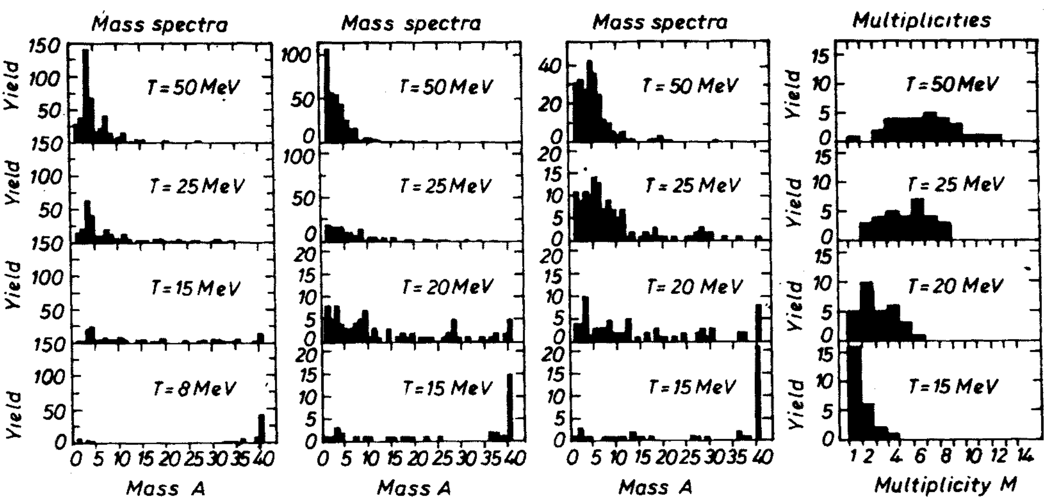

Fig. 2. Mass spectra at four values of T and initial compression of 2.5 ϱ^0 resulting from the ensemble average of thirty runs for each T. The spectra on the r.h.s. are extracted from 60 runs for each T. The figure contains from left to right the mass spectra for the cases (*a*) to (*c*) as explained in the text and the multiplicity distribution of case (*b*)

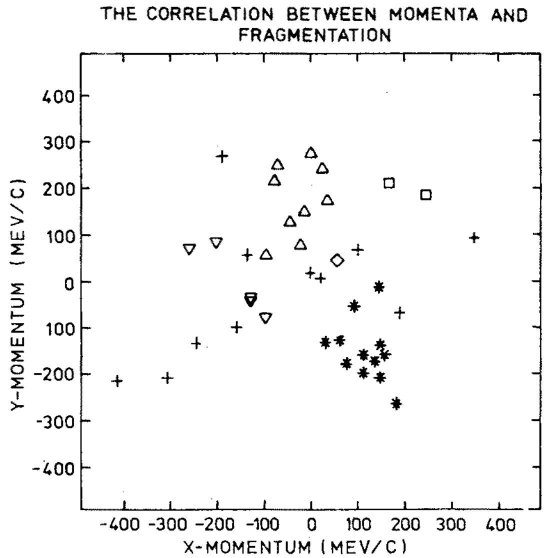

Fig. 3. Distribution of the initial momenta of the single particle wave functions of one event and their assignment to the different final fragments. The + denote those wave functions which essentially go into the back groud, i.e. into no stable fragment. Else the initial momenta of wave functions going into the same fragment are plotted by the same symbol

ved. The tendency of manufacturing smaller droplets with increasing T-parameter is obvious and seems so far neither to be strongly dependent on the number of nucleons of the system nor on the details of the force. At low excitation energies a highly excited compound nucleus remains, or at most, a binary fragmentation occurs. Interesting is the characteristic change of the mass spectra around $T = 20$ MeV, where the spectrum is relatively flat, indicating stron fluctuations in the resulting mass. In analogy to the theory of condensation, one may ask whether such a flat mass spectra represents a signal of a critical behaviour of the system.

5. *The role of initial fluctuations*

The picture employed is such that given the initial configuration the final outcome of the fragmentation dynamics is determined deterministically by solving the the equations of motion. To this extent the description preserves the entropy, certainly a limitation of the model as it omitts possible collision terms. In turn, however, given this model, one can ask the question which pieces of information contained in the initial state actually determine the fragmentation. In our case the initial state is entirely given by the initial position and momentum (cetroids of the corresponding Wigner distribution) of all the single-particle wave functions at $t = 0$. For this purpose we performed the following analysis: Each wave function fractions and goes with a certain probability into any of the fragments or into the back ground which does not belong to any of the fragments. However, it turns out that more than 50% of its probability goes into only one fragment or into the back ground density. We then looked into the distribution of all classical initial positions of the wave functions going essentially into one fragment, and likewise we did for the initial momenta. As a result of this analysis we stated a strong correlation among the distribution of the initial momenta, Fig. 3, and the final fragmentation, while such a correlation could not be established for the initial positions. Evidently a coalescence or percolation picture employed in momentum space may be a much better phenomenological approach to describe the dynamics than employed in coordinate space or actually the product space of both. Yet, a definite answer cannot yet be given as we may not have performed the analysis at a time which one likes to call the moment of freeze-out. This still has to be established. In a way it is a work similar to that of analysing an experiment, and a lot of experience is still needed to come behind the secrets of multifragmentation.

6. *Conclusions*

Within a field theoretical model we have shown that a series of numerical experiments with random initial conditions corresponding to hot nuclear systems leads to final stable fragments in a quite natural way. Besides, it is expected that this time-dependent break-up description could give a stimulation on future calculations for mass spectra and at least some hints concerning the questions of a quasi-critical behaviour of a finite system.

Certainly there are a lot of open questions relative to the presented approach. One concerns the neglect of the residual interactions in our approach. There are physical arguments in favour that they may not be that important once one considers a statistical ensemble, as we do. Second concerns the definition of the initial state. Here, a coupling to an other dynamical theory for the initial entropy generating phase is certainly desirable. The third concerns the generalisation to a genuine 3+1 dimensional model.

In conclusion, we think of having presented a full scale micro-dynamical model which opens a challenging perspective of studying many of the pending questions on micro--dynamical instabilities. Furthermore, we expect some insight from the comparison of this model study with quasi-static, i.e. freeze-out consideration to the same dynamical system. Some investigations in this direction are in progress [10].

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