The Path of Hot Nuclei Towards Multifragmentation

G. Papp [a,1] and W. Nörenberg [a,b]

[a] *Gesellschaft für Schwerionenforschung, D-64220, Darmstadt, Germany*

[b] *Institut für Kernphysik, TH Darmstadt, D-64289, Darmstadt, Germany*

Abstract

The initial production and dynamical expansion of hot spherical nuclei are examined as the first stage in the projectile-multifragmentation process. The initial temperatures, which are necessary for entering the adiabatic spinodal region, as well as the minimum temperatures and densities, which are reached in the expansion, significantly differ for hard and soft equations of state. Additional initial compression, occurring in central collisions leads most likely to a qualitatively different multifragmentation mechanism. Recent experimental data are discussed in relation to the results of the proposed model.

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[1] On leave from the Institute for Theoretical Physics of Eötvös University, H-1088 Budapest, Hungary

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1 Introduction

New results [1,2] on projectile multifragmentation in relativistic heavy-ion collisions indicate relations to the liquid-gas phase transition of nuclear matter. Motivated by these experiments we like to substantiate this conjecture by studying the evolution of the excited projectile residue into the region of instability.

In the following we report results on the expansion dynamics of hot spherical nuclei. We estimate the initial excitation energy from the abrasion model [3,4] using modifications introduced in [5]. The dynamical expansion of the heated spherical residue is calculated taking the evaporation of nucleons into account [6].

The expansion of the projectile residue can be regarded as the first stage in the multifragmentation process. For large enough initial excitation energies and temperatures the nuclear matter of the residue reaches states of mechanical volume instability, where small density fluctuations grow exponentially [7–9]. For an illustrative analysis of the instability evolution we refer to ref. [10]. The fragmentation process itself has been studied within molecular dynamics [11–14]. Studies by Friedman [15,16] within an expanding emitting source model (EES) show that intermediate mass fragments (IMFs) are indeed created within time intervals of about 50 fm/c indicating a simultaneous breakup of the residue.

2 The Model

In this section we describe a few essential features of the model. A more detailed description of the model will be published elsewhere [17].

We start out from a thermalized spherically symmetric projectile-like nucleus at ground state density, which has been created in the peripheral high-energy collision (cf. [18]). The typical temperature for such a hot nucleus is not too high, such that the mean free path of nucleons is still comparable or even larger than the size of the system [6]. Thus, we can approximately assume homogeneity in density and temperature for the expanding nucleus.

During the expansion the hot nucleus evaporates particles. We consider only neutron and proton evaporation. Deuterons may be considered to arise from coalescence of nucleons.

If the excitation energy is high enough, the expansion leads into the instabil-

ity region of the equation of state. For not too high excitation energies the expansion of the homogeneous system stops at a certain density. Around these turning points the system has enough time ($\geq$ 30 fm/c, [7,9]) to develop inhomogeneities in density, and subsequently decay into many fragments. The final mass and charge spectra is not given by this model, but the calculated turning-point parameters (temperature and density) can be applied to static statistical models [19,20] and related to experimental results (cf. sect. 3). In a complete dynamical treatment of multifragmentation the turning points are the initial states for the decay into the final fragments.

2.1 Abrasion

The starting point in our calculations is the determination of the projectile residue (prefragment) which is produced in the heavy-ion collision. A simple picture for relativistic collisions is obtained by assuming that the particles in the overlap zone of the two colliding nuclei are stopped, while the spectators are propagating with their initial velocities. In the original abrasion model [4] the excitation energy of the residues is calculated from the change of the surface. For this geometrical abrasion process simple expressions for the mass and energy of the participants and spectators have been given.

Gaimard and Schmidt [5] have improved this model by calculating the excitation energy of the residue from the hole-state creation with 13.3 MeV excitation energy in average for each abrased particle:

$$E^* = \alpha \cdot \Delta A, \quad \alpha = 13.3\mathrm{MeV}. \tag{1}$$

This prescription is in good agreement with the results of BUU calculations [21] , and yields the excitation energy of the projectile independent of the target. At small values of the mass loss this picture underestimates the BUU prediction of the excitation energy, and a higher value of α = 26.6 MeV was suggested. Also recent calculations of Campi et. al. [22] suggest somewhat higher value for the excitation energy. We have used both values in our calculations. The charge-to-mass ration is assumed not to change by the abrasion process.

Furthermore we assume, that after the abrasion step the system equilibrates fast. Estimating the equilibration times according to ref. [23], we find indeed values which are small compared to the expansion times.

2.2 Expansion

Due to the supposed homogeneity in density, the radial flow is of the form $\vec{v}(t,\vec{r}) = a(t)\vec{r}$ with $a = 0$ initially. All the other variables – the density $\varrho(t)$, the temperature $T(t)$, the mass number $A(t)$ and the charge $Z(t)$ depend only on time.

The evaporation of nucleons yields the time evolution of mass and charge, and is the only source for loss of energy and entropy. The evaporation integral is calculated according to [6], and evaluated numerically. In this evaporation model we need to know the mean free path not only at nuclear matter density, but at all densities reached during the expansion. We assume that the density dependence of the in-medium cross-section in the range of $0.3\varrho_0$ to ϱ_0 (normal nuclear density) is essentially due to the Pauli-blocking factor. We found that the contribution from the Pauli effect is inversely proportional to the density for the temperatures, energies and densities in question. Therefore, the mean free path is considered here as independ on the density.

The equation of motion is determined from energy and entropy conservations with loss terms which are due to the evaporation of nucleons.

The expansion is studied for a soft and a hard equation of state using, respectively, the Skyrme forces SkM* and SIII, cf. [24]. We follow the time evolution up to the turning point, where the density reaches its minimum. The system spends most of its time around the turning point, and hence the fragmentation process is expected to start here. For too low excitations the system cannot enter the ϱ, T region of instability, and hence a heavy residue will remain. For high excitations no turning point is encountered in the expansion and, therefore, the system is expected to explode [25].

3 Results and Discussion

As an example of projectile multifragmentation we consider the reaction Au (600 MeV/u – 1 GeV/u) +X with X=C,Al,Cu which has been studied experimentally by the ALADIN group [1,2].

3.1 Expansion trajectories

According to the abrasion model (subsect. 2.1), the initial excitation energy (temperature) is correlated with the charge number of the projectile residue.

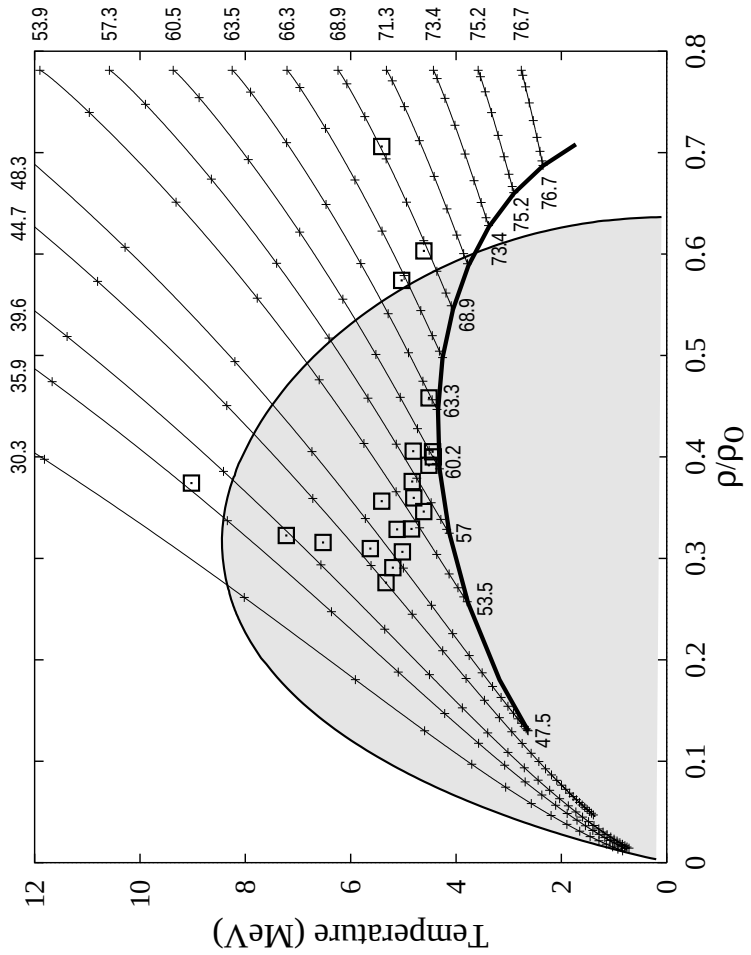

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Fig. 1. Time evolution in the (T, ϱ)-plane of the Au residue for a soft equation of state (SkM*). The crosses on the trajectories indicate time steps of 5 fm/c. The numbers give the charge numbers initially and at the turning points which are connected by the heavy solid line. The adiabatic spinodal region is shadowed. The open boxes denote the experimental data [2] (without error bars).

These numbers are given in Figs. 1 and 2. The calculated expansion trajectories in the (T, ϱ)-plane are significantly different for a soft (Fig. 1) and a stiff (Fig. 2) equation of state (EOS). They deviate from adiabats due to the evaporation of one to four nucleons. The number of evaporated nucleons is so small because of the fast cooling by the expansion of the system.

We follow the trajectories up to their turning points if reached within 200 fm/c. The turning points are indicated by the heavy solid lines. Turning points exist for initial temperatures up to about 14 MeV. We notice that the turning points for the same initial excitation lie one to two MeV in temperature and $0.1\varrho_0$ to $0.2\varrho_0$ in density higher for the stiff EOS as compared to the soft one. Moreover, we see that the turning points are located almost at the same temperatures

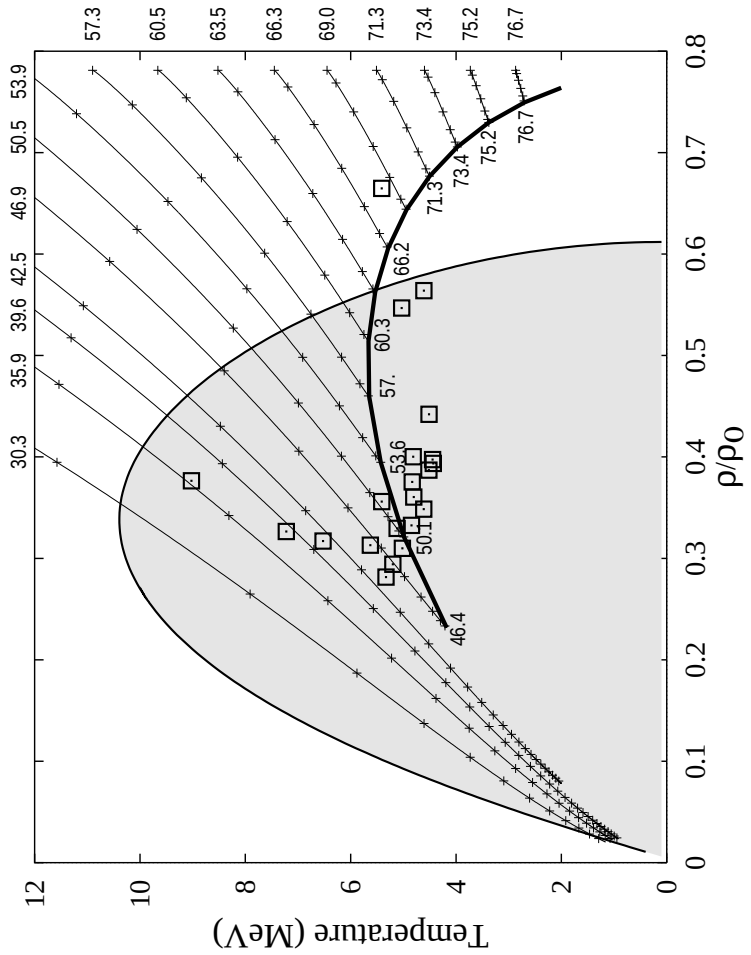

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Fig. 2. Same as Fig. 1 for a stiff equation of state (SIII)

independent of the initial excitation, i.e. around 4 MeV and 5 MeV for the soft and hard EOS, respectively. This plateau does not move if one changes the initial excitation energy (the α parameter in (1)), the only effect is, that the charge numbers become different initially and at the turning points.

3.2 Multifragmentation

A natural criterion for multifragmentation to occur, is whether the system reaches the region of volume instability (adiabatic spinodal region), where the derivative of the pressure with respect to the density along an adiabat becomes negative. Since the system is closed we consider the adiabatic process to be the relevant one. In Figs. 1 to 3 the region of instability is shadowed and bounded by the spinodal. To enter the spinodal region and stay there for more than 30 fm/c one needs initial temperatures of about 8 MeV and 11 MeV for the soft

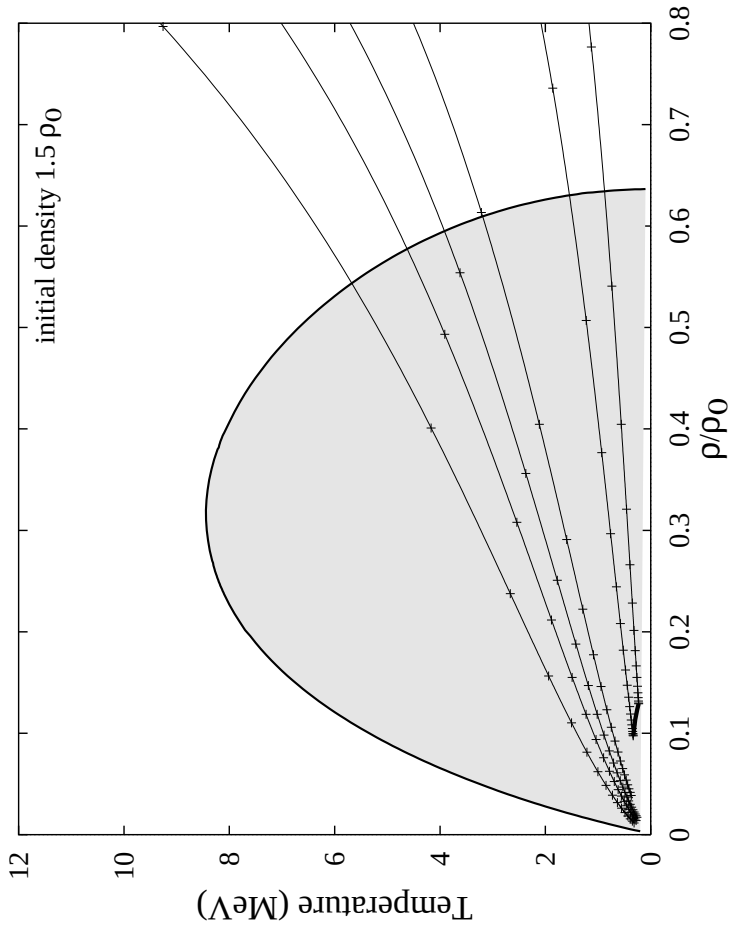

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Fig. 3. Same as Fig. 1 with additional initial compression to 1.5 ϱ_0 for the soft EOS

and hard EOS, respectively.

Because of the occurrence of turning points in the expansion, the multifragmentation process of the projectile residue has a unique feature: the subsequent decay into fragments is expected to be rather free from collective flow. This is different from the fragmentation of compressed compound systems which are formed in central collisions. As shown in Fig. 3, already for a small initial compression (1.5 ϱ_0) no turning points occur for realistic initial excitation energies. Thus the fragmentation process becomes qualitatively different and looks more like an explosion [25].

3.3 Comparison with experimental results

Pochodzalla et al. [2] have determined the temperature of the final break-up into fragments as function of the initial excitation energy. In Figs. 1 and 2 we have plotted the experimental break-up temperatures on the trajectories (or their extrapolations beyond the turning points) for the corresponding initial temperature. The experimental errors in the excitation energy transform into errors in the density of about $\pm 0.06\,\varrho_0$. We observe the following features.

- The onset of multifragmentation is around 8 MeV of initial temperature in agreement with the soft EOS.
- The experimental points, which are related to initial temperatures between 6 MeV and 8 MeV, correspond to large values for the maximum charge of the fragments, and hence suggest an evaporation-like process.
- For the stiff EOS no reasonable picture is obtained which would be consistent with the experimental results.
- There is some indication from molecular dynamics [11,12] that after a relatively fast expansion close to adiabats the system follows a path close to $T = const$ with some tendency to increase the temperature. Assuming that this is correct we would also conclude that the soft EOS gives results which are consistent with experiment, whereas the stiff EOS does not fit.
- For initial temperatures larger than about 12 MeV to 14 MeV the system reaches densities well below $0.3\varrho_0$ before approaching the turning point. At these densities collisions between nucleons become rare, and hence this temperature is expected to be observed in the final fragments.

4 Summary and Conclusion

We have studied the expansion of hot nuclei for a soft and a stiff equation of state. Turning points are encountered for initial temperatures smaller than about 14 MeV. Explosive events occurs for initial temperatures larger then 12 MeV to 14 MeV.

Projectile fragmentation appears to be the optimal process for the study of the phase-transition region, because there is no compression involved in the formation of initial state. Already small additional compression, as expected in central collisions, lead to explosion.

The occurrence of turning points in projectile fragmentation suggests to divide the multifragmentation process into two steps. The first step is approximately described by the expansion of a homogeneous nuclear drop, because the time necessary for the development of instabilities is too large. The second step

starts from the turning point and leads to a relatively slow further expansion by developing inhomogeneities. This slow evolution may be the reason why equilibrium models [19,20,22] describe the fragment distribution quite well.

Comparison with experimental results, obtained by the ALADIN collaboration [2], gives evidence that the soft equation of state is more realistic. In particular, the onset of multifragmentation at around 8 MeV initial temperatures is only consistent with the soft equation of state. Furthermore, the break-up into fragments around a freeze-out density of $\varrho/\varrho_0 = 0.3$ is indicated for initial temperatures higher than about 12 MeV to 14 MeV.

We conclude that further dynamical studies of the fragmentation process and comparison with experimental results may yield more precise information about the equation of state in the low-density region. In particular dynamical treatments of the fragmentation process starting at the turning points are needed.

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