

NON-EQUILIBRIUM PHASE TRANSITIONS IN ULTRARELATIVISTIC NUCLEAR COLLISIONS

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ABSTRACT. Highly excited nuclear matter created in ultrarelativistic heavy-ion collisions possibly reaches the phase of quark deconfinement. It quickly cools down and hadronises. We explain that the process of hadronisation may likely be connected with disintegration into fragments. Observable signals of such a scenario are proposed.

Ultrarelativistic nuclear collisions are probed with the aim to create and study nuclear matter under most extreme conditions ever created in laboratory [1]. In collisions at the Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory and in future collisions at the LHC (CERN) matter in state with deconfined quarks and restored chiral symmetry is produced. Due to initial conditions with longitudinally fast moving nuclei and strong inner pressure the created deconfined bulk matter expands very quickly. It cools down, returns into hadronic phase, and disintegrates into individual final state hadrons in a short time period of the order 10 fm/c, or 10^{-22} s. It is less clear whether deconfined and chirally restored matter is produced in collisions at lower energies, like those at CERN's Super-Proton Synchrotron (SPS) (see e.g. discussion in [1]). In any case, at lower collision energies matter is produced with higher baryochemical potential.

The phase diagram of strongly interacting matter is depicted in Figure 1. At vanishing and small baryo-

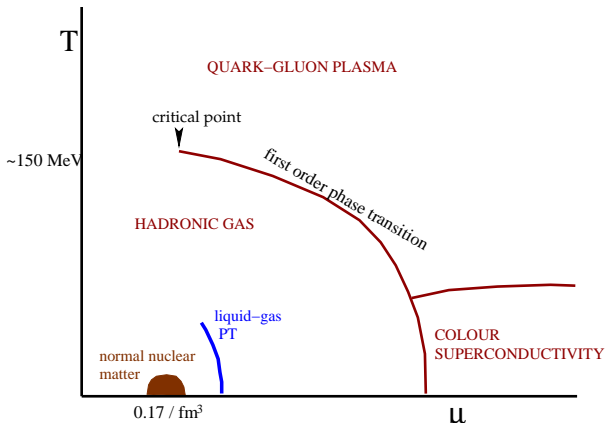


Figure 1: The phase diagram of strongly interacting matter.

ochemical potential hadronic phase changes smoothly (though rapidly) into quark-gluon phase and there is no phase transition (no discontinuity of any derivative of the energy). As the baryochemical potential is increased, a first order phase transition appears. The line of the phase transition ends in a critical point in which second order phase transition is realised. Its position is currently unknown and is subject of an intense search.

As we mentioned, the system expands rather rapidly. If it does reach the quark-gluon phase in the region with high baryochemical potential, then it rapidly passes through the boundary of the two phases in the phase diagram. It is quite general behaviour that

if thermodynamic system expands quickly through a phase boundary of a *first order phase transition* it remains in the high temperature phase and supercools. If the expansion is fast enough it reaches the spinodal and fragments into pieces of characteristic size. This process is studied in general physics [2] but appears also in multifragmentation in nuclear collisions at energies of the order 100 MeV per nucleon [3, 4].

On an elementary level spinodal fragmentation can be illustrated with the help of van der Waals equation of state (Fig. 2). Rapidly expanding system follows the

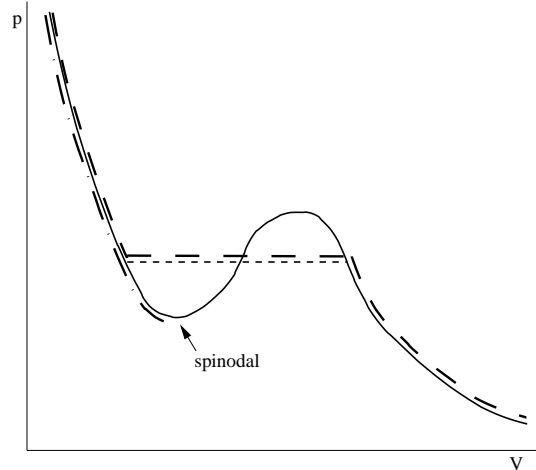


Figure 2: Isotherm of the van der Waals equation of state. Slow phase transition follows the Maxwell construction (long-dashed line). Fast expansion follows the original van der Waals curve until it reaches the local minimum of the isotherm (the spinodal) and fragments (dash-dotted line).

van der Waals curve rather than the Maxwell construction. It may follow that curve down to the first minimum; then dp/dV on the isotherm becomes positive, which is an instable solution. The system thus goes into spinodal fragmentation.

This scenario is realised if the expansion rate $V^{-1} dV/dt$ is larger than the nucleation rate of bubbles of the new phase $\Gamma \propto \exp(-\Delta F_*/T)$, where ΔF_* is the difference of free energies: that of the old phase minus free energy of a bubble of the new phase [5]. Model studies with linear sigma model coupled to quarks (to model chiral phase transition) indicate that realistic expansion rate indeed is larger than the bubble nucleation rate and thus spinodal decomposition is relevant scenario for heavy ion collisions [6].

One naively expects that such a decomposition sce-

nario may be disregarded at RHIC and LHC where the fireball most probably evolves through the rapid crossover transition and not first order phase transition (so no spinodal decomposition can be realised). However, it has been noted that even in the region of rapid crossover the *bulk* viscosity ζ (unlike the *shear* viscosity) suddenly shows a sharp peak as a function of temperature [7, 8]. Recall that the corresponding viscous force is proportional to $\zeta \partial_i u^i$ and that in strongly expanding fireball the divergence of velocity is large. Thus sudden peak in bulk viscosity corresponds to following scenario: First the fireball in high-temperature phase begins to expand strongly. Then, at crossover suddenly a force appears which basically makes it very stiff in the sense “not willing to expand”. This force tends to *decelerate* the expansion. However, there is inertia of the matter, so it may happen that the bulk will not be able to respond to the viscous force and fireball will be torn apart into pieces.

Assuming that this kind of breaking happens if the dissipated energy equals kinetic energy of the matter, in [9] it was estimated that characteristic size of fragments (in one-dimensional boost-invariant expansion scenario) is $L^2 = 24\zeta_c \tau_c / \varepsilon_c$, where τ_c is the time when crossover is reached, ε_c the energy density at that point, and ζ_c is a scaling factor of the bulk viscosity at the same point ($\zeta(\tau) = \zeta_c \tau_c \delta(\tau - \tau_c)$).

Such fragmentation would have implications on many observables, mainly correlations and fluctuations. A Monte Carlo generator of particles has been developed which simulates particle emission from such droplets.

It has been proposed that emission from droplets will lead to modifications of particle correlation functions [10, 11]. Due to their large mass, such a modification will be best visible for protons [11]. We sampled such correlation functions with our Monte Carlo generator and observed that the peak of the correlation function clearly appears with increasing fraction of particles produced from droplets and increasing droplet size (Fig. 3).

Emission of particles from fragments may result in non-statistically varying rapidity distributions in individual events. We propose a method for recognising non-statistical fluctuations of rapidity distributions based on Kolmogorov-Smirnov test [12].

A scenario of fireball fragmentation and subsequent emission of particles from fragments could also help to reconcile hydrodynamic simulations with femtoscopy data. Currently, there is a sharp disagreement which does not improve if freeze-out is treated “correctly” by using a cascade generator as an afterburner. Major part of the failure is due to the shape of freeze-out hypersurface in the simulations. This is modified if our fragmentation scenario is assumed [9].

Finally, let us note that there are other effects observed in RHIC data which indicate clustering of the hadrons at the emission. PHOBOS collaboration tested such hypotheses on data on multiplicity fluctuations [13] and two-particle correlations [14]. It was also conjectured that non-statistical fluctuations of mean p_t at RHIC may be due to clustering of particles [15].

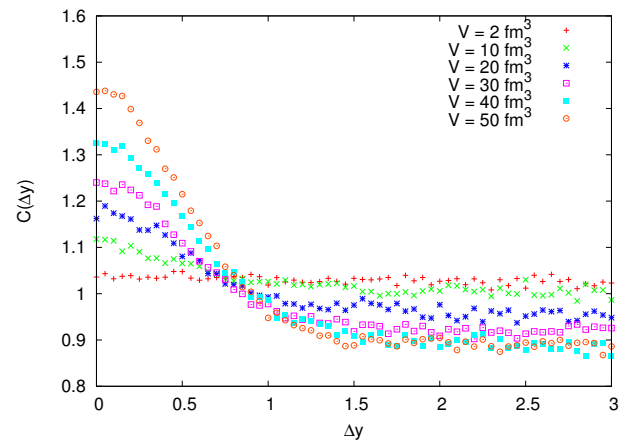


Figure 3: Proton-proton correlation as a function of the rapidity difference. No interactions between protons are taken into account, functions are not normalised. Protons come from events with 900 hadrons. All hadrons are emitted from droplets. Droplets are distributed according to Gaussian with rapidity width of 1.3. Indicated is the volume of fragments.

We shall continue to investigate phenomenological consequences of the fragmentation scenario.

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