Density Perturbations in Heavy-Ion Collisions below the Critical Point

A. Dumitru, K. Paech and H. Stöcker

Institut für Theoretische Physik, Universität Frankfurt a.M., Germany

Universality arguments suggest that the chiral phase transition for two massless quark flavors is second-order at baryon-chemical potential $\mu_B = 0$ [1], which then becomes a crossover for small quark masses. On the other hand, a first-order phase transition is predicted by a variety of low-energy effective theories for small temperature T and large μ_B [2]. Hence, the first-order phase transition line in the (μ_B, T) plane must end in a second-order critical point [3]. For $2+1$ quark flavors the critical point has been located at $T = 160$ MeV and $\mu_B = 725$ MeV [4]. However, a reliable extrapolation to the continuum limit and to physical pion mass has not been attempted so far.

There is an ongoing experimental effort to detect that critical point in heavy-ion collisions at high energies. It is hoped that by varying the beam energy, for example, one can "switch" between the regimes of first-order transition and cross over, respectively (higher energies correspond to larger entropy per baryon or T/μ_B).

To investigate collective dynamics in the vicinity of the critical endpoint we introduce a model for the real-time evolution of a relativistic fluid of quarks coupled to non-equilibrium dynamics of the long wavelength (classical) modes of the chiral condensate [5]:

$$\partial_\mu \partial^\mu \phi + \partial V_{\text{eff}}/\partial\phi = 0\ ,\ \partial_\mu \left(T^{\mu\nu}_{\text{fl}} + T^{\mu\nu}_{\phi} \right) = 0. \qquad (1)$$

Here, $T^{\mu\nu}_{\text{fl}}$ is the energy-momentum tensor of the fluid, $T^{\mu\nu}_{\phi}$ that of the classical modes of the chiral condensate, and V_{eff} is the effective potential obtained by integrating out the thermalized degrees of freedom. We focus first on energy-density inhomogeneities for vanishing baryon density (the nature of the transition is then determined by the effective quark-field coupling rather than the baryon-chemical potential [5, 6]). We allow for "primordial" Gaussian fluctuations of the condensate ϕ on length scales ~ 1 fm on top of a smoothly varying mean field. If propagated through a first-order chiral phase transition these fluctuations give rise to a rather inhomogeneous (energy-) density distribution as seen in Fig. 1. Such effects were previously studied in the context of the QCD transition in the early universe, where inhomogeneities of the entropy (or baryon to photon ratio) might affect BBN [7]. However, in the cross-over regime we find much smaller amplitudes of density perturbations [5].

In heavy-ion collisions the scale of the density perturbations is too small for them to be resolved in rapidity space. This would require a resolution $\Delta y < 1$, which is about the thermal width of the local particle momentum distributions. However, observable consequences of large density inhomogeneities created in a first-order transition at beam energies below the critical endpoint may still exist. (Inhomogeneities from fluctuations of particle production in the primary nucleon-nucleon collisions [8] should be largely washed out until decoupling.) For example, fluctuations of the energy-momentum tensor of matter in coordinate space are uncorrelated to the reaction

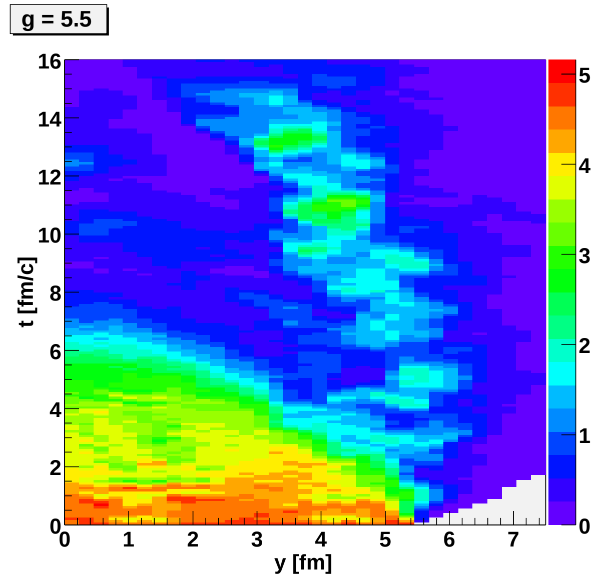

Figure 1: Fluid energy density distribution in space-time for a first-order chiral phase transition [5].

plane and should therefore reduce out-of-plane collective flow ($v_2/\langle p_t \rangle$) as compared to equilibrium hydrodynamics [5]. Moreover, by analogy to BBN, perturbations of the entropy per baryon s/ρ_B should affect abundances of rare hadrons: $\bar{B}/B$, $\bar{\Lambda}/\bar{p}$ [9] and K^+/π^+ [10] are larger than for a homogeneous system with the same total volume, baryon number and entropy.

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