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FRAGMENTATION OF THE FIREBALL AND HOW TO OBSERVE IT*

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We argue that fragmentation at hadronisation is likely scenario in ultrarelativistic nuclear collisions. In case of crossover phase transition it is driven by a singularity of the bulk viscosity. We claim that such a scenario can explain the "HBT puzzle" and can be identified by non-statistical differences between event-wise rapidity distributions and by proton–proton rapidity correlations.

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1. Introduction

In ultrarelativistic heavy ion collisions we aim at creating deconfined and chirally restored matter. Even if that goal is reached, the system expands dramatically and eventually undergoes transition to hadronic phase. From lattice QCD we know that at vanishing and/or small baryochemical potential the transition is a rapid though smooth crossover [1]. The crossover becomes sharper as the baryochemical potential increases and turns into a first order phase transition at a critical point.

It is rather well known that if a system expands very fast through a first order phase transition it supercools and fragments via spinodal decomposition. Fragmentation, however, can also occur in case of rapid crossover [2]. The culprit for this is singular behaviour of bulk viscosity near $T_{\rm c}$ [3, 4].

Fragmentation would affect measured sizes of the fireball, event-wise rapidity spectra, and clustering would be seen in rapidity correlations [5, 6].

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2. Fragmentation in rapid phase transitions

First order phase transitions run via nucleation initiated on impurities or thermal fluctuations. In general, time is needed to nucleate critical bubbles by thermal fluctuation. In rapidly expanding systems, if the expansion rate is bigger than the rate for critical bubble nucleation large supercooling can occur [7]. The system can reach the spinodal point in which mechanical instability leads to fragmentation [8].

It may seem that fragmentation scenario is irrelevant for heavy ion collisions at RHIC and LHC which run in the region of phase diagram where smooth crossover appears. However, even in this regime bulk viscosity as a function of temperature shows singular behaviour at $T_{\rm c}$ [3,4]. It is negligible otherwise. Bulk viscosity appears in the term $\zeta\partial_\mu u^\mu$ and thus scales the reluctance of the fluid to change its volume; large ζ means that the system resists against fast changes of the volume.

Hence, from the beginning of the collision the fireball expansion accelerates and large expansion velocity is built up. Then, at $T_{\rm c}$ suddenly large bulk viscosity appears and makes the fireball "rigid", *i.e.* not willing to expand. On the other hand, inertia tries to keep the expansion going. As a result of these two competing effects the bulk may break up into fragments if its inner forces cannot hold it together anymore. In [2] typical size of fragments was estimated for Bjorken one-dimensional expansion from energy considerations

$$L^2 = \frac{24\zeta_{\rm c}\tau_{\rm c}}{\varepsilon_{\rm c}}\,, \tag{1}$$

where $\tau_{\rm c}$ and $\varepsilon_{\rm c}$ are the proper time and energy density at $T_{\rm c}$, and $\zeta_{\rm c}$ parametrizes the singular behaviour of bulk viscosity $\zeta(\tau) = \zeta_{\rm c}\delta(\tau - \tau_{\rm c})$.

After the fragmentation, final-state hadrons evaporate from fragments.

3. Observable consequences: femtoscopy

A failure of hydrodynamic simulations to reproduce the measured correlation radii is known as the "HBT puzzle" [9]. Simulations yield the outward correlation radius $R_{\rm o}$ much too big in comparison with the sideward radius $R_{\rm s}$. In terms of second-order spatial moments of the source $R_{\rm o}^2 = \langle\tilde{x}^2\rangle - 2(K_t/K_0)\langle\tilde{x}\tilde{t}\rangle + (K_t^2/K_0^2)\langle\tilde{t}^2\rangle$, where K is the average pair momentum and the x-coordinate is directed parallel to K_t (tilde denotes coordinates w.r.t. mean position of the source). The correlation radii are determined by the size, orientation, and shape of the freeze-out hypersurface. A typical freeze-out hypersurface from hydrodynamic simulation leads to negative $\langle\tilde{x}\tilde{t}\rangle$ term and thus increases $R_{\rm o}$. In a scenario with freeze-out from fragments, hadrons are emitted from a different interval of the space-time and this could solve the "HBT puzzle" [2,10].

4. Event generator for droplet emission

In order to investigate various observables which could be measured in case of fireball fragmentation a Monte Carlo generator has been developed which generates positions and momenta of hadrons. In its spirit it is similar to Therminator [11], though partices are emitted from fragments. This leads to clustering in momentum space, since particles emitted from one fragment inherit their velocities close to that of the fragment. For the results presented here no resonance decays were included.

5. Observable consequences: event-wise rapidity distributions

If the fireball disintegrates then emitted particles will have rapidities close to those of the fragments. Therefore, there will be (possibly overlapping) clusters in hadronic rapidity distributions. Rapidities of the fragments will differ from event to event. Thus each event will be given by to different rapidity distribution. On the other hand, if there is no fragmentation then in a sample of carefully centrality-selected events rapidity distributions in each event will be the same.

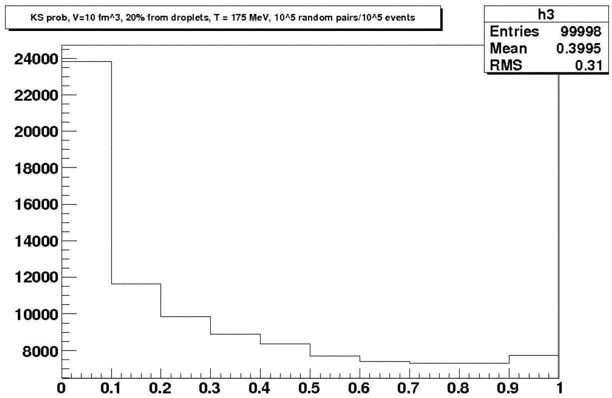

Fig. 1. Typical result of Kolmogorov–Smirnov test on a sample of 10^5 pairs out of 10^5 events events in which 20% of hadrons are emitted from fragments with average volume $10\,\mathrm{fm}^3$.

In statistical sense, we can ask to what extent two sets of measured rapidities from two events look like coming from the same underlying distribution. A standard tool for such a study is Kolmogorov–Smirnov test. An example of our use of the test is in Fig. 1. For shortness we can only mention that flat distribution would correspond to all events looking alike, while a peak at 0 indicates non-statistical differences between events. The signal is very clear. This study will be reported in a forthcoming paper.

6. Observable consequences: rapidity correlations

It has been also suggested that droplets should lead to a contribution to proton–proton correlation function in rapidity [5, 6]. Such correlation functions are shown in Fig. 2. We clearly observe that the visibility of the signal increases with the size of droplets (note that total multiplicity was kept constant in these simulations).

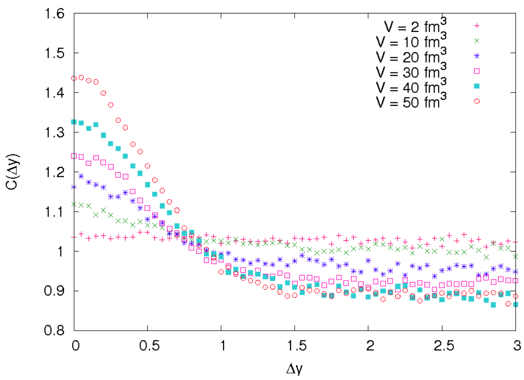

Fig. 2. Proton–proton correlation function in rapidity for varying average fragment sizes. All hadrons are emitted from droplets. Fermi–Dirac statistics and *pp* interaction have not been taken into account. Correlation functions are not normalised.

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