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Fluctuation probes of quark deconfinement

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Fluctuations in the multiplicities and momentum distributions of particles emitted in relativistic heavy-ion collisions have been widely considered as probes of thermalization and the statistical nature of particle production in such reactions [1]. The characteristic behavior of temperature and pion multiplicity fluctuations in the final state has been proposed as a tool for the measurement of the specific heat [2] and, specifically, for the detection of a critical point in the nuclear matter phase diagram [3].

Two recent papers [4,5] drew attention to a different type of fluctuations, which is sensitive to the microscopic structure of the dense matter. If the expansion is too fast for local fluctuations to follow the mean thermodynamic evolution of the system, it makes sense to consider fluctuations of locally conserved quantities that show a distinctly different behavior in a hadron gas (HG) and a quark-gluon plasma (QGP). Characteristic features of the plasma phase may then survive in the finally observed fluctuations. In this spirit we here focus on fluctuations of the net baryon number and net electric charge as probes of the transition from hadronic matter to a deconfined QGP. We consider matter which is meson-dominated, which renders our arguments applicable to SPS energies and above.

In a hadron gas nearly two thirds of the hadrons (for $\mu \ll T$ mostly pions, where μ and T are baryonic chemical potential and temperature, respectively) carry electric charge ± 1 . In the deconfined QGP phase the charged quarks and antiquarks make up only about half the degrees of freedom, with charges of only $\pm \frac{1}{3}$ or $\pm \frac{2}{3}$. Consequently, the fluctuation of one charged particle in or out of the considered subvolume produces a larger mean square fluctuation of the net electric charge if the system is in the HG phase. For baryon number fluctuations the situation is less obvious because in the HG baryon charge is now only carried by the heavy and less abundant baryons and antibaryons. Still, all of them carry unit baryon charge ± 1 , while the quarks and antiquarks in the QGP only have baryon number $\pm \frac{1}{3}$. It turns out that, as $\mu/T \rightarrow 0$, the fluctuations are again larger in the HG, albeit by a smaller margin than for charge fluctuations. At SPS energies and below the difference between the two phases increases since the stopped net baryons contribute to the fluctuations, and more so in the HG than in the QGP phase.

The value of a conserved quantum number of an isolated system does not fluctuate at

all. However, if we consider a small part of the system, which is large enough to neglect quantum fluctuations, but small enough that the entire system can be treated as a heat bath, the statistical uncertainty of the value of the observable in the subsystem can be calculated. This is the scenario considered here.

We first discuss fluctuations of the net baryon number. In the dilute HG phase, we can apply the Boltzmann approximation. The net baryon number is $N_b = N_b^+ - N_b^-$, where N_b^\pm denotes the number of baryons (+) and antibaryons (-), respectively. Then the net baryon number fluctuations in the hadronic gas are given by

$$(\Delta N_b)_{\text{HG}}^2 = 2 N_b(T) \cosh(\mu/T). \quad (1)$$

The late expansion of the fireball being nearly isentropic, the ratio of baryon number fluctuations to entropy S , $(\Delta N_b)^2/S$, provides a useful measure for the early fluctuations. For a transient quark phase the baryon fluctuations are given by [6]

$$\left. \frac{(\Delta N_b)^2}{S} \right|_{\text{QGP}} = \frac{5}{37\pi^2} \left(1 + \frac{22}{111} \left(\frac{\mu}{\pi T} \right)^2 + \dots \right), \quad (2)$$

assuming an ideal gas of massless quarks and gluons with two massless flavors. The entropy can be estimated from the final hadron multiplicity [7]. For high collision energies ($\mu/T \rightarrow 0$), the ratio (2) approaches a constant; even for SPS energies, the μ -dependent correction is at most 5%. The many resonance contributions make it difficult to write down an analytic expression for S_{HG}/V , but it is clear from (1) that the μ -dependence of the corresponding ratio in the HG phase is stronger than for the QGP phase. This translates into a stronger beam energy dependence of (2) near midrapidity.

The results for net charge fluctuations are similar. All stable charged hadrons have unit electric charge; again using the Boltzmann approximation we find $(\Delta Q)_{\text{HG}}^2 = N_{\text{ch}}$, where N_{ch} is the total number of charged particles emitted from the subvolume. The ratio $(\Delta Q)^2/S$ for the QGP is a factor $\frac{5}{2}$ larger than the corresponding ratio (2) for baryon number fluctuations, due to the larger electric charge of the u quarks, but shows the same weak μ -dependence. The main difference to baryon number fluctuations arises in the HG phase: Since at SPS and higher energies N_{ch} is dominated by pions and meson resonances, its μ -dependence is now also weak. In contrast to baryon number fluctuations, charge fluctuations thus show a weak beam energy dependence in either phase, and only their absolute values differ.

Numerical values for the ratios $(\Delta Q)^2/S$ and $(\Delta N_b)^2/S$ at SPS energies and above were derived in [4] and are shown in Fig. 1. The fluctuations in the QGP are typically a factor 2 below those in the HG, with a somewhat smaller reduction for baryon number than for charge fluctuations.

These estimates, including our corrections for resonance decays, refer to ideal gases in equilibrium. Future work should address interaction effects on the thermal fluctuations in HG and QGP [5] and treat resonance decays kinetically. We also point out potentially important non-equilibrium aspects: The fluctuation/entropy ratios in the QGP will be even lower (facilitating the discrimination against HG) if initially the QGP is strongly gluon dominated [8] and thus may lie below the equilibrium value (1) if the QGP hadronizes before the concentrations of the (baryon) charge carriers q and \bar{q} saturate [9].

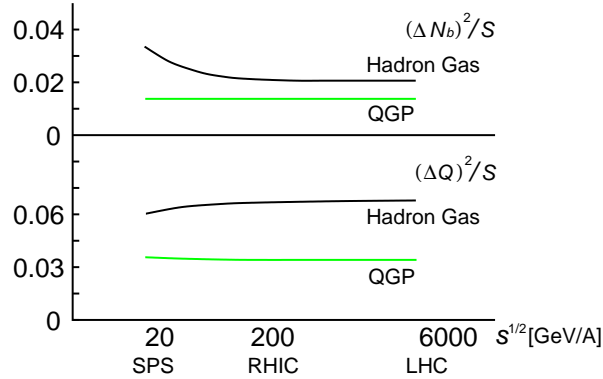


Figure 1. Schematic drawing of the beam energy dependence of the net baryon number and charge fluctuations per unit entropy for a hadronic gas and a quark-gluon plasma.

We now discuss whether the difference between the two phases is really observable. Even if a QGP is temporarily created in a heavy-ion collision, all hadrons are emitted after re-hadronization. Thus, it is natural to ask whether the fluctuations will not always reflect the hadronic nature of the emitting environment. It is essential to our argument that fluctuations of conserved quantum numbers can only be changed by particle transport (diffusion) and, due to the rapid expansion of the reaction zone, are likely to be frozen at an early stage. For our estimate we assume for simplicity that the fireball expands mostly longitudinally, with a boost invariant (Bjorken) flow profile. Strong longitudinal flow exists in collisions at the SPS [10], and the Bjorken picture is widely expected to hold for collisions at RHIC and LHC.

We here give a qualitative argument for the survival of a baryon number fluctuation within a rapidity interval $\Delta\eta \approx 1$ [11]. At RHIC energies, the reaction zone takes about 9 fm/c to cool from the hadronization temperature to the hadronic freeze-out point, and during this time this rapidity interval expands from a length of 5 fm to 14 fm [4]. We consider the diffusion of net baryon number in and out of this rapidity interval by hadronic rescattering processes after QGP hadronization. Baryons have an average thermal longitudinal velocity component $\bar{v}_z = 0.325$ at the hadronization temperature $T \approx 170$ MeV. Without rescattering, a baryon which at the point of hadronization is at the center of this interval can travel on average only about 3 fm in the beam direction before freeze-out. Hence it will not reach the edge of the rapidity interval. Rescattering in the hot hadronic matter inhibits baryon number diffusion, and a fluctuation will even survive in a smaller rapidity interval [4]. We conclude that the short time between hadronization and final freeze-out precludes the readjustment of net baryon number fluctuations in rapidity bins $\Delta\eta \geq 1$. A similar calculation applies to net charge fluctuations.

Stephanov and Shuryak recently derived a diffusive transport equation describing the evolution of fluctuations of conserved quantum numbers during the hydrodynamic expansion of a dense fireball [12]. Within this general framework they argued that quasi-elastic particle reactions through resonances such as $\pi\pi \rightarrow \rho \rightarrow \pi\pi$ and $\pi N \rightarrow \Delta \rightarrow \pi N$ lead to substantial rapidity shifts for the involved particles (in particular the pions) and thus dominate net baryon and electric charge diffusion in the hadronic phase. However, with

realistic estimates for the number of such reactions between hadronization and freeze-out, even the more fragile charge fluctuation signal should still survive hadronic rescattering in rapidity windows $\Delta\eta > 3$ [13]. The average rapidity shift for a nucleon is a factor four smaller than for pions, such that the critical rapidity window size for the survival of net baryon number fluctuations is less than unity, in agreement with our estimate [4].

Due to local charge and baryon number conservation, the rapid longitudinal expansion of the reaction zone may even freeze the fluctuations established during the initial particle production process [14], before reaching the equilibrium level corresponding to a thermalized QGP (even if average thermodynamic quantities reach their thermal values). A detailed study of initial state fluctuations would thus be desirable.

In conclusion, we have argued that the difference in magnitude of local fluctuations of the net baryon number and net electric charge between confined and deconfined hadronic matter is partially frozen at an early stage in relativistic heavy-ion collisions. These fluctuations may thus be useful probes of the temporary formation of a deconfined state in such collisions. The event-by-event fluctuations of the two suggested observables for collisions with a fixed value of the transverse energy dE_T/dy or of the energy measured in a zero-degree calorimeter would be appropriate observables that could test our predictions.

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