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Physics Letters B 660 (2008) 197–201

PHYSICS LETTERS B

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The effect of dynamical parton recombination on event-by-event observables

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Received 15 August 2007; received in revised form 12 November 2007; accepted 21 November 2007

Available online 28 November 2007

Editor: W. Haxton

Abstract

Within a dynamical quark recombination model, we explore various proposed event-by-event observables sensitive to the microscopic structure of the QCD-matter created at RHIC energies. Charge ratio fluctuations, charge transfer fluctuations and baryon-strangeness correlations are computed from a sample of central Au + Au events at the highest RHIC energy available ($\sqrt{s_{NN}} = 200$ GeV). We find that for all explored observables, the calculations yield the values predicted for a quark–gluon plasma only at early times of the evolution, whereas the final state approaches the values expected for a hadronic gas. We argue that the recombination-like hadronization process itself is responsible for the disappearance of the predicted deconfinement signals. This might explain why no fluctuation signatures for the transition between quark and hadronic matter was ever observed in the experimental data up to now.

PACS: 25.75.Nq; 24.60.-k; 12.38.Mh

Keywords: Event-by-event; Fluctuations; Recombination

It is widely believed that a crossover (phase-)transition from a quark–gluon plasma (QGP) to hadronic matter occurs in central ultra-relativistic heavy-ions collisions at RHIC. In order to study the properties of the extremely heated and compressed matter created in these events, numerous probes based on fluctuations have been proposed [1–25]. For a comprehensive overview in the physics of event-by-event fluctuations we refer the reader to [26]. Among them, especially charge ratio fluctuations, charge transfer fluctuations and baryon-strangeness correlations were prominently proposed to pin down the formation of a deconfined phase at RHIC [12,20,21,27–31].

These observables are based on event-by-event fluctuations of conserved charges within a given rapidity interval and are sensitive to the microscopic nature of the matter. It was pointed out that these quantities reflect the properties of the system in the first instant of the collision and should survive the whole course of the evolution of the system. The argument in favour of the survival of the signal is the following: With a strong longitudinal flow, locally conserved quantities (electric charge, baryon number and strangeness) will be frozen in a given rapidity window because the expansion is too quick for the charges to move in and out of the considered rapidity slice. Thus, if a QGP is created, the fluctuations of these quantities should survive the further evolution through the hadronic phase.

It is clear that the size of the rapidity window for the fluctuations study must not be too wide in order to avoid global conservation which would lead to a vanishing signal, but also neither too small to avoid purely statistical fluctuations and the transport of charges in and out of the window by hadronic rescattering. The generally accepted rapidity width is of the order of $\Delta y = 0.5$–1 units in rapidity.

A key point that is usually not fully addressed in the discussion of fluctuation signals is the influence of hadronization itself. A possible mechanism for the parton–hadron transition is the recombination of quarks and anti-quarks into hadrons [32]. Elliptic flow and nuclear modification factor R_{AA} measurements at RHIC [33] have given strong evidences supporting recombination as the mechanism responsible for hadronization.

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doi:10.1016/j.physletb.2007.11.038

First exploratory studies on the influence of parton recombination on charge ratio fluctuations were performed in [34,35]. There it was shown that the coalescence of quarks through the recombination mechanism does indeed leads to results compatible with the available experimental data on charge ratio fluctuations at RHIC.

In this Letter, we study charge ratio fluctuations, charge transfer fluctuations and baryon-strangeness correlations with a dynamical recombination model (the quark Molecular Dynamics model, qMD [36]). To pin down the influence of the hadronization process in detail we explore the suggested quantities over the whole time evolution of the system from the pure quark stage to the final hadrons. The set of events consists of central Au + Au collisions at the highest RHIC energy available ($\sqrt{s_{NN}} = 200$ GeV). We will finally conclude that the hadronization process itself is responsible for the change of all investigated observables from the initially partonic value to the finally observable hadronic value.

The qMD model [36] employed here is a semi-classical molecular dynamics approach where quarks are treated as point-like particles carrying color charges and interact via a linear heavy quark potential. Initial conditions[1] for the qMD are taken from the hadron-string transport model UrQMD [37]: After the two incoming nuclei have passed through each other, (pre-)hadrons from the string and hadron dynamics of the UrQMD model are decomposed into quarks with current masses $m_u = m_d = 10$ MeV and $m_s = 150$ MeV. At the highest RHIC energy, this occurs at a center of mass time of $t = 0.15$ fm/c. The quarks are then let to evolve and interact within the qMD via a linear potential $V(|\boldsymbol{r}_i - \boldsymbol{r}_j|) = \kappa|\boldsymbol{r}_i - \boldsymbol{r}_j|$, where κ is the string tension and $\boldsymbol{r}_n$ is the position of particle n. Therefore the full Hamiltonian of the model reads:

$$H = \sum_{i=1}^{N} \sqrt{p_i^2 + m_i^2} + \frac{1}{2}\sum_{i,j} C_{ij} V\big(|\boldsymbol{r}_i - \boldsymbol{r}_j|\big), \tag{1}$$

where N counts the number of particles in the system and the term C_{ij} takes into account the color dependence of the interaction. Note that gluons are not explicitly taken into account in the present model so that qMD solely describes quark matter. The (soft) gluons are included as the potential interaction between the quarks and not as dynamical degrees of freedom. Therefore, the model should not be used at too high temperatures where gluons have to be treated as particles. However, the qMD model aims at describing the recombination of quarks dynamically in the vicinity of the critical temperature.

The biggest part of the energy and mass of a cluster comes from the interaction potential:

$$E_{\text{clus}} = \sum_i \left[E_i + \frac{1}{2} \sum_{j,j\neq i} C_{ij} V\big(|\boldsymbol{r}_i - \boldsymbol{r}_j|\big)\right] + \delta E, \tag{2}$$

where the sums are performed over all quarks in the cluster, E being the energy and δE the small remaining interaction energy with the rest of the system, included here to fulfill energy conservation. The mass of the hadronic cluster is then:

$$M_{\text{clus}} = \sqrt{E_{\text{clus}}^2 - \vec{P}_{\text{clus}}^2}, \tag{3}$$

where the cluster's momentum $\vec{P}_{\text{clus}}$ is the sum of the quark's momenta.

When the system reaches the hadronization point, quarks acquire an effective mass of the order of 300–400 MeV due to the inter-quark potential. The binding inter-quark potential can be understood as an effective way to take into account the effect of the gluons by leading to the heavy mass of the clusters formed and subsequent decay.

The quark–(anti-)quark interaction within this potential naturally leads to confinement through the binding of (anti-)quarks into color neutral clusters. New hadrons are formed from quarks whose momentum and position are close to each others. Typical values for the relative momenta of the quarks in the two-particle rest frame at hadronization are $|p_q| = |p_{\bar{q}}| \leqslant 500$ MeV, the typical distance is below 1 fm. Hadronization thus occurs locally into hadronic clusters of mesonic and baryonic type that resemble the Yo–Yo states of the LUND model. These clusters are allowed to decay in the further evolution of the system and the hadronization process therefore allows to conserve entropy. The reader is referred to [36] for a detailed discussion of the qMD model. In the present calculations, u, d and s quarks are included and all parton production occurs in the early stage of the reaction during the UrQMD evolution. There is no further production of new (di-)quark pairs during the qMD evolution stage. Thus, the present model provides an explicit recombination transition from quark matter to hadronic matter in a dynamical and expanding medium.

With the given initial conditions, the fireball stays in a deconfined state during the first 6 fm/c where almost no quarks hadronize. As the system expands and the density decreases, quark recombination into baryons and mesons occurs and the number of deconfined quarks drops to zero.

Next we turn to the investigation of the various fluctuation signals. The electric charge ratio fluctuations were proposed as a clear signal for the onset of the quark–gluon plasma phase [27]. The basis for the argument is that the quanta of the electric charge are smaller in a quark gluon plasma phase than in a hadron gas and are distributed over a larger number of particles. Moving one charged particle from/to the rapidity window then leads to larger fluctuations in a hadron gas than in a QGP. The electric charge ratio fluctuations can be quantified by the measure $\tilde{D}$ defined as:

$$\tilde{D} = \frac{1}{C_\mu C_y} \langle N_{\text{ch}} \rangle \langle \delta R^2 \rangle_{\Delta y}, \tag{4}$$

where N_{ch} stands for the number of charged particles, $R = (1 + F)/(1 - F)$ with $F = Q/N_{\text{ch}}$, Q being the net electric charge. Following [13], charge ratio fluctuations are corrected with the factors C_μ and C_y. As suggested in [13,27], the quantity $\tilde{D}$ is calculated in a rapidity window of $y = \pm 0.5$. It was argued that depending on the initial nature of the system, $\tilde{D}$ will yield distinctly different results: $\tilde{D} = 1$ for a quark–gluon plasma,

[1] It should be noted that the qualitative results of the present study are not restricted to any specific initial state. The UrQMD model is solely used to provide an exemplary initial state after the initial $q\bar{q}$ production has taken place.

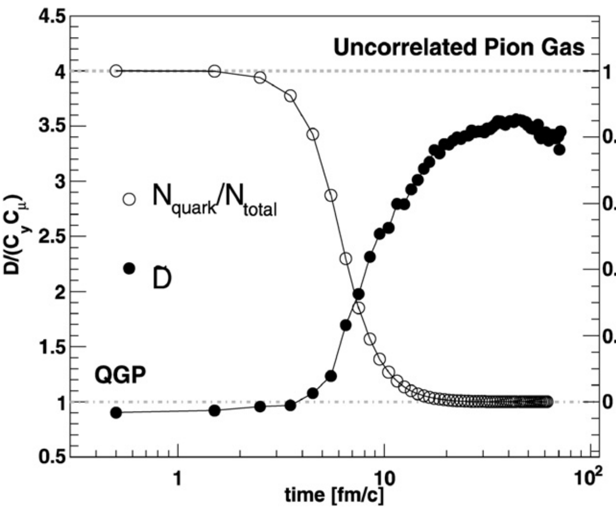

Fig. 1. Fraction of the number of quarks from the total number of particles (open symbols) and corrected charge ratio fluctuations $\tilde{D}$ as a function of time within the qMD model for Au + Au reaction at $\sqrt{s_{NN}} = 200$ GeV (full symbols). Also shown are the values for an uncorrelated pion gas and a quark–gluon plasma.

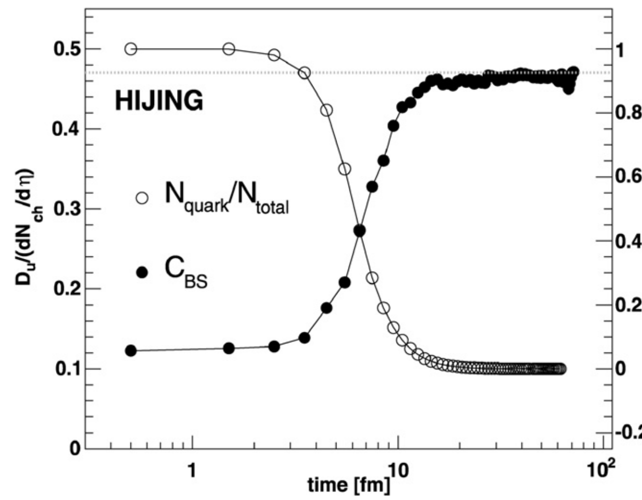

Fig. 2. Fraction of the number of quarks from the total number of particles (open symbols) and charge transfer fluctuations at midrapidity and $\eta = 0$ as a function of time within the qMD model (full symbols) for Au + Au reactions at $\sqrt{s_{NN}} = 200$ GeV. Also shown is the result obtained from HIJING calculations [20].

$\tilde{D} = 2.8$ for a resonance gas and $\tilde{D} = 4$ for an uncorrelated pion gas.

Experimentally, charge ratio fluctuations have been measured at RHIC energies by STAR [38] and PHENIX [39]. Both experimental analyses yield results compatible with a hadron gas. Further analyses from the CERN-SPS [40] based on a slightly different measure for the charge ratio fluctuations did also yield results compatible with the hadronic expectation. Fig. 1 shows the result for $\tilde{D}$ from the qMD recombination approach as a function of time. In the early stage, when the system is completely in the deconfined phase, $\tilde{D} = 1$ as expected. When approaching the hadronization time, $\tilde{D}$ starts to increase and reaches $\tilde{D} \approx 3.5$ after hadronization. The increase of $\tilde{D}$ occurs exactly at the same time as the recombination of the quarks and anti-quarks to hadrons proceeds. The slight decrease of $\tilde{D}$ at later times is related to the continuing decay of resonances.

As a next observable, we now turn to charge transfer fluctuations that were suggested to provide insight about the formation and extent of a QGP phase. Charge transfer fluctuations are a measure of the local charge correlation length. They are defined as [20]:

$$D_u(\eta) = \langle u(\eta)^2 \rangle - \langle u(\eta) \rangle^2, \tag{5}$$

with the charge transfer $u(\eta)$ being the forward-backward charge difference:

$$u(\eta) = \left[Q_F(\eta) - Q_B(\eta)\right]/2, \tag{6}$$

where Q_F and Q_B are the charges in the forward and backward hemisphere of the region separated at $\eta = 0$. In our calculations, we take a total window of $y = \pm 1$, corresponding to the STAR acceptance. Experimental data on this observable is not available up to now.

Because the measured quantity is local, it can give information about the presence and the extent of a QGP in rapidity space. Thus, one expects to observe the lowest value of the charge transfer fluctuations at midrapidity, where the energy density is the highest and where the plasma is located. The local charge fluctuation is expected to be much lower in a quark–gluon plasma than in a hadron gas.

The results from the present calculations are shown in Fig. 2. As expected, the correlation length (at central rapidities) is small, with $D_u/(dN_{\rm ch}/dy) \approx 0.1$, as long as the system is in the quark phase. However, similar to the charge ratio fluctuations discussed above, the charge transfer measure increases with time up to its hadronic value of $D_u/(dN_{\rm ch}/dy) \approx 0.5$ when the system hadronizes. The final state result is in agreement with the value given by HIJING calculations and therefore in line with the hadronic expectation [20].

Finally, we analyse the baryon-strangeness correlation coefficient C_{BS} [21]. This correlation was proposed as a tool to study the nature of the matter created in heavy ion collisions. The baryon-strangeness correlation coefficient is defined as:

$$C_{BS} = -3\frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}, \tag{7}$$

where B and S are the baryon number and strangeness in a given event.

The rationale behind this quantity is the fact that baryon number and strangeness are differently correlated, depending on the phase the system is in. In an ideal weakly coupled quark–gluon plasma, strangeness is carried by strange quarks and is therefore strictly coupled to baryon charge. Thus, a clear correlation between baryon charge and strangeness is expected in a quark–gluon plasma. The expected numerical value for an ideal QGP is $C_{BS} = 1$ [21]. In a hadron gas on the contrary, strangeness can be carried without baryon number (e.g., with strange mesons). As a result the correlation between strangeness and baryon number will be weakened compared to the quark matter scenario. The numerical value for a hadron resonance gas is $C_{BS} = 0.66$ [21].

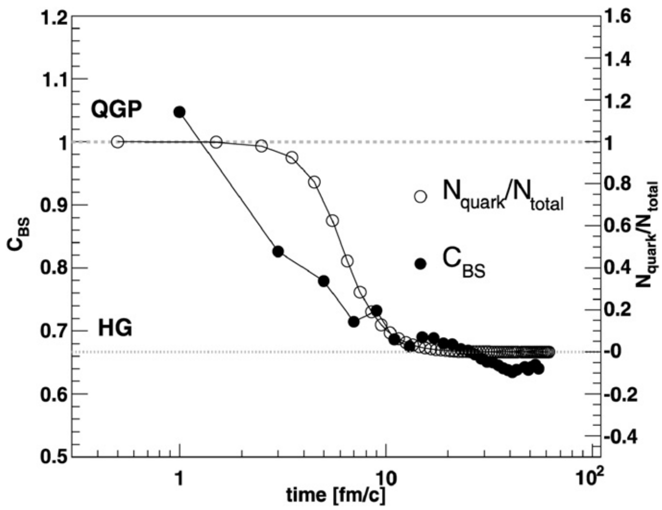

Fig. 3. Fraction of the number of quarks from the total number of particles (open symbols) and C_{BS} correlation coefficient as a function of time for central Au + Au reactions at $\sqrt{s_{NN}} = 200$ GeV (full circles). Also shown are the predicted values for a hadron gas and a QGP.

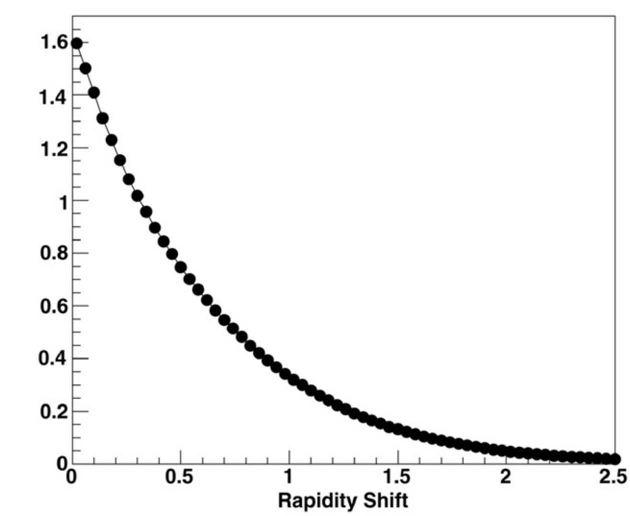

Fig. 4. Distribution of the rapidity shift of the quarks at hadronization $y_{\mathrm{quark}} - Y_{\mathrm{clus}}$ for central Au + Au reactions at $\sqrt{s_{NN}} = 200$ GeV (full circles). The mean rapidity shift is $\langle |y_{\mathrm{quark}} - Y_{\mathrm{clus}}|\rangle = 0.57$.

The behaviour of C_{BS} as a function of time for the dynamical recombination model under study is depicted in Fig. 3. For early times, C_{BS} starts from the expected value of unity in agreement with the ideal weakly coupled quark–gluon plasma value. During the recombination of the quarks, C_{BS} approaches the hadron-gas value $C_{BS} \approx 0.6$. Similar results on baryon-strangeness correlations were recently obtained within the AMPT model [41].

Finally, we discuss the capacity of our recombination-like hadronization procedure to move charges in and out of the considered rapidity window. Fig. 4 depicts the rapidity shift distribution of quarks at hadronization when mapped to a hadronic cluster $|y_{\mathrm{quark}} - Y_{\mathrm{clus}}|$. The average value obtained is $\langle |y_{\mathrm{quark}} - Y_{\mathrm{clus}}|\rangle = 0.57$.

In conclusion, we have studied a variety of suggested event-by-event signatures for the formation of a deconfined QGP state within a dynamical quark recombination approach. The analyses was performed with a set of central Au + Au events at $\sqrt{s_{NN}} = 200$ GeV and involved charge ratio fluctuations, charge transfer fluctuations and baryon-strangeness correlations. For all these predicted "smoking gun" QGP observables, we find that the hadronization by recombination leads to results expected for a hadron gas in the final state. This is especially remarkable, as the initial values for these observables were identical to the predicted QGP values.

For all these quantities, the change of the observables from their QGP value to the hadronic gas result can be traced back to the recombination hadronization mechanism because the change of the quantitative values of $\tilde{D}$, D_u and C_{BS} takes place during the time of hadronization. From these observations we conclude that the influence of the recombination/hadronization on fluctuation probes is strong enough to blur the initially present QGP signatures. Note that final state hadronic rescattering is not included in the present model and might act as a further source to blur the fluctuation signals. This might explain why fluctuation measurements have not provided the expected proof for the formation of a plasma of quarks and gluons.

Acknowledgements

We thanks Drs. S.A. Bass, S. Jeon, V. Koch for valuable suggestions and comments. The computational resources have been provided by the Center for Scientific Computing at Frankfurt. S.H. thanks FIGSS for financial support. This work was supported by GSI and BMBF.

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