The Effect of Dynamical Parton Recombination on Event-by-Event Observables

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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 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 signatures. 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. However, it might also be interpreted as a clear indication for a recombination like hadronization process at RHIC.

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It is widely believed that a 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\(^{11,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27}\). For a comprehensive overview in the physics of event-by-event fluctuations we refer the reader to\(^{28}\). 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\(^{12,21,22,23,24,30,31,32,33}\).

These observables are based on event-by-event fluctuations of conserved charges within a given rapidity range 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 through all the stages of the collision for the above mentioned fluctuations probes is the following: With a strong transverse and longitudinal flow, locally conserved quantities (charge, baryon number and strangeness) will be frozen in a given rapidity window because the expansion is too quick for the charges to move out of the respective rapidity slice. Thus, if a QGP is created, the fluctuation of these quantities should survive further evolution through the hadronic phase.

It is clear that the size of the rapidity window for the fluctuation 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. In contrast to the RHIC energies explored here, it was argued that the diffusion rate for secondaries at the CERN-SPS might be strong enough to blur the fluctuation signal almost to the (observed) resonance gas value\(^{34}\).

A key point that is usually not 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\(^ {35,36,37,38,39}\). Elliptic flow and nuclear modification factor \( R_{AA} \) measurements at RHIC\(^ {40,41}\) have given strong evidence supporting recombination as the mechanism responsible for hadronization. A first exploratory study on the influence of parton recombination on charge fluctuation was performed in\(^ {42}\). There it was shown that the coalescence of quarks through the recombination mechanism does indeed lead to results compatible with the available experimental data on charge fluctuations at RHIC.

In this paper, we study charge ratio fluctuations, charge transfer fluctuations and baryon-strangeness correlations with a dynamical recombination model (the quark Molecular Dynamics model, qMD\(^ {43,44,45}\)). 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

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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. Thus, providing evidence for a recombination like hadronization mechanism at RHIC energies.

The qMD model \cite{43, 44, 45, 46} 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 \cite{58} for the qMD are taken from the hadron-string transport model UrQMD \cite{47, 48}. 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 happens 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 $V(\mathbf{r}_i - \mathbf{r}_j) = \kappa |\mathbf{r}_i - \mathbf{r}_j|$, where $\kappa$ is the string tension and $\mathbf{r}_n$ is the position of particle $n$. Therefore the full Hamiltonian of the model reads:

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

Where $N$ counts the number of particles in the system and the term $C_{ij}$ takes into account the color dependence of the interaction.

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 $|p_q| = |p_\bar{q}| \leq 500$ 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.

As the initial state of the system is color neutral, all the quarks of the system will eventually gather into color neutral clusters. Electric charge and strangeness are conserved during the whole evolution of the system, i.e. $s = \bar{s} = 0$ and the net-charge equals the initial charge of the incoming nuclei. The reader is referred to \cite{43, 44, 45} for a detailed discussion of the qMD model. Note that in the present calculations, only $u$, $d$ and $s$ quarks are included. Furthermore, all parton production occurs in the early stage of the reaction during the UrQMD evolution. There is presently no mechanism to create 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.

Let us set the stage by exploring the time evolution of the hadronization dynamics in the model. Fig. 1 depicts the fraction of quark matter on the total number of particles in the system (i.e. quark fraction $= (n_q + n_{\bar{q}})/(n_{hadron} + n_q + n_{\bar{q}})$) as a function of time. One observes that the fireball stays in a deconfined state during the first 6 fm/c where almost no quarks hadronize. As the system expands further 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 \cite{29}. 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 fluctuation can be quantified by the measure $\tilde{D}$ defined as:

$$\tilde{D} = \frac{1}{C_\mu C_\gamma} \langle N_{ch} \rangle \langle \delta R^2 \rangle \Delta y . \quad (2)$$

Where $N_{ch}$ stands for the number of charged particles, $R = (1+F)/(1-F)$ with $F = Q/N_{ch}$, $Q$ being the electric charge. Following \cite{13, 29}, charge fluctuations are corrected with the factors $C_\mu$ and $C_\gamma$ to take into account the finite acceptance. As suggested in \cite{13, 29}, 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, $\tilde{D} = 2.8$ 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, PHENIX and HIJING. Both experimental analyses yield results compatible with a hadron gas - in strong contrast to the CERN-SPS based on a slightly different measure for the charge ratio fluctuations did also yield results compatible with the hadronic expectation. Fig. 2 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. As can be seen from Fig. 1, 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 decay of resonances.

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

$$D_u(\eta) = \langle u(\eta)^2 \rangle - \langle u(\eta) \rangle^2 ,$$  \hspace{1cm} (3)

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

$$u(\eta) = [Q_F(\eta) - Q_B(\eta)]/2 ,$$  \hspace{1cm} (4)

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. 3. As expected, the correlation length (at central rapidities) is small, with $D_u/(dN_{ch}/dy) \approx 0.1$, as long as the system is in the quark phase. However, similar to the charge ratio fluctuation discussed above, the charge transfer measure increases with time up to its hadronic value of $D_u/(dN_{ch}/dy) \approx 0.5$ when hadronization has happened. The final state result is in agreement with the value given by HIJING calculations and therefore in line with the hadronic expectation.

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

$$C_{BS} = -3 \frac{(BS) - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2} ,$$  \hspace{1cm} (5)

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 will be
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 $C_{BS} = 1$ [23, 57]. 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 non-interacting hadron gas is $C_{BS} = 0.66$ [23, 57].

The behaviour of $C_{BS}$ as a function of time for the dynamical recombination model under study is depicted in Fig. 4. 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 course of the recombination of the quarks, $C_{BS}$ approaches the hadron-gas value $C_{BS} \approx 0.6$.

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 done for 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 there QGP value to the hadronic gas value can be traced back to the recombination hadronization mechanism because the change of the quantitative values of $\bar{D}$, $D_u$ and $C_{BS}$ takes place during the time of hadronization.

From these observations we draw two mutually converse conclusions:

1. The influence of the recombination/hadronization on fluctuation probes is strong enough to blur the initially present QGP signature. This might explain why fluctuation measurements have not provided the expected proof for the formation of a plasma of quarks and gluons.

2. However, if one assumes that a QGP was indeed formed at RHIC energies, the experimental fact that all of the discussed fluctuation probes turn out to yield the hadronic value can be seen as a strong argument supporting recombination as the mechanism responsible for hadronization at RHIC.

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