Parton rearrangement and fast thermalization in heavy-ion collisions at RHIC and LHC energies

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The implications of parton rearrangement processes on the dynamics of ultra-relativistic heavy-ion collisions have been investigated. A microscopic transport approach, namely the quark gluon string model (QGSM) which has been extended for a locally density-dependent partonic rearrangement and fusion procedure served as the tool for this investigations. The model emulates effectively the dynamics of a strongly coupled quark plasma and final hadronic interactions. Main QGSM results on anisotropic flow components $v_1$ and $v_2$ at top RHIC energy are compiled. Predictions for the pseudorapidity dependence of directed and elliptic flow in Pb+Pb collisions under LHC conditions are presented.

I. INTRODUCTION

Calculations within Quantum Chromodynamics (QCD) realized on the lattice predict a new state of matter consisting of deconfined partons at energy densities above $\approx 1 \text{ GeV/fm}^3$ and temperatures above $\approx 170 \text{ MeV}$ [1, 2, 3]. Experimental investigations of Au+Au reactions at center of mass energies up to $\sqrt{s_{NN}} = 200 \text{ GeV}$ at the Relativistic Heavy Ion Collider (RHIC) led to observations of large elliptic flow [4, 5, 6, 7, 8, 9], which is one of the key signals justifying a strongly coupled quark-gluon plasma (sQGP) formed in the early phase of such high-energetic heavy-ion collisions (see [1] and references therein for a detailed discussion). A system of this kind, which does not behave like a weakly interacting gas of quarks and gluons, implies large pressure gradients and short equilibration times [10, 11]. Both are necessary conditions for the development of large elliptic flow. The description of various measured anisotropic flow patterns by hydrodynamic approaches (see, e.g., [12]) together with the scaling behavior of the elliptic flow with the number of constituents (see, e.g., [13, 14]) well explained by parton recombination/coalescence approaches [15, 16, 17, 18, 19, 20, 21, 22, 23, 24], give hints towards the partonic nature of the created matter which equilibrates very fast.

In this paper, the main anisotropic flow results obtained with a microscopic transport approach, namely the Quark-Gluon String Model (QGSM) extended for a dynamical mechanism which allows for quark rearrangement and fusion processes during the very dense stages of ultra-relativistic heavy-ion reactions, are summarized [25, 26]. After a brief account of the approach and its conceptual ideas in Sect. [11] the implications on kinetic equilibration and anisotropic flow components ($v_1, v_2$) at top RHIC energy are compiled in Sect. [11] followed by QGSM predictions for the pseudorapidity dependence of $v_1$ and $v_2$ in Pb+Pb collisions under LHC conditions.
II. QUARK GLUON STRING MODEL WITH QUARK REARRANGEMENT

The standard version of the QGSM – a microscopic string cascade transport approach using Monte-Carlo simulation techniques in order to study theoretically heavy-ion collisions at high energies – describes particle production by excitation and decay of classical strings with (anti)quarks or (anti)diquarks at their ends, like other transport approaches of this kind. A more detailed description of the standard QGSM can be found in [27, 28, 29]. Since in the very dense stages of a heavy-ion reaction “hadrons” overlap each other and consequently are rather strongly correlated partonic states than real bound states (schematically depicted by the left picture of Fig. 1), locally density-dependent partonic rearrangement and fusion processes have been implemented in the QGSM. Above a critical local particle density, “hadronic correlations” are decomposed into their constituent partons which afterwards rearrange among themselves into new hadron-like correlations. This rearrangement process is sketchily displayed in the middle of Fig. 1. A quark-antiquark pair of same flavor may additionally annihilate during the rearrangement process. Thus, a $3 \to 2$ reaction is effectively implemented, which is a new feature within a string cascade approach. Rearrangement and fusion processes become unimportant when the system increasingly thins out due to ongoing expansion. Finally, hadrons are the relevant degrees of freedom as shown in the right picture of Fig. 1. In this spirit the extended QGSM emulates the dynamics of a sQGP and final hadronic interactions from a microscopical point of view. The concept and procedure of the quark rearrangement and fusion mechanism and its implementation into the QGSM are described in detail in Refs. [25, 26].

III. KINETIC EQUILIBRATION AND ANISOTROPIC FLOW AT RHIC AND LHC

It has been demonstrated in [25] that dynamical parton rearrangement which occurs in the very dense medium created in ultra-relativistic heavy-ion reactions during the early stages drives the system to fast kinetic equilibrium. The time dependence of the equilibration ratio $R_{LE}$ in the overlap zone of Au+Au collisions simulated by using QGSM with and without quark rearrangement has been extensively discussed in references [25, 30]. Quark rearrangement processes reduce the local equilibration time of the system roughly by a factor of 5, i.e., from $\approx 10 \, \text{fm/c}$ to $\approx 2 \, \text{fm/c}$. Moreover, the rearrangement mechanism improves significantly on the theoretical description of measured directed and elliptic flow, i.e., $v_1$ and $v_2$ distributions and their pseudorapidity dependence in Au+Au collisions at top RHIC energy of $\sqrt{s_{NN}} = 200 \, \text{GeV}$ as shown in Fig. 2. In particular the shape of $v_2(\eta)$ is found to be closely related to fast thermalization. A detailed comparison and discussion of the simulation results on $v_1$ and $v_2$ using the QGSM with and without implementation of quark rearrangement and fusion processes can be found in [25, 31, 32, 33]. The centrality dependence of $v_2(\eta)$ has been discussed in [25, 31]. A fair description of this observable has been achieved so far only by a hydro-cascade hybrid model [12], the partonic rearrangement ansatz within the microscopic QGSM [25], and recently by a parton cascade approach [34].
FIG. 2: Directed flow (left panel) and elliptic flow (right panel) of charged hadrons as function of pseudorapidity $\eta$. The results from simulations of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the QGSM including quark rearrangement (filled circles) [25] together with corresponding results from an analysis applying a cumulant method (diamonds) are shown in comparison to PHOBOS data (filled squares) [9]. Systematic errors of the experimental data are indicated by gray boxes, statistical errors by bars.

Predictions by the improved QGSM for the pseudorapidity dependence of the azimuthal anisotropy parameters $v_1$ and $v_2$ of charged hadrons produced in central and semiperipheral Pb+Pb reactions at a LHC energy of $\sqrt{s_{NN}} = 5.5$ TeV are compiled in Fig. 3 [26].

![Graph showing directed flow and elliptic flow](image1.png)

FIG. 3: The same as in Fig. 2, but for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Predictions by QGSM simulations including quark rearrangement and fusion processes are depicted for impact parameters $b = 2.3$ fm (filled circles) and $b = 8$ fm (filled squares), respectively [26]. Error bars denote statistical uncertainties.

The simulation results, e.g., an increasing magnitude of $v_2$ around midrapidity under LHC conditions by about 10-20% compared to the RHIC results, suggest in comparison with results of other transport approaches and hydrodynamical calculations that the hydrodynamical limit will be reached at this collision energy. A more detailed discussion can be found in [26].
IV. SUMMARY AND CONCLUSIONS

The implications of locally density dependent quark rearrangement and fusion processes on the collision dynamics have been compiled. In addition to a much faster kinetic equilibration achieved in simulated ultra-relativistic heavy-ion reactions, the magnitude and shape of $v_1(\eta)$ and $v_2(\eta)$ within the rearrangement scenario are in nice agreement with the experimental data of the RHIC program. From a microscopical point of view, this is a strong indication for a partonic medium with short mean free path and accordingly rather low viscosity created in such collisions at early times. The predicted increase of the elliptic flow at $\sqrt{s_{NN}} = 5.5$ TeV is in line with conclusions that the hydrodynamical limit will be reached under LHC conditions.

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