Pseudorapidity shape of elliptic flow as signature for fast equilibration in relativistic heavy-ion collisions at energies up to $\sqrt{s_{NN}} = 200$ GeV

J. Bleibel, G. Burau, Amand Faessler, and C. Fuchs
Institute for Theoretical Physics, University of Tübingen,
Auf der Morgenstelle 14, D-72076 Tübingen, Germany

The implications of parton recombination processes on the dynamics of ultrarelativistic heavy-ion reactions are investigated. To do so, the quark-gluon string transport model has been extended for partonic recombination and fusion processes. Parton recombination leads to short equilibration times and improves significantly on the theoretical description of measured directed and elliptic flow, i.e., $v_2$ and $v_3$, distributions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, in particular what concerns their pseudorapidity dependence. The shape of $v_2(\eta)$ is found to be closely related to fast thermalization.

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I. INTRODUCTION

Among the various experimental studies of ultrarelativistic heavy-ion collisions operates the Relativistic Heavy Ion Collider (RHIC), at Brookhaven National Laboratory since 2000, to investigate gold-on-gold collisions up to $\sqrt{s_{NN}} = 200$ GeV. After many years of operation strong experimental evidence has been accumulated that at RHIC energies indeed a new state of matter is created that is qualitatively different from a hadron gas (see Ref. [1] and references therein). This state seems, however, not to behave like a weakly interacting gas of deconfined partons – as could have been naively expected – but rather like a strongly coupled quark-gluon plasma (sQGP). One argument toward such a scenario is the large elliptic flow observed at RHIC [2, 3, 4, 5]. The development of strong elliptic flow requires short equilibration times and large pressure gradients to drive the dynamics, both being characteristic features of a strongly interacting system [6, 7].

Another evidence for this picture is provided by the hadron species dependence of the elliptic flow [8, 9]. The observed scaling with the number of constituent quarks can naturally be explained by the assumption that the elliptic flow is to most extent already created in the partonic phase and transferred to the hadrons through a partonic recombination mechanism [10, 11, 12, 13, 14, 15, 16, 17].

In the present work we demonstrate that not only the size but also the shape of the observed pseudorapidity profiles of the elliptic flow $v_2$ provide strong evidence for a partonic recombination mechanism in combination with fast thermal equilibration inside a sQGP phase. As basis for these investigations serves a microscopic quark-gluon string model (QGSM) that has been extended to allow for a partonic recombination procedure motivated by parton coalescence models [13, 14, 15, 16], i.e., to model effectively the dynamics of a strongly coupled quark plasma formed in the very dense stages of ultrarelativistic heavy-ion collision. By construction, string cascade models do not contain an explicit quark-hadron phase transition. However, during the temporal evolution of a heavy-ion reaction a dense and strongly interacting plasma is formed within such approaches as well. The system consists of partons and color-flux tubes (or strings). Thus, such models can serve as starting base to study the dynamics of the dense and strongly interacting medium created at RHIC, in particular because transverse as well as elliptic flow at SPS energies are well reproduced within the string-cascade approach [18, 19, 20, 21].

It was shown in Refs. [22] that the standard version of the microscopic quark-gluon string cascade model (QGSM) is able to describe fairly well the bulk properties of the elliptic flow $v_2$ measured in $\sqrt{s_{NN}} = 200$ GeV Au+Au reactions at RHIC. However, a difference in shape in particular between the pseudorapidity distributions of the elliptic flow at midrapidity determined in the experiment and in the simulation has rankled. The shape of the $v_2$ distributions have been found to be closely related to anisotropies in the corresponding energy density profiles and the degree of equilibration [23]. Although the system reaches quickly some sort of a pre-equilibrium stage within standard QGSM the processes included are not sufficient to drive the system to a completely thermalized state. As shown in the following, this changes dramatically when partonic recombination processes are included. The final consequences for the anisotropic flow turned out to be even more remarkable.

II. QUARK-GLUON STRING MODEL WITH PARTON RECOMBINATION

The standard Monte Carlo version of the quark-gluon string model [22] that serves as the basis for the present investigations has been described in detail in Refs. [22, 23]. Based on Gribov-Regge Theory, the production of hadrons is described by excitation and decay of open strings with different quarks or diquarks on their ends. In that sense the model already incorporates the
partonic structure of hadrons and therefore can provide a framework for the inclusion of partonic recombination processes. To trigger these processes, a certain critical (energy) density is needed to allow the hadrons to overlap. Concerning the implementation of partonic recombination processes we apply essentially the method proposed in Ref. [12]: The partons of three hadrons are allowed to enter into a recombination process if their spatial distance, in the center-of-mass (c.m.) frame of the corresponding hadrons, is less than $\Delta_x = 0.85$ fm. From all possible triplets of hadrons satisfying these spatial constraints one is randomly chosen according to usual Monte Carlo methods and the corresponding hadrons are then decomposed into their constituent partons (quark-antiquark or quark-diquark). Each parton is given a momentum fraction $z$ of the initial momentum of its hadron and, additionally, the partons of each pair obtain a transverse momentum $p_T$ of opposite sign. Both, $z$ and $p_T$ are generated from the standard parton distribution functions used within QGSM. The (random) selection of a triplet of hadrons by the coordinate space criterion $\Delta_x$ is based on the approximation that distances of hadrons are equal to (averaged) distances of their constituent partons. In that sense the selection procedure really acts on the partonic level.

The recombination process itself requires also an overlap of the participating partons in momentum space. The distance in momentum space between the pairs of partons is evaluated in the center-of-mass frame. The probability for recombination of two partons is then given by the covariant distribution \[ f_2(x_1, x_2, p_1, p_2) = \frac{9 \pi}{2\Delta^3_p} \Theta \left[ \Delta^2_p - (x_1 - x_2)^2_{c.m.} \right] \times \Theta \left[ \Delta^2_p - (p_1 - p_2)^2_{c.m.} \right]. \] (1)

Additionally, if the partons of three mesons participate, recombination of three quarks and three antiquarks is possible with a probability distribution \[ f_3(x_1, x_2, p_1, p_2) = \frac{9 \pi}{2\Delta^3_p} \Theta \left[ \Delta^2_p - (x_1 - x_2)^2_{c.m.} \right] \times \Theta \left[ \Delta^2_p - (p_1 - p_2)^2_{c.m.} \right] \times \frac{9 \pi}{2\Delta^3_p} \Theta \left[ \Delta^2_p - \left( -\frac{x_1 + x_2}{2} - x_3 \right)^2_{c.m.} \right] \times \Theta \left[ \Delta^2_p - (p_1 + p_2 - 2p_3)^2_{c.m.} \right]. \] (2)

leading effectively to the fusion of three mesons into a baryon-antibaryon pair. We want to stress at this point that our fusion process, which allows pseudoscalar and vector mesons to “rearrange” to $BB$ on the partonic level (no cross sections have been introduced), is qualitatively consistent with the method applied in Ref. [27], where a quark rearrangement model for $BB$ annihilation to three mesons (pseudoscalar and vector, which later decay to additional pions) has been employed. For example: The fusion of two $\rho$ mesons and a pion into $\rho\rho$ is kinematically favored compared to the fusion of three pions (phase space). However, a more quantitative investigation has to be delayed to future work.

The momentum coalescence radius $\Delta_p$, which enters in the distributions (1) and (2), is given by the uncertainty principle $\Delta_x\Delta_p = 1$, where the actual distance between the participating partons is used for $\Delta_x$. To exclude recombination of particles with highly different momenta high-momentum cutoffs of $\Delta_{p, max} = m_1 + m_2$ for recombination processes $3H \rightarrow 3H$ ($H = M, B, \bar{B}$) and $\Delta_{p, max} = m_1 + m_2 + m_3 + 0.2$ GeV for the aforementioned fusion process $3M \rightarrow BB$ are used, where $m_i$ corresponds to typical constituent masses. We want to stress that recombination and fusion happen on the partonic level, i.e., the notation denotes the contained partons, which participate in those processes, in the following way: $M = (q\bar{q})_M$, $B = (qq\bar{q})_B$, and $\bar{B} = (\bar{q}\bar{q}\bar{q})_B$, respectively.

The recombination (or fusion) processes can take place if the quantum numbers allow the partons of at least two of the three overlapping hadrons to recombine into new hadronic correlations, whereas this process is mediated by the partons of the third hadron. Effectively, this is a three-body interaction or at most a kind of in-medium two-body interaction but no additional two-body interaction in the vacuum. Hence the total vacuum hadron-hadron cross section implemented in the QGSM is not changed. Anyway, as mentioned above no explicit in-medium cross sections have been introduced because all recombination processes are dynamically treated on the partonic level. Nevertheless it is possible to estimate effective cross sections for the implemented partonic recombinations between the hadronic correlations. The maximum value of the inclusive cross section for recombination processes like $3M \rightarrow 3M$ or $3M \rightarrow BB$ is basically determined by the aforementioned spatial coalescence radius $\Delta_x$. The allowed maximum value of 0.85 fm \[ \Delta_x \] is geometrically related to a cross section not larger than about 23 mb. Because the dense medium produced in the overlap zone of a highly energetic Au+Au collision is dominated by “pionic correlations”, the recombination of partons coming from and going to two “pions” in presence of the partons of a third (medium) “pion” happens most frequently. Nearly 90% of all recombination processes with three pionic states in the initial channel are reactions of this kind, whereas the “fusion process” $3\pi \rightarrow pp\bar{p}$ is distinctly suppressed. Accordingly, the effective cross section of the latter process is several orders of magnitude smaller than the estimated cross section of the first process, which turns out to be not larger than 20 mb. Furthermore, we have estimated effective cross sections for the partons (quarks and antiquarks) involved in recombinations by their distance in momentum space using $\sigma_{pq} \propto (\Delta_p(q, \bar{q}))^{-2}$. Depending on the center-of-mass energy of the (anti)quarks, the partonic cross section is in the order of a few millibarn but definitely not larger than the aforementioned 23 mb. The rate of recombination processes is determined by the cutoff parameter for high momenta $\Delta_{p, max}$: increasing $\Delta_{p, max}$ increases the
recombination rate. However, the additional recombination processes with highly different momenta have only very small cross sections. Because the bulk of recombination processes happens to take place with $\Delta p(q,q)$ close to the cutoff $\Delta p_{\text{max}}$, an averaged cross section would yield a value comparable to parton scattering cross sections used, e.g., in the AMPT model \[28\].

The implemented procedure always ensures that only physical particles can be final hadronic states, e.g., no final diquark states are possible. Also the reaction $HBB \rightarrow H3M$, i.e., the partons of a hadron and a baryon-antibaryon pair form finally a hadron and three mesons, which contains as a subprocess the backreaction to “meson fusion”, is not included in the recombination scheme because annihilation of baryons and antibaryons is already implemented in the QGSM as a standard two-particle reaction $B + \bar{B} \rightarrow X$. Furthermore, the model allows for the formation of resonance states and their decay. Consequently, subprocesses such as $2M \rightarrow 3M$, which can also increase the particle number, are incorporated in the model. However, if the outcome of a recombination process would yield any unphysical particle it cannot take place. Either an other valid recombination process is then chosen or, if none is possible, no recombination occurs.

Apart from recombining to new mesons, (anti)protons or baryon-antibaryon pairs, quark-antiquark annihilation is possible when the partons of three mesons participate in a recombination process. Thus a quark-antiquark pair of the same flavour, but belonging to different mesons, may annihilate with a redistribution of its energy and momentum to the new mesons formed by the remaining partons. The probability of this annihilation process $3M \rightarrow 2M$ with respect to $3M \rightarrow 3M$, i.e., $P_3 = 0.04$, has been adjusted to reproduce the experimental $dN/d\eta$ charged hadron multiplicities. By means of this annihilation process $3M \rightarrow 2M$ an effective backward reaction for diffractive scattering is included. From the possible recombination and annihilation processes, including the case that nothing happens at all, i.e., all partons recombine to the original hadrons, the actual reaction is randomly chosen. These processes are checked for all combinations of overlapping hadrons, making thereby sure, however, that the particular partons of the selected hadron triplet can only once per time step – which is about $10^{-3} \cdots 10^{-5}$ fm/c – participate in such processes. If no recombination (annihilation) or fusion processes take place normal elastic or inelastic scattering occurs.

Charge conservation is automatically guaranteed within our approach, but conserving energy and threemomentum simultaneously is not possible for the recombination processes described above. Generally, there are problems to conserve simultaneously energy and momentum within partonic coalescence/recombination approaches, see, e.g., Ref. \[17\], where conservation of momentum has been chosen whereas conservation of energy has been violated. In our model, conservation of energy is violated in most recombination processes on the level of few percentages only. However, applying a rescaling procedure for the momenta in the center-of-mass system of the produced hadronic correlations, we are able to ensure simultaneous conservation of energy and threemomentum with a precision better than 1 MeV. To conserve the initial energy the three-momentum components of all particles involved in a particular reaction are scaled by a constant factor which is determined iteratively. Moreover, by such a procedure ratios of momenta, e.g., anisotropic flow coefficients, are remain unchanged. In other words, the anisotropic flow is not artificially influenced by the momentum rescaling.

All particles are allowed to interact via the recombination procedure described above, even non-formed (pre-) hadrons. In this spirit the model does not create a “system of free partons” but effectively emulates a medium of very strongly correlated partons, i.e., quark-antiquark and (anti)quark-(anti)diquark states. To not shorten or modify the formation times of the nonformed “hadrons”, their formation time is now interpreted on the quark level, meaning the time for the constituent partons to be fully created. As a consequence of that each hadron gets a formation time for each constituent [quark, antiquark or (anti-) diquark] $t_1$ and $t_2$. Within a normal production process such as string-breaking $t_1$ and $t_2$ are equal. For the recombination mechanism the newly produced hadronic states get the formation times of their constituents. The new hadron will be fully formed if the lifetime exceeds the larger formation time and partially formed (like a leading hadron) if the lifetime exceeds the smaller formation time. These partially formed hadrons are allowed to rescatter assuming additive constituent cross sections.

III. EQUILIBRATION AND ANISOTROPIC FLOW OF CHARGED HADRONS

First we examine the influence of parton recombination on the kinetic equilibration in the central cell of the overlap zone of Au+Au collisions. This cell is given by $-2 \text{ fm} < x, y, z < 2 \text{ fm}$ for a central Au+Au reaction with impact parameter $b = 0 \text{ fm}$ and $2 \text{ fm} < x < 6 \text{ fm}$, $-2 \text{ fm} < y, z < 2 \text{ fm}$ for a semiperipheral reaction ($b = 8 \text{ fm}$), respectively. The corresponding equilibration ratio $R_{\text{LE}} = (P_x + P_y)/2P_z$ is determined by the pressure components in x, y and z directions, $P_{x,y,z}$ (see discussion in Ref. \[24\]). The QGSM results with and without implementation of parton recombination are depicted in Fig. \[1\]. A difference in the degree of local kinetic equilibration is clearly seen when one compares the standard QGSM results with the parton recombination scenario. The latter mechanism leads very effectively to a much faster and smoother equilibration for both, the central and semiperipheral collisions. Essentially, the decomposition and recombination procedure resuffles rapidly the momenta of partons and finally of the hadrons which drive the system undoubtedly into kinetic equilibrium within short times.
For central reactions, the matter in the central cell is practically fully equilibrated, i.e., $R_{\text{LE}} \approx 1$, after very few fm/c time of evolution. Here, of course, the effect of the recombination mechanism is strongest, because it is clearly a density-dependent mechanism. But even for semiperipheral collisions the local pre-equilibrium stage identified by $R_{\text{LE}} > 1$ is remarkably shortened compared to the scenario without recombination of partons in the dense stages of the expanding medium. It should be noticed that the offset of $t_{\text{evol}}$ seen in Fig. 1 is due to the chosen cell size and is of technical nature. In the first few time steps the pressure is dominated by the longitudinal flow of the nuclei penetrating the cell. Disregarding this offset one can see that parton recombination reduces the equilibration time of the system approximately by a factor of 5 from $\sim 10$ fm/c to $\sim 2$ fm/c.

The interplay between fast thermal equilibration and the amount of anisotropic flow, in particular the elliptic flow, measured in high-energy heavy-ion reactions is strongly debated (see e.g. 2, 3, 4, 5, 6, 9, 29, 30 and references therein). In Ref. 24 the idea has been supported that a fast and complete thermal equilibration is not strictly necessary to produce large elliptic flow. Nevertheless, a conspicuous difference in shape in particular between the pseudorapidity distributions of the elliptic flow at midrapidity determined in the experiment and in the simulation was observed. Hence it is very natural to study the effect of the quark recombination mechanism on the azimuthal anisotropy parameter $v_2$ within the QGSM 22. Figure 2 shows the pseudorapidity dependence of the elliptic flow $v_2$ of charged hadrons for minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The QGSM results including parton recombination and the standard approach without recombination 22 are compared with the experimental data of the PHOBOS Collaboration 3. The elliptic flow obtained within the standard QGSM displays a strong in-plane alignment in accordance with the experimental findings. At midrapidity $|\eta| < 1$ the flow parameter $v_2$ is almost constant, but then it rises up slightly followed by a rapid drop at $|\eta| > 2$. The emergence of this peculiar double bump structure in $v_2(\eta)$ was strongly connected with the model dynamics (for more details, see Ref. 22). In contrast, the experimentally observed elliptic flow shows a pronounced peak at midrapidity and a steady decrease for $|\eta| > 1$. This behaviour is remarkably well reproduced when partonic recombination processes are taken into account. The parton rearrangement processes in the dense medium lead to a redistribution of the elliptic flow of the final hadrons toward midrapidity, i.e., $v_2$ is accumulated at $|\eta| \approx 0$, whereas it is distinctly reduced in the region around $|\eta| \approx 2$. Thus, the double bump structure in $v_2(\eta)$ obtained in the standard version of the QGSM disappears.

This striking feature holds also for the centrality dependence of $v_2(\eta)$ as depicted in Fig. 3. Here, the results from the QGSM simulations and the PHOBOS analysis
(combined data from the hit- and track-based methods) for three different centrality classes are overlaid. The QGSM, including partonic recombination processes, is able to describe the magnitude as well as the pseudorapidity dependence of $v_2(\eta)$ remarkably well for all the centrality classes, ranging from central via midcentral to peripheral in accordance with the definitions in Ref. [5].

![Graph](image1)

**FIG. 3:** Pseudorapidity distributions of $v_2$ for charged hadrons from $\sqrt{s_{NN}} = 200$ GeV Au+Au reactions for three centrality classes according to the PHOBOS analysis [5]. The identification marking is the same as in Fig. 2.

This is a highly non-trivial result, since a simultaneous description of both observables has neither been achieved by other standard string-cascade transport models such as relativistic quantum molecular dynamics (RQMD) or ultrarelativistic quantum molecular dynamics (UrQMD) [22, 23], nor by purely hydrodynamical calculations [34, 35]. So far, only a hydrodynamics+cascade hybrid approach with Glauber model initial conditions was able to give a fair description of the experimental data, with the exception of the midrapidity region in the most central collision class [36]. There it has been argued that the hadronic cascade provides the right amount of dissipation to bring the ideal fluid prediction down to the measured values, especially in peripheral collisions and away from midrapidity.

Following this argument, the $v_2$ results obtained with the extended QGSM may be interpreted in a complementary way as follows: In contrast to a highly dissipative hadronic medium, the parton recombination processes lead to a reduction of the mean free path in the very dense stages of a heavy-ion collision at midrapidity. Accordingly, the viscosity of this strongly interacting partonic medium is effectively lowered in comparison to the pure hadronic medium, i.e., the rearrangement processes on the partonic level reduce the amount of dissipation in the highly dense matter and enhance the elliptic flow, especially in the midrapidity region, to bring the theoretical predictions in line with the data. Thus far the QGSM upgraded by the locally density-dependent parton recombination mechanism quasi models the possible dynamics of a sQGP from a microscopic point of view.

A complementary observable regarding anisotropic flow phenomena is the directed flow $v_1$ of produced particles. In Fig. 4 the results for the pseudorapidity dependence of this flow component, i.e., $v_1(\eta)$ of charged final hadrons, obtained by QGSM simulations with and without parton recombination processes are compared to the corresponding experimental data from the PHOBOS Collaboration for 0% to 40% central Au+Au collisions at the highest RHIC energy of $\sqrt{s_{NN}} = 200$ GeV. The result of the standard QGSM shows a characteristic wiggle structure extensively discussed in Ref. [22], whereas the scenario with parton recombination is able to reproduce the experimentally observed directed flow very well in the broad midrapidity region where $v_1$ is essentially flat and close to zero. From the microscopical point of view, this is another hint for a strongly interacting partonic medium which exists during the early dense stage of ultrarelativistic heavy-ion collisions around midrapidity. Thus, our findings are in line with the results of an anisotropic flow study using a multiphase transport

![Graph](image2)

**FIG. 4:** Influence of parton recombination processes on the pseudorapidity shape of the directed flow $v_1$ for charged hadrons. The results obtained with the standard QGSM (open symbols) [22] and those from a simulation using the QGSM extended by parton recombination (filled symbols) are shown in comparison to PHOBOS data [37]. The systematic errors of the experimental data are indicated by gray boxes and the statistical errors are indicated by bars.
(AMPT) model that includes both initial partonic and final hadronic interactions [28]. There also the conclusion has been drawn that the matter produced during the early stage of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the pseudorapidity region $|\eta| \leq 3$ is dominated by partons.

IV. SUMMARY AND CONCLUSIONS

In summary, it has been demonstrated that partonic fusion and recombination processes which occur in the very dense medium created in ultrarelativistic heavy-ion reactions during the early stages lead to short relaxation times and drive the system to fast kinetic equilibrium. The basis for these investigations was a microscopic transport model, namely the quark-gluon string model (QGSM) based on the color exchange mechanism for string formation, which has been extended by a locally density-dependent partonic recombination procedure to model effectively the dynamics of a strongly coupled quark plasma and final hadronic interactions.

Moreover, the pseudorapidity distributions of the anisotropy parameter $v_2(\eta)$ of final charged hadrons has been found to be intimately related to the corresponding dynamics. Fast equilibration due to parton recombination is necessary in order to obtain $v_2(\eta)$ profiles which are clearly peaked at midrapidity as seen in the data. We want to note that the other observables studied with the standard QGSM [22] turned out to be essentially robust against the inclusion of quark recombination. In particular the particle species dependence of $v_2(p_T)$ is still reproduced with the extended QGSM. The rapidity distribution for the final hadrons and their directed flow $v_1(\eta)$ are even considerably improved.

In conjunction with our aforementioned results for the local equilibration behavior, this is from the microscopic point of view a strong indication for the creation of a strongly interacting partonic medium in Au+Au collisions at RHIC that is thermally equilibrated on a very short time scale.

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