PHYSICAL REVIEW C **76**, 041901(R) (2007)

Charmonium dynamics in Au+Au collisions at $\sqrt{s} = 200$ GeV

O. Linnyk* and E. L. Bratkovskaya
Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany

W. Cassing
Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany

H. Stöcker†
Institut für Theoretische Physik, Johann Wolfgang Goethe University, D-60438 Frankfurt am Main, Germany

(Received 30 May 2007; published 12 October 2007)

The formation and suppression dynamics of J/Ψ, χ_c, and Ψ' mesons is studied within the hadron-string-dynamics (HSD) transport approach for Au+Au reactions at the top energy currently available at the BNL Relativistic Heavy Ion Collider (RHIC) of $\sqrt{s} = 200$ GeV. Two prominent models, which have been discussed for more than a decade, are incorporated, i.e., the hadronic comover absorption and reformation model as well as the quark-gluon plasma (QGP) threshold scenario, and compared with available experimental data. Our studies demonstrate that both scenarios, which are compatible with experimental observation at SPS energies, fail severely at RHIC energies. This combined analysis, together with the underestimation of charm elliptic flow, proves that the dynamics of c, $\bar{c}$ quarks are dominated by partonic interactions in the strong QGP and can be neither modeled by hadronic interactions nor described appropriately by color screening alone.

DOI: 10.1103/PhysRevC.76.041901 PACS number(s): 25.75.Dw, 12.38.Mh, 13.60.Le, 14.65.Dw

According to current understanding, the evolution of the universe in the Big Bang scenario proceeded from a quark-gluon plasma (QGP) to color neutral hadronic states within the first second of its lifetime. In this context, the dynamics of ultrarelativistic nucleus-nucleus collisions at energies currently available at the CERN Super Proton Synchrotron (SPS) and the BNL Relativistic Heavy Ion Collider (RHIC) are of fundamental importance as reflecting the properties of hadronic/partonic systems at high energy densities. The c, $\bar{c}$ quark degrees of freedom are of particular interest with respect to a phase transition from baryonic matter to the QGP, since $c\bar{c}$ meson states might not be formed in the very hot fireball due to color screening [1–3]. This initial intuitive expectation has guided experimental studies for almost two decades. However, more recent lattice QCD (lQCD) calculations have shown that the J/Ψ survives up to at least $1.5T_c (T_c \approx 170$–185 MeV) such that the lowest $c\bar{c}$ state remains bound up to a rather high energy density [4–6]. On the other hand, the χ_c and Ψ' appear to melt soon above T_c. It is presently not clear if the D and D^* mesons will also survive at temperatures $T > T_c$, but strong correlations between a light quark (antiquark) and a charm antiquark (quark) are likely to persist [7]. One may speculate that similar correlations survive also in the light quark sector above T_c, such that "hadronic comovers"—most likely with different spectral functions—might show up also at energy densities above 1 GeV/fm^3, which is taken as a characteristic scale for the critical energy density.

The production of charmonium in heavy-ion collisions, i.e., of $c\bar{c}$ pairs, occurs dominantly at the initial stage of the reaction in primary nucleon-nucleon collisions. At the very early stage, the $c\bar{c}$ pairs are expected to form color dipole states which experience (i) absorption by interactions with further nucleons of the colliding nuclei (cf. Refs. [8,9]). These $c\bar{c}$ color dipoles can be absorbed in a 'preresonance state' before the final hidden charm mesons or charmonia (J/Ψ, χ_c, Ψ') are formed. This absorption (denoted as "normal nuclear suppression") is also present in $p + A$ reactions and determined by a dissociation cross section $\sigma_B \sim 4$–7 mb. Those charmonia or preresonance states that survive normal nuclear suppression during the short overlap phase of the Lorentz contracted nuclei furthermore suffer from (ii) a possible dissociation in the deconfined medium at sufficiently high energy density and (iii) the interactions with secondary hadrons (comovers) formed in a later stage of the nucleus-nucleus collision.

In the QGP threshold scenario, e.g., the geometrical Glauber model of Blaizot *et al.* [10] as well as the percolation model of Satz [3], the QGP suppression (ii) sets in rather abruptly as soon as the energy density exceeds a threshold value ε_c, which is a free parameter. This is motivated by the idea that the charmonium dissociation rate is drastically larger in a QGP than in a hadronic medium [3]. On the other hand, the extra suppression of charmonia in the high density phase of nucleus-nucleus collisions at SPS energies [12,13] has been attributed to inelastic comover scattering (cf. Refs. [9,14–19] and references therein) assuming that the corresponding J/Ψ-hadron cross sections are on the order of a few mb [20–23]. In these models, comovers should not be viewed as asymptotic hadronic states in vacuum but rather as hadronic correlators (essentially of the vector meson type) that might well survive at energy densities above 1 GeV/fm^3. Additionally, alternative absorption mechanisms might play a role, such as gluon scattering on color dipole states as

*linnyk@fias.uni-frankfurt.de
†Also at Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany.

suggested in Refs. [24–27] or charmonium dissociation in the strong color fields of overlapping strings [28].

We recall that apart from absorption or dissociation channels for charmonia, recombination channels such as $D + \bar{D} \to X_c + \text{meson}$ $[X_c = (J/\Psi, \chi_c, \Psi')]$ also play a role in the hadronic phase. A previous analysis within the (HSD) transport approach [29,30]—employing the comover absorption model—demonstrated that the charmonium production from open charm and anticharm mesons indeed becomes essential in central Au+Au collisions at RHIC energies. This is in accordance with independent studies in Refs. [22,25] and also with the data from PHENIX [31]. On the other hand, the backward channels, relative to charmonium dissociation with comoving mesons ($X_c + \text{meson} \to D + \bar{D}$), were found to be practically negligible at the SPS energies.

In the present study, we extend our previous investigation [32] within the comover model and the QGP threshold scenario to the energy of $\sqrt{s} = 200$ GeV and compare the results with the PHENIX data. The questions we aim to solve are (1) can any of the models be ruled out by the present data sets and (2) do the recent PHENIX data suggest a different dynamics of charm quarks at the top RHIC energies?

The explicit treatment of initial $c\bar{c}$ production by primary nucleon-nucleon collisions is the same as in Ref. [32] (see Fig. 1 of Ref. [32] for the relevant cross sections) and the implementation of the comover model—involving a single matrix element M_0 fixed by the data at SPS energies—as well as the QGP threshold scenario is the same as in Ref. [32]. Consequently, no free parameters enter our studies below. We recall that the threshold scenario for charmonium dissociation is implemented as follows: whenever the local energy density $\varepsilon(x)$ is above a threshold value ε_j, where the index j stands for $J/\Psi, \chi_c, \Psi'$, the charmonium is fully dissociated to $c + \bar{c}$. The default threshold energy densities adopted are $\varepsilon_1 = 16$ GeV/fm^3 for J/Ψ, $\varepsilon_2 = 2$ GeV/fm^3 for χ_c, and $\varepsilon_3 = 2$ GeV/fm^3 for Ψ' and provide a fair reproduction of the data at SPS energies (except for Ψ' in the threshold scenario). The reader is referred to Ref. [32] for details.

The energy density $\varepsilon(\mathbf{r}; t)$, which is identified with the matrix element $T^{00}(\mathbf{r}; t)$ of the energy momentum tensor in the local rest frame at space-time $(\mathbf{r}, t)$, becomes very high in a central Au+Au collision at $\sqrt{s} = 200$ GeV, according to the HSD calculations, where baryons with approximately projectile or target rapidity are omitted. In the center of the reaction volume, $\varepsilon(\mathbf{r}; t)$ initially reaches values well above 30 GeV/fm^3 and drops below 1 GeV/fm^3 roughly within 5–7 fm/c. We recall that in HSD, explicit hadronic states are allowed to be formed only for $\varepsilon(\mathbf{r}; t) \leqslant 1$ GeV/fm^3.

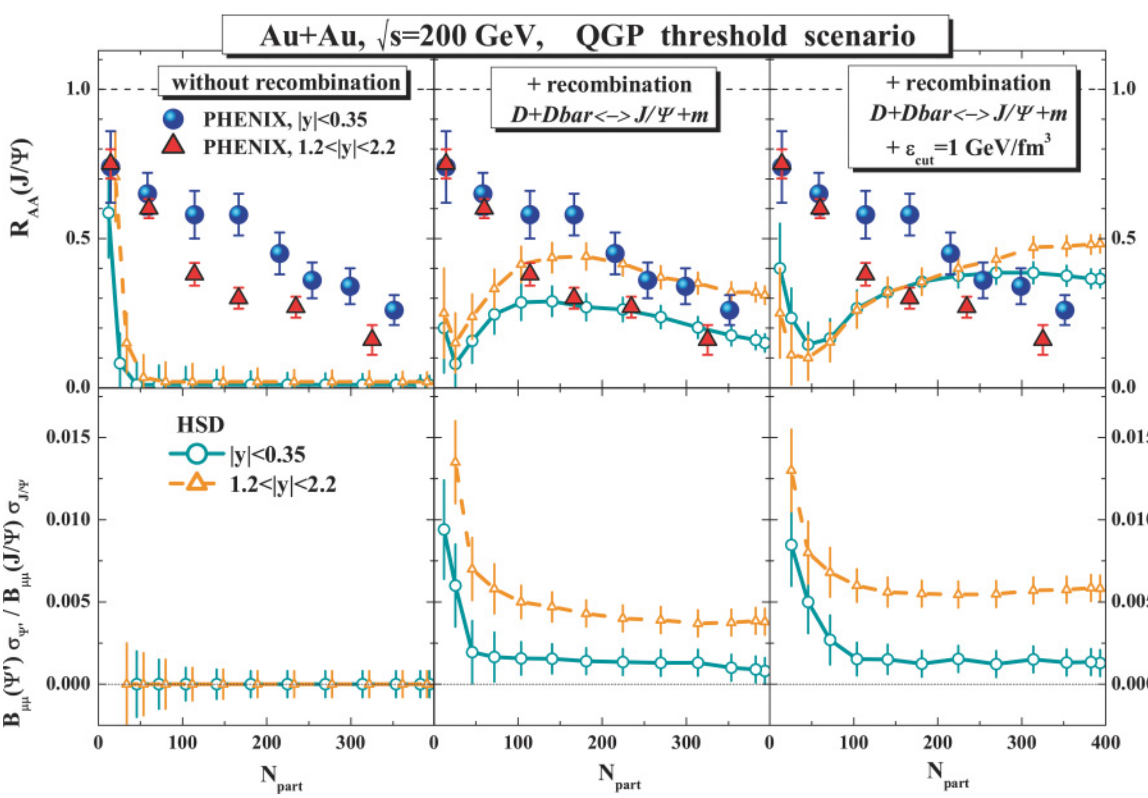

FIG. 1. (Color online) J/Ψ nuclear modification factor R_{AA} [Eq. (2)] for Au+Au collisions at $\sqrt{s} = 200$ GeV as a function of the number of participants N_{part} in comparison with the data from Ref. [11] for midrapidity (full circles) and forward rapidity (full triangles). HSD results for the QGP threshold melting scenarios are displayed in terms of the lower (green solid) lines for midrapidity J/Ψ's ($|y| \leqslant 0.35$) and in terms of the upper (orange dashed) lines for forward rapidity ($1.2 \leqslant y \leqslant 2.2$) within different recombination scenarios (see text). The error bars on the theoretical results indicate the statistical uncertainty due to the finite number of events in the HSD calculations. Predictions for the ratio $B_{\mu\mu}(\Psi')\sigma_{\Psi'}/B_{\mu\mu}(J/\Psi)\sigma_{J/\Psi}$ as a function of the number of participants N_{part} for Au+Au at $\sqrt{s} = 200$ GeV are shown in the lower set of plots.

In the theoretical approach, we calculate the J/Ψ survival probability $S_{J/\Psi}$ and the nuclear modification factor R_{AA} as

$$S_{J/\Psi} = \frac{N_{\rm fin}^{J/\Psi}}{N_{BB}^{J/\Psi}}, \quad (1)$$

$$R_{AA} = \frac{dN(J/\Psi)_{AA}/dy}{N_{\rm coll} \cdot dN(J/\Psi)_{pp}/dy}, \quad (2)$$

where $N_{\rm fin}^{J/\Psi}$ and $N_{BB}^{J/\Psi}$ denote the final number of J/Ψ mesons and the number of J/Ψ's produced initially by BB reactions, respectively. Note that $N_{\rm fin}^{J/\Psi}$ includes the decays from the final χ_c. In Eq. (1), $dN(J/\Psi)_{AA}/dy$ denotes the final yield of J/Ψ in AA collisions, $dN(J/\Psi)_{pp}/dy$ is the yield in elementary pp reactions, while $N_{\rm coll}$ is the number of binary collisions.

We start with a comparison of $R_{AA}(J/\Psi)$ [Eq. (2)] for Au+Au collisions as a function of the number of participants $N_{\rm part}$ against the data from Ref. [11] in the upper part of Fig. 1. The results for the threshold melting scenario [without the reformation channels $D + \bar{D} \to (J/\Psi, \chi_c, \Psi')+$ meson] are displayed on the left-hand side of Fig. 1 in terms of the lower (green) solid line for midrapidity $J/\Psi's(|y| \leqslant 0.35)$ and in terms of the upper (orange) dashed line at forward rapidity $(1.2 \leqslant |y| \leqslant 2.2)$. The experimental data from PHENIX [11] are given by the full circles at midrapidity and by triangles at forward rapidity. In this simple scenario, practically all charmonia are dissolved for $N_{\rm part} > 50$, because of the high energy densities reached in the overlap zone of the collision, which is clearly not compatible with the PHENIX data and indicates that charmonium reformation channels are important. Here we explore two scenarios for charmonium reformation: (a) we adopt the notion that hadronic correlators (with the quantum number of hadronic states) survive above T_c and the reformation and dissociation channels $[D + \bar{D} \leftrightarrow (J/\Psi, \chi_c, \Psi')+$ meson] are switched on after a formation time $\tau_f = 0.5$ fm/c (in the local rest frame) and (b) the hadronic states are assumed to persist only below $\varepsilon(\mathbf{r}; t) \leqslant 1$ GeV/fm^3, and thus the reformation and dissociation channels $[D + \bar{D} \leftrightarrow (J/\Psi, \chi_c, \Psi')+$ meson] are switched on only for energy densities below 1 GeV/fm^3. The results for the model (a) are displayed in the upper middle part of Fig. 1 and demonstrate that for $N_{\rm part} > 200$, an approximate equilibrium between the reformation and dissociation channels is achieved. However, here the calculations for forward rapidity match the data at midrapidity and vice versa, showing that the rapidity dependence is fully wrong. Furthermore, the J/Ψ suppression at more peripheral reactions is severely overestimated. The results for model (b) are shown in the upper right part of Fig. 1 and demonstrate that the dissociation and reformation channels no longer reach an equilibrium even for most central collisions. The J/Ψ suppression as a function of centrality as well as rapidity is fully off. Summarizing our model studies, we have to conclude that the threshold melting + reformation scenario is incompatible with the PHENIX data and has to be ruled out at top RHIC energies.

In the lower parts of Fig. 1, we show the results for the ratio of the Ψ' and J/Ψ dilepton yields (given by their cross sections multiplied by the corresponding branching ratios) which have no experimental counterpart. Here the two recombination models give finite ratios as a function of centrality but predict a

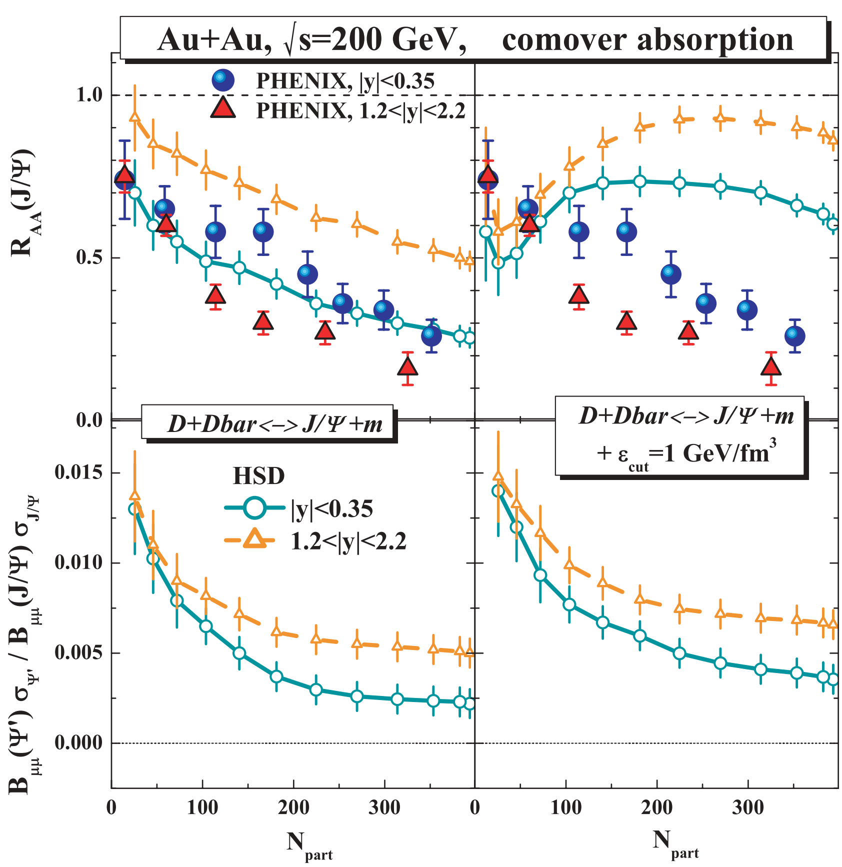

FIG. 2. (Color online) Same as Fig. 1, but for the comover absorption scenario including the charmonium reformation channels without cut in the energy density (left-hand side) and with a cut in the energy density $\varepsilon_{\rm cut} = 1$ GeV/fm^3 (see text for details).

larger Ψ' to J/Ψ ratio at forward rapidity than at midrapidity which is a consequence of the higher comover density at midrapidity. Experimental data on this ratio should provide further independent information.

The ratio $R_{AA}(J/\Psi)$ in the comover + recombination model is displayed in the upper part of Fig. 2 in comparison with the data from Ref. [11] using the same assignment of the lines as in Fig. 1. The left-hand side shows the results for the 'default' comover reformation and dissociation channels (as in Ref. [32]), whereas the right-hand side corresponds to the results when the comover channels are switched on only for energy densities $\varepsilon(\mathbf{r};t) \leqslant \varepsilon_{\rm cut} = 1$ GeV/fm^3. The latter scenario shows a suppression pattern which is in strong contrast to the data both as a function of $N_{\rm part}$ and rapidity. The default scenario (left) gives a continuous decrease of $R_{AA}(J/\Psi)$ with centrality and, however, an opposite dependence on rapidity y due to the higher comover density at midrapidity. The Ψ' to J/Ψ ratio is displayed in the lower parts of Fig. 2 and shows a decreasing ratio with centrality similar to the results at SPS energies [32]. However, independent from experimental results on this ratio, the comover + recombination model has to be ruled out at RHIC energies, too.

In conclusion and to summarize our study, we have investigated the formation and suppression dynamics of J/Ψ, χ_c, and Ψ' mesons—within the HSD transport approach—for Au+Au reactions at the top RHIC energy of $\sqrt{s} = 200$ GeV. Two controversial models, which have been discussed in the community for more than a decade, i.e., the hadronic comover absorption and reformation model as well as the QGP threshold melting scenario, have been compared with the available experimental data from the PHENIX Collaboration [11]. When adopting the same parameters for cross sections (matrix elements) or threshold energies as at SPS energies [32], we find that both scenarios—compatible with experimental observation at SPS energies—fail severely at RHIC energies and can safely be excluded. This provides a clear answer to question (1) raised in the Introduction.

We point out, furthermore, that the failure of the hadronic comover absorption model goes in line with its underestimation of the collective flow v_2 as well as the underestimation of $R_{AA}(p_T)$ of leptons from open charm decay as investigated in Ref. [33]. This strongly suggests that the dynamics of c, $\bar{c}$ quarks are dominated by partonic interactions in the strong QGP (sQGP) which can be neither modeled by hadronic interactions nor described appropriately by color screening alone. This also gives an answer to question (2) of the Introduction.

Since the open charm suppression is also underestimated severely in perturbative QCD approaches, the nature of the sQGP and its transport properties remain an open question (and challenge).

The authors acknowledge stimulating correspondence with T. Gunji and valuable discussions with L. Tolos and M. Gyulassy and the financial support of BMBF.

[1] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
[2] H. Satz, Rep. Prog. Phys. **63**, 1511 (2000).
[3] H. Satz, J. Phys. G **32**, R25 (2006).
[4] S. Datta, F. Karsch, P. Petreczky, and I. Wetzorke, J. Phys. G **30**, S1347 (2004).
[5] M. Asakawa and T. Hatsuda, J. Phys. G **30**, S1337 (2004).
[6] F. Karsch, J. Phys. G **30**, S887 (2004).
[7] H. van Hees and R. Rapp, Phys. Rev. C **71**, 034907 (2005).
[8] D. Kharzeev, C. Lourenco, M. Nardi, and H. Satz, Z. Phys. C **74**, 307 (1997).
[9] N. Armesto and A. Capella, Phys. Lett. **B430**, 23 (1998).
[10] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).
[11] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **98**, 232301 (2007).
[12] M. C. Abreu *et al.* (NA50 Collaboration), Phys. Lett. **B410**, 337 (1997).
[13] A. Foerster *et al.* (NA60 Collaboration), J. Phys. G **32**, S51 (2006).
[14] W. Cassing and E. L. Bratkovskaya, Nucl. Phys. **A623**, 570 (1997).
[15] W. Cassing and E. L. Bratkovskaya, Phys. Rep. **308**, 65 (1999).
[16] R. Vogt, Phys. Rep. **310**, 197 (1999).
[17] C. Gerschel and J. Hüfner, Annu. Rev. Nucl. Part. Sci. **49**, 255 (1999).
[18] W. Cassing, E. L. Bratkovskaya, and S. Juchem, Nucl. Phys. **A674**, 249 (2000).
[19] C. Spieles *et al.*, J. Phys. G **25**, 2351 (1999); Phys. Rev. C **60**, 054901 (1999).
[20] K. L. Haglin, Phys. Rev. C **61**, 031902 (2000).
[21] Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000).
[22] Z. Lin and C. M. Ko, J. Phys. G **27**, 617 (2001).
[23] A. Sibirtsev, K. Tsushima, and A. W. Thomas, Phys. Rev. C **63**, 044906 (2001).
[24] B. Zhang, C. M. Ko, B.-A. Li, Z. Lin, and B.-H. Sa, Phys. Rev. C **62**, 054905 (2000).
[25] L. Grandchamp and R. Rapp, Phys. Lett. **B523**, 60 (2001); Nucl. Phys. **A709**, 415 (2002).
[26] D. Blaschke, Y. Kalinovsky, and V. Yudichev, Lect. Notes Phys. **647**, 366 (2004).
[27] M. Bedjidian *et al.*, in Hard Probes in Heavy-Ion Collisions at the LHC, eds. M. Mangano, H. Satz, and U. Wiedemann, CERN Yellow Report CERN-2004-009 (2004), arXiv:hep-ph/0311048.
[28] J. Geiss, C. Greiner, E. L. Bratkovskaya, W. Cassing, and U. Mosel, Phys. Lett. **B447**, 31 (1999).
[29] E. L. Bratkovskaya, W. Cassing, and H. Stöcker, Phys. Rev. C **67**, 054905 (2003).
[30] E. L. Bratkovskaya, A. P. Kostyuk, W. Cassing, and H. Stöcker, Phys. Rev. C **69**, 054903 (2004).
[31] H. Büsching *et al.* (PHENIX Collaboration), Nucl. Phys. **A774**, 103 (2006).
[32] O. Linnyk, E. L. Bratkovskaya, W. Cassing, and H. Stöcker, Nucl. Phys. **A786**, 183 (2007).
[33] E. L. Bratkovskaya, W. Cassing, H. Stöcker, and N. Xu, Phys. Rev. C **71**, 044901 (2005).