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

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The formation and suppression dynamics of $J/\Psi$, $\chi_c$ and $\Psi'$ mesons is studied within the HSD transport approach for $Au+Au$ reactions at the top RHIC energy 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 ‘QGP threshold’ scenario, and compared to available experimental data. Our studies demonstrate that both scenarios – 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 ($s$QGP) and can neither be modeled by ‘hadronic’ interactions nor described appropriately by color screening alone.

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According to current understanding, the evolution of the universe in the ‘Big Bang’ scenario has 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 ultra-relativistic nucleus-nucleus collisions at Super-Proton-Synchrotron (SPS) and Relativistic-Heavy-Ion-Collider (RHIC) energies 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 no longer be formed in the very hot fireball due to color screening [1,2,3]. This initial intuitive expectation has guided experimental studies for almost two decades. However, more recent lattice QCD (lQCD) calculations have shown that the $J/\Psi$ survives up to at least 1.5 $T_c$ ($T_c \approx 170$ to 185 MeV) such that the lowest $c\bar{c}$ state remains bound up to rather high energy density [4,5,6]. On the other hand the $\chi_c$ and $\Psi'$ appear to melt soon above $T_c$. It is presently not clear, if also the $D$ and $D^*$ mesons will survive at temperatures $T > T_c$, but strong correlations between a light quark (antiquark) and a charm antiquark (quark) are likely to persist [6]. 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 ‘pre-resonance state’ before the final hidden charm mesons or charmonia $(J/\Psi, \chi_c, \Psi')$ are formed. This absorption – denoted by ‘normal nuclear suppression’ – is also present in $p + A$ reactions and determined by a dissociation cross section $\sigma_B \sim 4$ to 7 mb. Those charmonia or ‘pre-resonance’ 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. [11] 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 $\varepsilon_c$, which is a free parameter. This is motivated by the idea that the charmonium dissociation rate is drastically larger in a quark-gluon-plasma (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. [3,14,15,16,17,18,19] and Refs. therein) assuming that the corresponding $J/\Psi$-hadron cross sections are in the order of a few mb [20,21,22,23]. In these models, ‘comovers’ should not be viewed as asymptotic hadronic states in vacuum but rather as hadronic
correlators (essentially of 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 suggested in Refs. [24, 25, 26, 27] or charmonium dissociation in the strong color fields of overlapping strings [28].

We recall that apart from absorption or dissociation channels for charmonia also recombination channels such as $D + \bar{D} \rightarrow X_c + \text{meson} (X_c = (J/\Psi, \chi_c, \Psi')$ play a role in the hadronic phase. A previous analysis within the HSD transport approach [24, 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. 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 – ($X_c + \text{meson} \rightarrow D + \bar{D}$) 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 to the PHENIX data. The questions we aim at solving is: 1) can any of the models be ruled out by the present data sets and 2) do the recent PHENIX data provide a hint to a different dynamics of charm quarks at 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 are as in [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 $\varepsilon_j$, 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 $J/\Psi$, $\varepsilon_2 = 2$ GeV/fm$^3$ for $\chi_c$, and $\varepsilon_3 = 2$ GeV/fm$^3$ for $\Psi'$ and provide a fair reproduction of the data at SPS energies (except for $\Psi'$ in the ‘threshold scenario’). The reader is
reactions, respectively. Note that the number of binary collisions.
comes very high in a central Au+Au collision at √s = 200 GeV.
lh.s. of Fig. 1 in terms of the lower (green) solid line for midrapidity J/Ψ's
and terms of the upper (orange) dashed line at forward rapidity (1.2 ≤ |y| ≤ 2.2).
The experimental data from PHENIX 10 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_{part} > 50, due to 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 + D → (J/Ψ, χ_c, Ψ') + meson) are switched on after a formation time τ = 0.5 fm/c (in the local rest frame)
and b) the hadronic states are assumed to persist only below ε(r; t) ≤ 1 GeV/fm³ and thus the reformation
and dissociation channels (D + D → (J/Ψ, χ_c, Ψ') + meson) are switched on only for energy densities below
1 GeV/fm³. The results for the model a) are displayed in the upper middle part of Fig. 1 and demonstrate that
for N_{part} > 200 an approximate equilibrium between the reformation and dissociation channels is achieved.
However, 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 over-
estimated. The results for the 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 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/Ψ) in the ‘comover + recombination model’ is displayed in the upper part of Fig. 2 in comparison
to the data from 10 using the same assignment of the lines as in Fig. 1. The l.h.s. shows the results for the
‘default’ comover reformation and dissociation channels

![Figure 2](image-url)

**FIG. 2:** Same as Fig. 1 for the ‘comover absorption scenario’ including the charmonium reformation channels without cut in the energy density (l.h.s.) and with a cut in the energy density ε_{cut} = 1 GeV/fm³ (see text for details).

The energy density ε(r; t) – which is identified with the matrix element T^{00}(r; t) of the energy momentum
tensor in the local rest frame at space-time (r, t) – becomes very high in a central Au+Au collision at √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, ε(r; t) initially reaches values well above 30 GeV/fm³ and drops below
1 GeV/fm³ roughly within 5-7 fm/c. We recall that in HSD explicit hadronic states are allowed to be formed
only for ε(r; t) ≤ 1 GeV/fm³.

In the theoretical approach, we calculate the J/Ψ survival probability S_{J/Ψ} and the nuclear modification fac-
tor R_{AA} as

\[ S_{J/Ψ} = \frac{N_{fin}^{J/Ψ}}{N_{BB}^{J/Ψ}} \]

\[ R_{AA} = \frac{dN(J/Ψ)_{AA}/dy}{N_{coll} \cdot dN(J/Ψ)_{pp}/dy}, \]

where \( N_{fin}^{J/Ψ} \) and \( N_{BB}^{J/Ψ} \) denote the final number of J/Ψ mesons and the number of J/Ψ’s produced initially by
BB reactions, respectively. Note that \( N_{fin}^{J/Ψ} \) includes the decays from the final χ_c. In (2), \( dN(J/Ψ)_{AA}/dy \) denotes
the final yield of J/Ψ in AA collisions, \( dN(J/Ψ)_{pp}/dy \) is the yield in elementary pp reactions, while \( N_{coll} \) is the
number of binary collisions.

We start with a comparison of \( R_{AA}(J/Ψ) \) for Au + Au collisions as a function of the number of partic-

tants \( N_{part} \) to the data from 10 in the upper part of Fig. 1. The results for the ‘threshold melting’ scenario
(without the reformation channels D + D → (J/Ψ, χ_c, Ψ') + meson) are displayed on the l.h.s. of Fig. 1 in terms
of the lower (green) solid line for midrapidity J/Ψ's (|y| ≤ 0.35) and in terms of the upper (orange) dashed line
at forward rapidity (1.2 ≤ |y| ≤ 2.2). The experimental data from PHENIX 10 are given by the full circles at midrapidity
and by triangles at forward rapidity.
(as in Ref. [32]) whereas the r.h.s. corresponds to the results when the comover channels are switched on only for energy densities $\varepsilon(r; t) \leq \varepsilon_{\text{cut}} = 1 \text{ GeV/fm}^3$. The latter scenario shows a suppression pattern which is in strong contrast to the data both as a function of $N_{\text{part}}$ and rapidity. The default scenario (l.h.s.) gives a continuous decrease of $R_{AA}(J/\Psi)$ with centrality, however, an opposite dependence on rapidity $y$ due to the higher comover density at midrapidity. The $\Psi'$ to $J/\Psi$ 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 concluding and summarizing our study, we have investigated the formation and suppression dynamics of $J/\Psi$, $\chi_c$, and $\Psi'$ mesons – within the HSD transport approach – for Au+Au reactions at top RHIC energies of $\sqrt{s} = 200$ GeV. Two controversial models – 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 to the available experimental data from the PHENIX Collaboration [10]. 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 the 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 neither be 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).

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