Charmed hadron signals of partonic medium

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Abstract. We present a short review of our results on the collectivity and the suppression pattern of charmed mesons in heavy-ion collisions based on the microscopic Hadron-String Dynamics (HSD) transport approach for different scenarios of charm interactions with the surrounding matter – the ‘comover’ dissociation by mesons with further recreation by $D-\bar{D}$ channels and ‘pre-hadronic’ interaction scenarios. While at SPS energies the hadronic ‘comover’ absorption scenario is found to be compatible with the experimental data, the dynamics of $c, \bar{c}$ quarks at RHIC are dominated by partonic or ‘pre-hadronic’ interactions in the strongly coupled quark-gluon plasma stage and cannot be modeled by pure ‘hadronic’ interactions. We find that the collective flow of charm in the purely hadronic scenario appears compatible with the data at SPS energies but underestimates the data at top RHIC energies. Thus, the large elliptic flow $v_2$ of $D$-mesons and the low $R_{AA}(p_T)$ of $J/\Psi$ seen experimentally at RHIC have to be attributed to early interactions of non-hadronic degrees of freedom. Simultaneously, we observe that non-hadronic interactions are mandatory in order to describe the narrowing of the $J/\Psi$ rapidity distribution from $pp$ to central $Au + Au$ collisions at the top RHIC energy. We demonstrate additionally that the strong quenching of high-$p_T$ $J/\Psi$’s in central $Au + Au$ collisions indicates that a fraction of final $J/\Psi$ mesons is created by a coalescence mechanism close to the phase boundary.

1. Introduction

The phase transition from partonic degrees of freedom to interacting hadrons, as occurring in relativistic nucleus-nucleus collisions, is a central topic of modern high-energy physics. The main difficulty in the interpretation of the data is that the information about the initial strongly interacting quark-gluon-plasma (sQGP) stage of matter can be obtained only indirectly from the measurement of hadronic observables; it might be strongly distorted by the hadronization process and final state interactions of the hadrons. In order to reliably subtract the hadronic contribution from the sQGP signal carried by charmed mesons (as well as hadronic final-state interactions) we apply a microscopic transport approach.

Our study is based on the Hadron-String-Dynamics [1] transport approach, which simulates the time-dependent ‘hadronic environment’ for open charm mesons and
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charmonia in heavy-ion collisions rather well [2]. Upon being produced in initial $N+N$ collisions, charmonia in HSD are absorbed on baryons (normal nuclear absorption) as well as on ‘comoving’ mesons by the process $c\bar{c} + \text{meson} \rightarrow D + \bar{D}, D^* + \bar{D}, D^* + \bar{D}^*$ etc. Note that the latter interactions lead also to a recreation of charmonia via the inverse recombination process. The $J/\Psi, \chi_c, \Psi'$ formation cross sections by open charm mesons or the ‘comover’ dissociation cross sections are not well known. In HSD a simple 2-body transition model is employed that allows to implement the backward reactions uniquely by exploiting detailed balance for each individual channel. The details of the model are described in the review [3]. In the current proceedings we concentrate on the results and the comparison to data.

In the hadronic comover dissociation and recombination scenario only formed comoving mesons participate in the dissociation of charm or $D\bar{D}$ recombination reactions. Indeed, in the default HSD all newly produced hadrons (by string fragmentation) have a formation time of $\tau_F \approx 0.8 \text{ fm/c} \approx 1/\Lambda_{QCD}$ in their rest frame and do not interact hadronically during the ‘partonic’ propagation. Furthermore, hadronization is inhibited, if the energy density – in the local rest frame – is above $1 \text{ GeV/fm}^3$, which roughly corresponds to the energy density for QGP formation in equilibrium. Being hard probes, $c\bar{c}$ pairs are created in the early stage of the collision, while the comoving mesons are formed at a later stage.

In order to simulate partonic interaction effects we have included explicit interactions of pre-hadrons with the charmed mesons [4]. In HSD a pre-hadron is defined as a state with the quantum numbers of a hadron being at time $t$ under ‘formation’ ($t < \tau_F\gamma$) or in a cell with local energy density above $\approx 1 \text{ GeV/fm}^3$ (cf. Ref. [3]). Since the cross sections of elastic $c\bar{c}$ scattering on ‘pre-mesons’ and ‘pre-baryons’ are unknown, we have adjusted them to RHIC data on $J/\Psi$ suppression (cf. Ref. [3]). It has to be stressed that further explicit partonic degrees of freedom, i.e. gluons and their mutual interactions and gluon interactions with quarks/antiquarks, have not been taken into account explicitly so far.

2. Comparison to data

We start our comparison to data with the charmonium production and suppression at SPS energies within the default ‘hadronic comover’ scenario. As found in Ref. [6], the comover absorption model performs well with respect to all data sets at SPS. Indeed, the extra suppression of charmonia by comovers, seen in Fig. [1] matches the $J/\Psi$ suppression in In+In and Pb+Pb as well as the $\Psi'$ to $J/\Psi$ ratio rather well. One may conclude that the comover absorption model so far cannot be ruled out on the basis of the available data sets from the SPS within error bars.

Further information may be gained from the $J/\Psi$ rapidity distributions in Au+Au collisions at RHIC. The latter distribution is shown in Fig. [2] in comparison to the PHENIX data in the standard ‘comover’ scenario (dashed blue lines) and the ‘comover’ model including pre-hadronic interactions of charm (solid red lines). Whereas for
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Figure 1. Left panel: The ratio $B_{pp} \sigma(J/\Psi) / \sigma(DY)$ as a function of the number of participants $N_{part}$ in In+In (red line with open squares) and Pb+Pb reactions (blue line with open circles) at 158 A-GeV relative to the normal nuclear absorption given by the straight black line. The full dots and squares denote the respective data from the NA50 and NA60 Collaborations. The model calculations reflect the hadronic comover absorption scenario. Right panel: The $\Psi'$ to $J/\Psi$ ratio as a function of the transverse energy $E_T$ for Pb+Pb at 160 A-GeV. The full dots and stars denote the respective data from the NA50 Collaboration [5]. The HSD result [6] for the comover absorption scenario is shown by the red line. The figures are taken from Ref. [6].

Peripheral reactions the additional early interactions practically play no role, the pre-hadron elastic scatterings lead to a dynamical narrowing of the $J/\Psi$ rapidity distribution with the centrality of the collision (roughly in line with the data). In the standard ‘comover’ model an opposite trend is seen: here the interactions of charmonia with formed hadrons produce a dip in the rapidity distribution at $y \approx 0$ which increases with centrality since the density of formed hadrons increases accordingly around mid-rapidity. Since the total number of produced $c\bar{c}$ pairs is the same (for the respective centrality class) and detailed balance is incorporated in the reaction rates, we find a surplus of $J/\Psi$ at forward rapidities. The net result is a broadening of the $J/\Psi$ rapidity distribution with centrality in the purely hadronic scenario opposite to the trend observed in experiment. Consequently, the PHENIX data on $J/\Psi$ suppression indicate the presence and important impact of pre-hadronic or partonic interactions in the early charm dynamics.

A significant suppression of high transverse momentum hadrons in Au+Au collisions compared to $pp$ is observed at RHIC energies of $\sqrt{s} = 200$ GeV and is attributed to the energy loss of highly energetic particles in a hot colored medium (QGP). In order to quantify the effect of hadronic final state interactions, we show in the left panel of Fig. 3 the HSD predictions from Ref. [8] for the ratio of the final to the initial transverse $p_T$ spectra of $D + \bar{D}$-mesons from Au + Au collisions at $\sqrt{s} = 200$ GeV. HSD predicts an enhancement of $D, \bar{D}$ mesons at low momenta with a maximum at $p_T \approx 1$ GeV/c and a relative suppression for $p_T > 2$ GeV/c. These effects increase with the centrality of the Au+Au collision. We note that the maxima in the ratios
disappear when switching off the rescattering with mesons in the transport approach. Thus a collective acceleration of the $D + \bar{D}$ mesons occurs also via elastic scattering with mesons. As shown in Fig. 3, the suppression seen by PHENIX may well be explained by hadronic comover interactions up to transverse momenta about 4 GeV/c. Only for higher $p_T$ a clear signal for parton energy loss – either gluon bremsstrahlung or parton elastic scattering – may be extracted from comparison to the data!

The suppression pattern $R_{AA}(J/\Psi)$ from HSD (in the comover scenario) is quite analogous to that of $D$-mesons showing a slight maximum for transverse momenta of $\sim 2$ GeV/c and a steady decrease for higher $p_T$. In the right panel of Fig. 3, the predictions (from Ref. [8]) for the ratio of the final to the initial transverse $p_T$ spectra of $J/\Psi$-mesons as well as new calculations in the extended version of the comover approach (grey dashed bands) from Au + Au collisions at $\sqrt{s} = 200$ GeV are displayed. The preliminary PHENIX data for $R_{AA}(J/\Psi)$ from Ref. [7] – added later – show a substantially different pattern, especially for non-peripheral interactions. The strong suppression for low $p_T$ $J/\Psi$ mesons seen experimentally suggests that not primordial $J/\Psi$’s are accelerated during the dynamical evolution but that at least a part of initially formed $J/\Psi$’s are dissolved and recreated later, e.g. by $c\bar{c}$ coalescence. We stress that the reformation of charmonia in the hadronic phase (by $D + \bar{D}$ etc.) carries the flow from the $D$-mesons and thus does not lead to suppression at small $p_T$ as seen experimentally. This observation supports the idea that part of the charmonia are produced in the hadronization process!

A further possible way to disentangle hadronic from partonic dynamics is the elliptic flow $v_2(y, p_T)$. In Ref. [1] we compared the HSD result for $v_2(J/\Psi)$ at SPS in the purely hadronic ‘comover’ scenario to the data for $v_2(J/\Psi)$ of the NA60 collaboration for In+In collisions [12]. The agreement found between the theory and the data indicates that – in line with the reproduction of the $J/\Psi$ suppression data [6] (cf. Fig. 1) – the (low) $v_2(J/\Psi)$ does not point towards additional strong partonic interactions at SPS energies.

The situation is, however, different for the collective flow of $D$-mesons at top RHIC energies. In Fig. 4 one sees that the elliptic flow of $D$-mesons is clearly underestimated
3. Conclusions

The above findings suggest that the charmonium dynamics in heavy-ion reactions is dominantly driven by hadronic interactions in the SPS energy regime. Since energy densities above 1 GeV/fm$^3$ are reached in central nucleus-nucleus collisions at 158 A·GeV, our observation indicates that hadronic correlators (with quantum numbers in the default (purely hadronic) HSD model (cf. Ref. [8]). Only when including pre-hadronic charm interactions, the elliptic flow moderately increases, but still stays below the PHENIX data. We thus conclude that the modeling of charm interactions by pre-hadronic interactions accounts for part of the non-hadronic generation of the $v_2$, but does not provide enough interaction strength in the early phase of the collision.

Since a large fraction of $J/\Psi$’s in central Au+Au collisions at RHIC are created by $D + \bar{D}$ recombination, the elliptic flow of $J/\Psi$’s obtained from HSD in the comover (purely hadronic) case is comparatively small, too. The accuracy of the preliminary PHENIX data so far does not allow for a differentiation between the different model predictions (cf. Ref. [3]).
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Figure 4. Elliptic flow of $D$-mesons produced in $Au + Au$ collisions at $\sqrt{s} = 200$ GeV as a function of $p_T$ from HSD (solid blue line with open circles) in comparison to the PHENIX data [10] on $v_2$ of non-photonic electrons. The red line with open stars shows the HSD result for the $v_2$ of $D$-mesons when including additionally pre-hadronic charm interactions. The figure is taken from Ref. [4].

of the familiar hadrons) still persist above the critical energy density for the formation of a QGP.

In contrast, the study of the formation and suppression dynamics of charmonia within the HSD transport approach for Au+Au reactions at the top RHIC energy has demonstrated that the hadronic ‘comover absorption and recreation model’ fails severely at $\sqrt{s}=200$ GeV. This is found in the $J/\Psi$ rapidity distribution, in the differential elliptic flow of $J/\Psi$ and the charmonium nuclear modification factor $R_{AA}$ as a function of transverse momentum $p_T$. Only when including pre-hadronic degrees in the early charm reaction dynamics, the general suppression pattern of charmonia may be reasonably described; though, the elliptic flow $v_2$ is still (slightly) underestimated. On the other hand, $R_{AA}(p_T)$ for $J/\Psi$ mesons cannot be described appropriately in the comover approach even when incorporating the early pre-hadron interactions. The latter observable indicates that at least part of the final $J/\Psi$’s are created by coalescence of $c\bar{c}$ pairs in the hadronization phase. Our analysis demonstrates that the dynamics of $c, \bar{c}$ quarks in heavy-ion reactions at RHIC energies are dominated by partonic interactions in the sQGP.

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