In-Medium Effects on Charmonium Production in Heavy-Ion Collisions

Loïc Grandchamp,[1,2] Ralf Rapp,[3,4] and Gerald E. Brown[1]
[1]*Department of Physics, SUNY, Stony Brook, New York 11794-3800, USA*
[2]*IPN Lyon, 69622 Villeurbanne Cedex, France*
[3]*Nordita, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[4]*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843, USA*
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Charmonium production in heavy-ion collisions is investigated within a kinetic theory framework incorporating in-medium properties of open- and hidden-charm states in line with recent QCD lattice calculations. A continuously decreasing open-charm threshold across the phase boundary of hadronic and quark-gluon matter is found to have important implications for the equilibrium abundance of charmonium states. The survival of J/ψ resonance states above the transition temperature enables their recreation also in the quark-gluon plasma. Including effects of chemical and thermal off-equilibrium, we compare our model results to available experimental data at CERN SPS and BNL RHIC energies. In particular, earlier found discrepancies in the ψ'/ψ ratio can be resolved.

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The production systematics of heavy-quark bound states in (ultra-) relativistic collisions of heavy nuclei (A-A) is believed to encode valuable information on the hot and dense strong-interaction matter formed in these reactions [1]. Based on the notion that charm-quark pairs ($c\bar{c}$) are exclusively created in primordial (hard) nucleon-nucleon (NN) collisions, it has been suggested [2] that a suppression of observed J/ψ mesons in sufficiently central and/or energetic A-A reactions signals the formation of a deconfined medium [quark-gluon plasma (QGP)], as tightly bound $c\bar{c}$ states are conceivably robust in hadronic matter. While theoretical [3] and (indirect) experimental evidence [4] supports NN collision scaling of total charm production, it has recently been realized [5–7] that coalescence of c and $\bar{c}$ quarks can induce significant regeneration of charmonium states in later stages of A-A collisions, especially if several pairs are present [e.g., $N_{c\bar{c}} = 10$–20 in central Au-Au at the Relativistic Heavy-Ion Collider (RHIC)]. This is a direct consequence of (elastic) c-quark reinteractions, facilitating the backward direction of charmonium dissociation reactions, $J/\psi + X_1 \rightleftharpoons X_2 + c + \bar{c}(D + \bar{D})$.

Recent lattice computations of quantum chromodynamics (QCD) have revealed important information on charm(onium) properties at finite temperature T, most notably (i) an in-medium reduction of the open-charm threshold which is surprisingly continuous even across the phase transition region [8] and (ii) the survival of J/ψ and η_c states as resonances in the QGP phase [9,10], with essentially unmodified masses. Note that the use of charmonium spectral functions, in connection with appropriate asymptotic states, incorporates both (static) screening and (dynamical) dissociation mechanisms.

In this Letter, we propose an approach that implements charm properties inferred from lattice QCD as microscopic in-medium effects into a kinetic rate equation. It enables a comprehensive treatment of charmonium dissociation and regeneration across the phase transition, connecting hadronic and QGP phases in a continuous way, not present in previous calculations. For example, in the kinetic approach of Ref. [6], J/ψ's were only considered in the QGP phase using their vacuum binding energy, whereas recent transport calculations [11,12] do not invoke the notion of a (equilibrium) phase transition. In addition, in-medium open-charm masses will significantly affect the equilibrium levels of charmonium, as employed in statistical models [5,7]. We thus conceptually improve our earlier constructed "two-component" model [13], which combined statistical production at hadronization with suppression in hadronic and QGP phases. Employing a schematic thermal fireball model, the rate equations are applied to heavy-ion reactions at the Super Proton Synchrotron (SPS) and at the RHIC.

We begin by evaluating in-medium masses of charm states. Charmonium masses appear to be essentially unaffected at finite T, even above T_c (critical temperature) [9,10], which we assume from now on. Unquenched QCD lattice studies of the free energy, $F_{Q\bar{Q}}(r, T)$, of a heavy-quark pair [8], however, exhibit a plateau value for large Q-$\bar{Q}$ separations r, which gradually decreases with increasing T. In the hadron gas (HG), this can be interpreted as a reduction of D-meson masses (supported by QCD sum rules [14]) being driven by a reduced constituent light-quark mass, m_q^*, due to (partial) chiral symmetry restoration [15]. We implement this also for other open-charm hadrons by employing a Nambu-Jona-Lasinio model calculation for m_q^* at finite T and quark chemical potential μ_q [16], neglecting heavy-light quark interaction and kinetic energies. For small μ_q, the typical light-quark mass reduction amounts to $\Delta m_q(T_c) \simeq 140$ MeV. To assess open-charm states in the QGP, a key element is the essentially continuous behavior of the open-charm threshold through T_c. Within a quark description above T_c, we propose to identify this with an in-medium c-quark mass, $m_c^* \simeq 1.6$–1.7 GeV [17]. In fact, $m_c^*(T_c)$ is fixed such that the *total* open-charm density smoothly matches the hadronic side. The difference to the bare mass, $m_c \simeq 1.3$ GeV, is naturally attributed to a thermal correlation energy of heavy quarks in the QGP.

Next, we determine the thermal widths (or inverse lifetimes), $\Gamma_\Psi = (\tau_\Psi)^{-1}$, of charmonium states Ψ. They are related to (inelastic) dissociation cross sections, $\sigma_{\Psi i}^{\rm diss}$, by

$$\Gamma_\Psi(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} f^i(k;T)\sigma_{\Psi i}^{\rm diss} v_{\rm rel}, \qquad (1)$$

where i runs over all matter constituents with thermal distributions f^i. In the QGP, parton-induced "quasi-free" breakup, $i + \Psi \rightarrow i + c + \bar{c}$ ($i = g, q, \bar{q}$), is utilized [13]. For small binding energies, $E_B = 2m_c^* - m_\Psi \lesssim \Lambda_{\rm QCD}$, the latter (with $\alpha_s \simeq 0.25$) has been shown [13] to dominate over standard gluodissociation [18], $i + \Psi \rightarrow c + \bar{c}$. In addition, essentially unbound charmonium resonances such as ψ' and χ states can be treated on an equal footing. The thermal J/ψ width turns out to be $\sim$100 MeV at $T \simeq 250$ MeV, reminiscent to (quenched) lattice results [10] under comparable conditions.

For J/ψ's in the HG, we compute inelastic cross sections with π [19] and ρ mesons within a flavor SU(4) effective Lagrangian formalism [20,21], including in-medium charm-hadron masses [22] as described above. The free χ and ψ' cross sections are approximated by geometric scaling [23], supported by quark-model calculations [24]. If the $D\bar{D}$ threshold moves below the charmonium mass, we additionally evaluate direct decays, $\Psi \rightarrow D\bar{D}$, accounting for wave-function-node effects according to Ref. [25]. Despite the increase in available phase space due to reduced masses, the charmonium lifetimes in the HG remain longer than in the QGP.

In-medium charm properties have important consequences for charmonia in heavy-ion reactions. To illustrate this point, consider the J/ψ number in thermal equilibrium, $N_\psi^{\rm eq} = V_{\rm FB} n_\psi^{\rm eq}$ ($V_{\rm FB}$ is fireball 3-volume [26]), with the density

$$n_\psi^{\rm eq}(T, \gamma_c) = 3\gamma_c^2 \int \frac{d^3q}{(2\pi)^3} f^\psi(m_\psi, T). \qquad (2)$$

Here, we have included chemical off-equilibrium effects through the charm-quark fugacity γ_c which is adjusted to the total number, $N_{c\bar{c}}$, of $c\bar{c}$ pairs in the system via [5,7]

$$N_{c\bar{c}} = \frac{1}{2}\gamma_c N_{\rm op}\frac{I_1(\gamma_c N_{\rm op})}{I_0(\gamma_c N_{\rm op})} + V_{\rm FB}\sum_{\eta_c, J/\psi,\ldots} n_\Psi^{\rm eq}(T, \gamma_c), \qquad (3)$$

where $N_{\rm op} = V_{\rm FB} n_{\rm op}(m_{c,D}^*; T)$ denotes the total equilibrium number of open-charm states (c quarks or charmed hadrons) in either the QGP or the HG phase of the fireball. This procedure resides on the expectation that essentially all charm quarks are created in primordial NN collisions; i.e., $N_{c\bar{c}}$ does not chemically equilibrate during the fireball lifetime $\tau_{\rm FB}$ [3,27]. Thermal equilibration of charm quarks, however, is conceivable [28], implying a hierarchy of relaxation times as $\tau_{c,\bar{c}}^{\rm chem} \gg \tau_{\rm FB} \gg \tau_{c,\bar{c}}^{\rm therm}$. The resulting J/ψ equilibrium abundances, $N_\psi^{\rm eq}$, are shown in Fig. 1 under conditions resembling central Pb-Pb (Au-Au) collisions at SPS (RHIC). One observes a large sensitivity to the (in-medium) open-charm masses. At fixed $N_{c\bar{c}}$, larger values for m_c^* (or m_D^*) imply a thermal suppression of open-charm states so that an increasing number of anti-/charm quarks is redistributed into charmonia ($c\bar{c}$ states). Enforcing continuity on the open-charm spectrum across T_c then has the interesting consequence that, due to the volume increase in the hadronic phase (reducing γ_c), the equilibrium charmonium level on the QGP side is significantly *larger* than on the HG side [17]; i.e., J/ψ formation is *favored* in the QGP.

Also note that, due to a constant $N_{c\bar{c}}$, the equilibrium J/ψ numbers in the hadronic phase *grow* with decreasing temperature. Thus, if J/ψ's equilibrate close to T_c, subsequent hadronic reactions will tend to increase their abundance (which has indeed been found in transport calculations at RHIC energies [11,12]), quite contrary to the commonly assumed hadronic dissociation.

To model the time dependence, $N_\Psi(\tau)$, of charmonia in heavy-ion collisions, we utilize the dissociation (formation) time τ_Ψ, Eq. (1), and equilibrium density, Eq. (2), within a kinetic rate equation,

$$\frac{dN_\Psi}{d\tau} = -\frac{1}{\tau_\Psi}[N_\Psi - N_\Psi^{\rm eq}]. \qquad (4)$$

The underlying temperature and volume evolution, $T(\tau)$ and $V_{\rm FB}(\tau)$, are taken from a (schematic) thermal fireball expansion which is consistent with observed hadrochemistry and radial flow characteristics (as employed earlier for thermal dilepton and photon production) [26].

The simple form of the gain term in Eq. (4) resides on the assumption that the surrounding light and open-charm constituents (quarks or hadrons) are in thermal equilibrium. Following Ref. [23], we relax this assumption for c quarks by introducing a thermal relaxation time

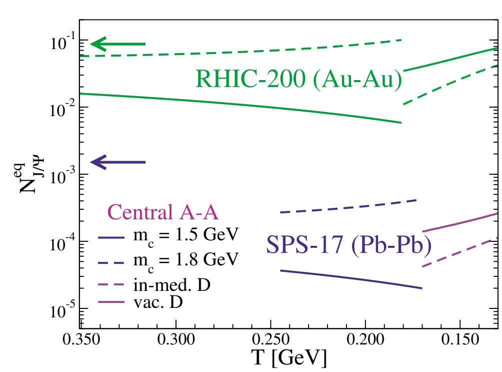

FIG. 1 (color online). Equilibrium J/ψ abundances [with $m_\psi(T) \equiv m_\psi^{\rm vac}$] in an isotropic, adiabatically expanding system at fixed $N_{c\bar{c}}$ for SPS and RHIC conditions for two values of the charm-quark mass above T_c, and for free and in-medium charmed hadron masses below T_c.

correction, $\mathcal{R} = 1 - \exp(-\int d\tau/\tau_c^{\rm therm})$, which reduces $N_\Psi^{\rm eq}$ in the early phases. Varying $\tau_c^{\rm therm}$ within a factor of 2 affects the thermal yield by $\pm 10\%$.

Another correction concerns the effective volume over which the charm quantum number is conserved [figuring into Eq. (3) via the Bessel functions]. Clearly, if only a few $c\bar{c}$ pairs are present, their pointlike primordial production implies that they cannot explore the entire fireball volume in the early stages. This problem is well known from strange particle production at fixed target energies, where a phenomenological "correlation volume" V_0 has been introduced to *localize* strangeness conservation [29,30]. We adopt the same procedure here for local charm conservation by replacing $V_{\rm FB}(\tau)$ in the argument of the Bessel functions in Eq. (3) with $V_0(\tau) = 4\pi(r_0 + \langle v_c\rangle\tau)^3/3$. $r_0 \simeq 1.2$ fm represents a minimal radius characterizing the range of strong interactions, and $\langle v_c\rangle \simeq 0.5c$ is the average relative speed of produced c and $\bar{c}$ quarks as inferred from experimental D-meson $p_\perp$ distributions [31]. We checked that our results are not very sensitive to the parametrization for V_0 (e.g., varying $\langle v_c\rangle$ within a factor of 2 requires a change in the effective coupling constant α_s by $\pm 30\%$, to fit SPS data).

The rate Eq. (4) is readily integrated over the fireball evolution of the collision for J/ψ, ψ', and χ's, once initial conditions are specified. In an A-A reaction at given centrality, $N_{c\bar{c}}$ is determined by the collision-scaled NN cross section. The initial charmonium numbers are also assumed to follow hard production (i.e., empirical fractions of $N_{c\bar{c}}$ observed in NN collisions), subject to (pre-equilibrium) nuclear absorption with a recently updated absorption cross section $\sigma_{\rm abs} = 4.4$ mb [32]. Typical values for the fireball thermalization time τ_0 range from $\frac{1}{3}$ (RHIC-200) to 1 fm/c (SPS).

We first confront our approach to NA50/NA38 data in $\sqrt{s_{NN}} = 17.3$ GeV Pb-Pb at CERN SPS. Figure 2 displays the ratio of $J/\psi \to \mu\mu$ to Drell-Yan dimuons vs centrality. The agreement between model (solid line) and data is fair for semi-/central collisions [at $E_T > 100$ GeV, the data can be reproduced by accounting for transverse energy fluctuations and losses in the minimum bias analysis at impact parameters close to zero [33] (cf. Ref. [23])]. Since the initial J/ψ number is well above the equilibrium level (cf. the lower arrow in Fig. 1), J/ψ regeneration [the gain term in Eq. (4)] is very moderate (dot-dashed line). Therefore, in line with our previous findings [13], *J/ψ suppression* is the main effect at SPS energies.

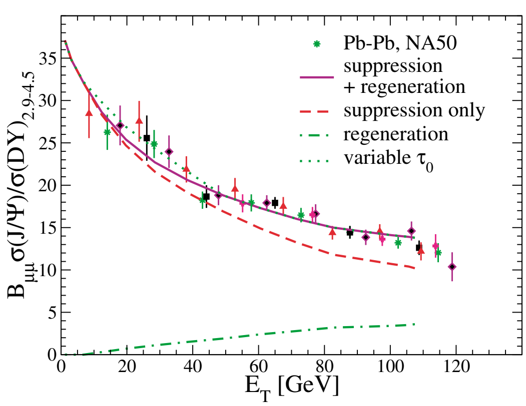

FIG. 2 (color online). Centrality dependence of J/ψ/Drell-Yan dimuons at SPS; NA50 data [32] are compared to our results with (solid line) and without (dashed line) charmonium regeneration (represented by the dot-dashed line). The dotted line includes longer thermalization times τ_0 in peripheral collisions.

In peripheral collisions, the suppression appears to be slightly overestimated. We believe this discrepancy resides in the limitations of our fireball description. In particular, thermalization is expected to be delayed (and/or incomplete) at large impact parameters due to less energetic initial conditions. This is also borne out of hydrodynamic models, which, e.g., reproduce the observed elliptic flow for midcentral collisions, but overestimate it for peripheral ones. A suitable increase of the equilibration time by up to a factor of ~ 3 [34] indeed improves the agreement at small E_T (cf. the dotted line in Fig. 2).

Another important observable is the ψ'/ψ ratio. In Ref. [23], the ψ' dissociation rates were too small by a factor of ~ 5 to account for NA50 data [35]. With in-medium D-meson masses, however, $\Gamma_{\psi'}^{\rm had}$ increases substantially, primarily due to the opening of the $\psi' \to D\bar{D}$ decay channel. As a result, the ψ'/ψ data are reasonably well described (cf. Figure 3).

We finally examine the impact of in-medium modifications at RHIC (cf. Fig. 4). Since reduced D-meson masses entail a lower J/ψ equilibrium level (cf. Fig. 1), the regeneration of J/ψ's is somewhat less pronounced than the statistical production with free hadron masses in the two-component model [23,37]. Nevertheless, in central Au-Au collisions, regenerated J/ψ's still exceed the suppressed primordial contribution, with the total yield (solid curve) in line with the first PHENIX data [36]. The uncertainty in the charm-hadron mass reduction is illustrated by the band in Fig. 4, corresponding to

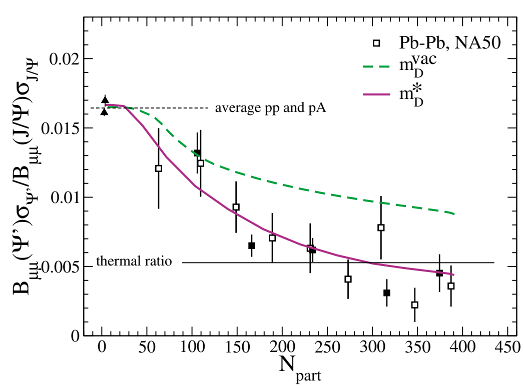

FIG. 3 (color online). Centrality dependence of the ψ'/ψ data [35] at SPS compared to our results with (full line) and without (dashed line) in-medium reduced D-meson masses.

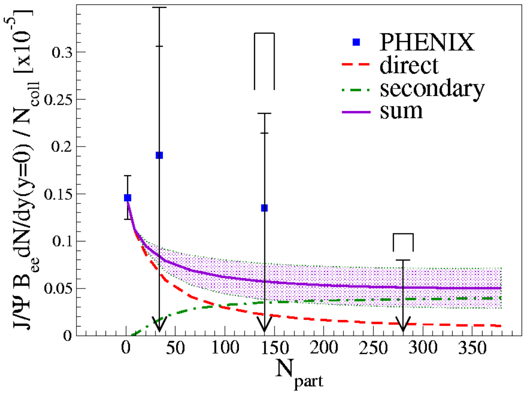

FIG. 4 (color online). J/ψ yield per binary NN collision versus participant number in $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions. PHENIX data [36] are compared to our model calculations: dot-dashed line, thermal regeneration; dashed line, suppressed primordial production; band, total J/ψ yields with different values for in-medium open-charm masses.

$80 < \Delta m_q(T_c) < 250$ MeV with accordingly matched charm-quark masses in the QGP. In any case, most of the regeneration occurs above T_c.

To summarize, we have proposed a conceptually improved model of charmonium production in heavy-ion collisions. In-medium modifications of both open-charm and charmonium states have been modeled in accordance with recent finite-T QCD lattice calculations. The apparent reduction of the open-charm threshold with increasing T has been linked to (partial) chiral symmetry restoration in the SU(2) sector via decreasing constituent light-quark masses in charmed hadrons. The continuity of the open-charm threshold across the phase transition has been encoded in thermal charm-quark masses in the QGP phase, together with T-independent charmonium masses and J/ψ resonance states surviving above T_c. Upon inclusion of chemical and thermal off-equilibrium effects, we solved kinetic rate equations for the time evolution of charmonia in heavy-ion reactions. The results for J/ψ centrality dependences compare well with data from the SPS and the RHIC. The earlier predicted transition from suppressed production at the SPS to predominant (thermal) regeneration at the RHIC persists, with both mechanisms residing on QGP formation. A much improved description of the ψ'/ψ ratio at the SPS emerged due to hadronic in-medium effects, accelerating ψ' dissociation. Forthcoming measurements by NA60 (SPS) and PHENIX (RHIC) will be of great importance toward scrutinizing the proposed approach.

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