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Charmonium production in high-energy nuclear collisions

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Abstract. We discuss some issues concerning the evolution of charmonia as they interact with the constituents of the fireball produced in high-energy nucleus-nucleus collisions. We study in detail the evolution in different regimes, controlled by collision energy, kinematics and geometry.

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The initial proposal of studying charmonium production in heavy-ion collisions [1] generated a lively dabate on whether or not the experimentally observed anomalous suppression can be attributed to QGP formation. Various effects can potentially account for the observed data because they provide the necessary non-linear dependence on the number of participating particles which becomes significant only when going beyond pA collisions.

In view of the uncertainties inherent in the construction of models which consider such effects, we attempt an approach to the problem which maximizes the number of independent physical constraints, making use of the knowledge of the medium evolution as inferred by a variety of other observables. We then explore whether the same description is consistent with the observed J/ψ measurements. We stress that this is possible because the specific time evolution of the medium is not constructed or fitted in order to reproduce the J/ψ suppression effect, but it is constrained beforehand.

The medium itself is constituted, in the QGP phase, by quark and gluon quasiparticles, with an equation of state in accordance with lattice calculations [2]. It evolves in time following a fireball construction as explained in [3]. Charmonium production is treated as a two-step process, factorizing direct production from the subsequent evolution in the medium. The first part includes the conventional description [4] of nuclear effects within the Glauber model framework, with values of the absorption cross section either extrapolated from the suppression observed experimentally already in pA collisions, or fitted to reproduce the results of more sophisticated computations [5, 6]. The second part is a description within kinetic theory of the interaction of J/ψs with the different degrees of freedom that populate the evolving medium at different times.

In the following we will assume that J/ψs are fully formed hadrons by the time the thermalized medium is produced, and they will subsequently interact with its degrees of freedom. Since the medium itself consists of a QGP for a significantly long time, we begin discussing how J/ψ interacts with quark and gluon quasi-particles.

It is clear that collisions of Ψ with either quarks or gluons will lead to dissociation of the bound state. On the other hand, a quark can interact only via gluon exchange. Within the quasi-particle model, the latter process is effectively already included in the definition of the temperature dependent gluon mass. In other words, Ψs only see gluonic quasi-particles in the plasma. We concentrate now on the process $\Psi(p) + g(k) \to c(q_1) + \bar{c}(q_2)$, and label momenta as indicated in parentheses. We then come to the problem of computing cross sections involving a relativistic bound state. In the present case one can argue that the $c\bar{c}$ system is, to first approximation, non-relativistic, greatly simplifying the treatment. Moreover, as was done originally by Bhanot and Peskin [7] one can argue that the lowest-lying quarkonium levels can be approximately described using the Coulomb part of the potential. Then, with operator product expansion methods or more recent non-relativistic factorization techniques [8], it is possible to obtain an analytic expression for the cross section for the cases of $J/\psi, \psi'$ and χ_c. The calculated cross sections are not necessarily reliable since the Coulomb potential approximation is used without rigorous justification. This problem is serious especially for the ψ' and χ_c states, which have much too large dissociation cross sections. Within the adopted framework we choose to re-scale the ψ' and χ_c cross sections by a multiplicative factor κ such that the obtained J/ψ suppression pattern at SPS energies is in agreement with experiment. The required value is $\kappa = 0.2$

We now consider the possibility of $c\bar{c}$ coalescence in the QGP, a manner for production of Ψ which has been recently considered by several authors [9,10,11,12]. We do this by means of a cross section, applying detailed balance to the reaction $\Psi g \leftrightarrow c\bar{c}$, and use the cross section calculated above for Ψ dissociation by gluons.

Coming now to the case of hadronic dissociation, we recall that many approaches have been developed in the literature to compute mesonic dissociation cross sections of Ψ. In our approach the medium evolution is constrained by the freeze-out analysis, leaving no room for adjustments. Since the particle densities in the hadronic phase are almost two orders of magnitude lower than in the QGP phase, unless one employs exceptionally large cross sections, it seems unlikely that hadronic dissociation can be at all relevant. Given the inherent uncertainties we will not consider the possibility of hadronic dissociation of Ψ.

The natural framework in which to study the time evolution of Ψ is that of kinetic theory. We use a semi-classical treatment, setting up a relativistic kinetic equation for the Ψ phase-space distribution. The general problem of kinetic evolution of bound states in a strongly interacting medium was studied recently [13]. Here we make use of those results, adapting the treatment to our needs. For details see [14]. We then assume that the kinetic equation describing the time evolution of the phase-space density f_Ψ of Ψ is

$$p^\mu \partial_\mu f_\Psi(p,x) = C_F^\Psi(p,x) - C_D^\Psi(p,x)\, f_\Psi(p,x)\,, \qquad (1)$$

consisting of the drift term $p^\mu \partial_\mu f_\Psi$ on the l.h.s. and of a collision term on the r.h.s. The collision term is made of a dissociation (loss) part

$$C_D^\Psi(p,x) = \frac{1}{2}\int d\Phi_3(k,q_1,q_2)\;(2\pi)^4\delta^4(p+k-q_1-q_2) \times \overline{W}_{\Psi g\to c\bar{c}}\; f_g(k,x) \qquad (2)$$

describing Ψ dissociation by quasi-particle gluons, studied in [15,16] to address the problem of charmonium suppression, and a formation (gain) part

$$C_F^\Psi(p,x) = \frac{1}{2}\int d\Phi_3(k,q_1,q_2)\;(2\pi)^4\delta^4(p+k-q_1-q_2) \times \overline{W}_{c\bar{c}\to\Psi g}\; f_c(q_1,x)\, f_{\bar{c}}(q_2,x) \qquad (3)$$

describing Ψ formation by $c\bar{c}$ fusion, introduced in a simplified manner in [10]. In the equations above $f_c, f_{\bar{c}}$ and f_g are the phase-space distributions of the degrees of freedom participating in the collisions. The Lorentz invariant 3-body the phase-space integration measure is $d\Phi_3$, and the transition probabilities $\overline{W}$ are averaged over the initial color and spin polarizations and summed over the final ones. They are related to the dissociation and formation cross sections discussed before, which can be expressed as

$$\sigma_D^\Psi(s) = \frac{1}{4F_{\Psi g}}\int d\Phi_2(q_1,q_2)(2\pi)^4\delta^4(p+k-q_1-q_2)\,\overline{W}_{\Psi g\to c\bar{c}} \qquad (4)$$

for dissociation and

$$\sigma_F^\Psi(s) = \frac{1}{4F_{c\bar{c}}}\int d\Phi_2(p,k)\,(2\pi)^4\delta^4(p+k-q_1-q_2)\;\overline{W}_{c\bar{c}\to\Psi g} \qquad (5)$$

for formation. Here $d\Phi_2$ is the 2-body phase-space integration measure

Concerning the definitions of the phase-space distribution of gluons, we adopt the expression

$$f_g(k,T) = \nu_g\, C(T)\left\{\exp\left[E_g(k,T)/T\right] \pm 1\right\}^{-1}, \qquad (6)$$

where ν_g is the number of gluon degrees of freedom, $C(T)$ is the confinement factor [2] and E_g is the gluon quasiparticle energy. The time evolution of the gluon distribution is all contained in the proper time dependence of the temperature.

For c quarks, as they are produced in the hard initial collision, we take their spectrum as computed with pQCD. We assume that they do not interact significantly with the medium, approximately moving on straight lines according to the free streaming equation. Then, we define the phase-space density of charm quarks as

$$f_c(q,x) = \frac{(2\pi)^3}{\tau\, m_\perp^c}\,\frac{dN_{AB}^c}{dy_c d^2\mathbf{q}_\perp}\;\delta(y_c-\eta)\,\rho_\perp\big(r_\perp(\tau)\big)\,\theta\big(T(\tau)-T_c\big) \qquad (7)$$

and analogously for $\bar{c}$ quarks. The step function θ is introduced to account for the fact that below T_c c and $\bar{c}$ quarks have hadronized into D mesons and are no more available to coalesce into Ψ. For simplicity in numerical computations, the transverse position density is taken as a box of the same radius of the fireball. The δ-function, arising from the assumption that c quarks are produced in a very narrow longitudinal region, strongly correlates the momentum rapidity y_c and the space-time rapidity η.

With several simplifications [14] it is possible to reduce (1) to a simple first order differential equation for the rapidity distribution of Ψ as function of proper time as

$$\frac{\partial}{\partial\tau}\frac{dN_\Psi}{dy}(\tau) = \lambda_F^\Psi(y,\tau) - \lambda_D^\Psi(y,\tau)\,\frac{dN_\Psi}{dy}(\tau)\,, \qquad (8)$$

whose solution, valid at $y=0$, is obtained with few elementary steps and provides the final Ψ rapidity distribution at $y=0$ as

$$\frac{dN_\Psi^f}{dy} = \left\{\frac{dN_\Psi^0}{dy}\,\exp\left[-\int_{\tau_0}^{\tau_f} d\tau'\,\lambda_D^\Psi(y,\tau')\right] + \int_{\tau_0}^{\tau_f} d\tau'\,\lambda_F^\Psi(y,\tau')\,\exp\left[-\int_{\tau'}^{\tau_f} d\tau''\,\lambda_D^\Psi(y,\tau'')\right]\right\}. \qquad (9)$$

Again, the solution found holds for the different charmonia J/ψ, ψ' and χ_c. The rates λ_D^Ψ and λ_F^Ψ are given respectively by

$$\lambda_D^\Psi(\tau) = \int\frac{d^3k}{(2\pi)^3}\,V_{\Psi g}\;\sigma_D^\Psi(s)\;f_g\big(k,T(\tau)\big) \qquad (10)$$

and

$$\lambda_F^\Psi(\tau) = \frac{1}{\tau}\int d^2p_\perp d^2q_\perp^{\,1} d^2q_\perp^{\,2}\;K\,\sigma_F^\Psi(s)\,S_c(\bar{y}_c,q_\perp^1)S_c(\bar{y}_c,q_\perp^2), \qquad (11)$$

with K representing a collection of factors [14]. The structure of this solution is self-evident. The first term describes the dissociation of Ψs initially produced in the hard collision, with the usual exponential suppression acting at all times from τ_0 to τ_f, while the second term describes formation of Ψs from $c\bar{c}$ in the QGP, from the initial time τ_0 up to an intermediate value τ' and their subsequent suppression from τ' to τ_f, integrated over all values of τ'. This last term may become important as soon as the number of charmed quarks is large enough.

Using the elements of the calculation as discussed previously, we can now compute the time dependence of dissociation and formation rates. The dissociation rate depends on the fireball temperature which, in turn, depends on time. How T depends in detail on τ, was evaluated for different impact parameters and collision energies [3, 14] Dissociation and formation rates are then combined together according to (9) to give the observed Ψ rapidity distribution. Since we are interested for the final J/ψ yield, we need to take into account decays into the charmonium ground state of ψ' and χ_c. Experimentally is has been observed that measured J/ψs come in a fraction of 60 % from direct production, while a fraction of 10 % comes from ψ' decays and a fraction of 30 % is from χ_c.

We now look at the case of $Pb+Pb$ collision at $\sqrt{s} = 17.4$ GeV and compute the J/ψ spectrum as function of the impact parameter b. Then we construct the $J/\psi/DY$ ratio

$$R_{J/\psi/DY}(b) = N_0 \, \frac{dN_{J/\psi}(b)/dy}{dN^{pp}_{\Psi}/dy \; N_{coll}(b)}, \qquad (12)$$

where we assume that the Drell-Yan spectrum in $Pb+Pb$ collisions scales with the number of collisions N_{coll}. The overall normalization is fixed at $N_0 = 53.5$. The ratio is then plotted in Fig. 1 (solid line) as function of the mean transverse energy

$$E_T(b) = \epsilon_T \, N_p(b) \,. \qquad (13)$$

The quantity $\epsilon_T = 0.274$ is the amount of produced transverse energy per participant. As reference, we also plot the curve obtained by considering only nuclear effects (dotted line) and neglecting the contribution of the produced medium. The agreement with the NA50 data [17] is quite remarkable, in particular the slope of the curve, considering that fireball parameters have not at all been tuned to this particular observable.

We now proceed to examine central collisions at RHIC energy. In order to compare with data from the PHENIX experiment [18], obtained at mid-rapidity from Ψ decays into e^+e^- pairs, we construct the quantity

$$N^*_{J/\psi}(b) = B_{e^+e^-} \frac{dN_{J/\psi}(b)/dy}{N_{coll}(b)} \qquad (14)$$

and plot it in Fig. 2 as function of the number of participants. The quantity $B_{e^+e^-}$ is the branching of J/ψ into e^+e^- pairs, while the overall normalization is fixed at $N^*_{J/\psi}(N_p = 0) = 0.15$. Although a comparison with the data is, at present, premature, we see that our results lie within experimental errors. Again, the contribution from

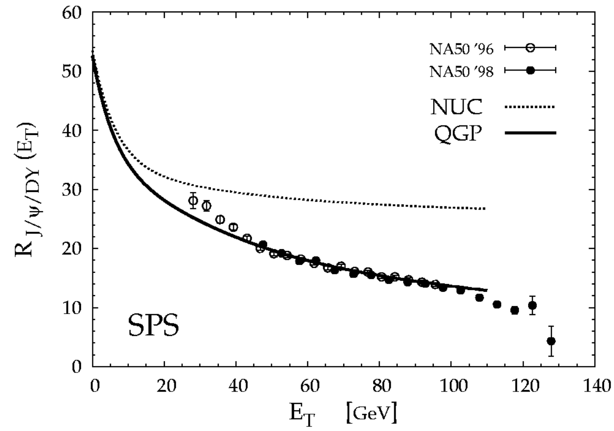

Fig. 1. Result at SPS energy for the $J/\psi/DY$ ratio as function of the transverse energy. The *dotted curve*, labelled "*NUC*", includes only nuclear effects, while the *solid line*, labelled "*QGP*", is the complete result including dissociation by collisions with gluonic quasi-particles

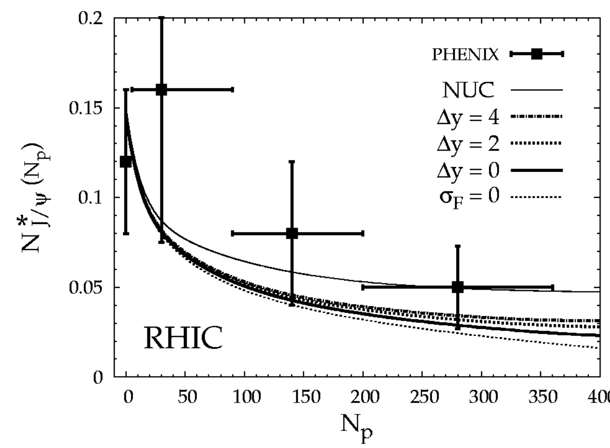

Fig. 2. Result at RHIC energy for the J/ψ yield, scaled by the number of binary collisions, as function of the number of participants

$c\bar{c}$ coalescence into J/ψ is significant, although not dramatic. All the obtained curves are monotonically decreasing and we do not find any inversion of this tendency at any large value of N_p. In other words, we do not find a net enhancement of J/ψ, but this result needs to be confirmed by more accurate calculations.

Summarizing, we have calculated J/ψ production from an expanding fireball created in relativistic heavy-ion collisions over a wide range of centralities and beam energies, from SPS at $\sqrt{s} = 17.3$ GeV ($E_{lab} = 158$ GeV) to RHIC at $\sqrt{s} = 200$ GeV. The produced medium was described assuming QGP formation and thermalization. A phenomenological quasi-particle model for quarks and gluons, in accordance with lattice QCD thermodynamics, was applied to model the partonic phase. This provided a realistic EoS which we then used to drive the expansion dynamics of the medium by means of a fireball model, characterized by time dependent temperature and volume.

We then set up a kinetic equation with a collision term incorporating both gain and loss terms. These stand for Ψ formation due to coalescence of $c\bar{c}$ quark pairs and Ψ dissociation due to collisions with gluon quasi-particles, respectively. The elementary process $\Psi g \to c\bar{c}$ was modeled by a simplified dissociation cross section, approximating Ψ as a Coulomb bound state. The corresponding back reaction $c\bar{c} \to \Psi g$ could then be obtained by detailed balance.

With proper averaging of the kinetic equation over the spatial extent of the fireball, we then found a simple solution, which allowed direct comparison with experiment. At SPS energy we were able to describe the suppression effect in the data, without the need to invoke hadronic comovers. These results support the hypothesis that the QGP is actually produced, at a transient stage, in Pb+Pb collisions at $\sqrt{s} = 17.3$ GeV. We also considered extrapolations up to RHIC energies where, despite the more extreme conditions as compared to SPS, a sizable fraction of primordial J/ψs still survives. Although a clear trend towards more copious J/ψ production in by $c\bar{c}$ coalescence was found, no net J/ψ enhancement was present in the end.

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