Quarkonium production in ultra-relativistic nuclear collisions: suppression vs. enhancement

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Abstract. After a brief review of the various scenarios for quarkonium production in ultra-relativistic nucleus-nucleus collisions we focus on the ingredients and assumptions underlying the statistical hadronization model. We then confront model predictions for $J/\psi$ phase space distributions with the most recent data from the RHIC accelerator. Analysis of the rapidity dependence of the $J/\psi$ nuclear modification factor yields first evidence for the production of $J/\psi$ mesons at the phase boundary. We conclude with predictions for charmonium production at the LHC.

1. General considerations

Charmonium production is, since the original proposal about its possible suppression in a Quark-Gluon Plasma (QGP) [1], considered as an important tool to diagnose the fireball produced in ultra-relativistic nucleus-nucleus collisions. The original idea of $J/\psi$ 'melting' via Debye screening [1] implies rapid production of charmonia in initial hard collisions and their subsequent destruction in the QGP. For efficient melting all $J/\psi$ mesons have to be formed well before the QGP temperature has fallen below $T_D$, the temperature above which screening takes place. A detailed discussion of this scenario and of the various time scales involved can be found in [2, 3].

Recent studies of charmonium survival in a hot plasma performed within the framework of lattice QCD indicate that $T_D$ may be significantly higher than the critical temperature $T_c$, reaching 2 $T_c$ for $J/\psi$ mesons while excited states would melt much earlier. If substantiated in unquenched calculations this could have significant influence on the production pattern expected in nucleus-nucleus collisions. Here we remark that in such considerations the widths of charmonia in the QGP should also be taken into account. A simple estimate of collisional broadening will illustrate this. The mean free path of the $J/\psi$ in the QGP is the $\lambda = 1/(n_p \sigma)$. Since we are interested in temperatures substantially higher than $T_c$ we assume a QGP with 3 massless flavors plus gluons, leading to a parton density $n_p = 4.25 T^3$. For the specific case of $J/\psi$ mesons we assume a $J/\psi$ - parton cross section $\sigma \approx 2$ mb. Estimating the relative velocity $v_{rel}$ of $J/\psi$ vs partons from its thermal velocity we obtain the in-medium width $\Gamma = v_{rel}/\lambda$. Numerical values reach $\Gamma(T=300$ MeV) $= 320$ MeV and $\Gamma(T=400$ MeV) $= 760$ MeV. These large
widths imply that most of the charmonia will decay inside the QGP and thus are not likely reconstructed in an actual experiment. Consideration of such widths is obviously important if one looks for a characteristic pattern due to sequential melting of various charmonium states.

Another issue to be considered is 'cold nuclear matter' suppression. Here the idea is that the 'instantaneously' produced charmonia are partially destroyed by the passing of the two Lorentz contracted nuclei. While the time scales involved are such that this may happen at SPS energy (here production and passing-by times are of the order of 1 fm, $[3]$), at LHC energy the passing-by time is about 1/200 fm, and cold nuclear matter effects should be very small.

2. Ingredients and assumptions of the statistical hadronization model

The statistical hadronization model $[4, 5, 6]$ assumes that all charm quarks are produced in initial hard collisions while charmonia which are produced early are completely destroyed in the QGP. Cold nuclear matter effects or destruction by comoving hadrons are consequently not considered. The entire production of charmonia rather takes place at chemical freeze-out, i.e at $T_c$. In this sense charmonia and also all hadrons with charm are produced by a mechanism similar to that for hadrons containing u, d, and s quarks, although charm quarks are very far out of chemical equilibrium. A proposal for a detailed mechanism of hadron production at the phase boundary can be found in $[7]$. We note that a two-component model including (partial) screening, nuclear absorption, and generation at the phase boundary was developed in $[8]$.

Under these conditions charmonium production yields scale quadratically with the number of produced charm quarks, implying little suppression or even enhancement at the highest energies even though there is complete suppression in the QGP. We note that, in general, charmonium generation can only take place effectively if the charm quarks reach thermal (not chemical) equilibrium and are free to travel over large distances corresponding to about 1 unit in rapidity $\text{‡}$, implying deconfinement.

A crucial assumption in the statistical hadronization model is that the number of charm quarks stays constant during the evolution of the plasma. This has been analyzed in some detail in $[6]$ by evaluation of the rate equation

$$\frac{d\rho_{c\bar{c}}}{d\tau} = n_c n_{\bar{c}} \langle \sigma_{c\bar{c} \rightarrow gg} v_r \rangle,$$

where $\langle \sigma_{c\bar{c} \rightarrow gg} v_r \rangle$ is the thermal average of the annihilation cross section times the relative velocity $v_r$ in the QGP, and $n_c = n_{\bar{c}}$ is the charm quark density. The quantity $d\rho_{c\bar{c}}/d\tau$ is the annihilation rate per volume or the rate of change of the charm quark density. The total annihilation rate is then obtained by folding with the temperature evolution of the QGP. Results are given in Fig. $[1]$.

For RHIC and LHC energies these estimates imply that charm quark annihilation in the plasma can be safely neglected. Along the same line, production of charmonia via $\text{‡}$ For a translation of rapidity into longitudinal distance see $[9]$. 


uncorrelated charm quark annihilation in the QGP is expected to fall significantly below the above computed annihilation yield into gluons, lending strong support to the above interpretation that all quarkonia are produced late, when the system reaches the critical temperature and hadronizes. These results are not likely to be changed if annihilation into 3 or more gluons were taken into account. We first note that annihilation into $n$ gluons are suppressed by a factor $\alpha_s(m_{J/\psi})^{3+n}$, and one can get an impression of the suppression by comparison of the width of $J/\psi$ (decaying into 3 gluons) with that of the $\eta_c$ (decaying into 2 gluons). Furthermore, gluons in the QGP acquire thermal masses $\propto gT$, implying a further reduction.

The above discussion underlines the differences between the statistical approach, where, except for corona effects [6], all charmonia are formed non-perturbatively at $T_c$, and the kinetic model of [10, 11, 12], where charmonia are recombined during plasma evolution from, in general, uncorrelated charm quarks.

3. Confrontation of statistical hadronization model predictions with data

In the following we base our quantitative comparisons of model predictions to data on the approach developed in [6]. For the production of charm quarks via initial hard collisions we use the calculations of [13, 14], for RHIC energy and the predictions of [15] for LHC energy. All calculations are performed in the framework of perturbative QCD for nucleon-nucleon collisions and scaled to nucleus-nucleus collisions with the appropriate (geometric) number of binary collisions.
The resulting rapidity dependence of the $J/\psi$ yield for Au-Au collisions at top RHIC energy is shown in Fig. 3 for two centrality bins. The PHENIX data \[16\] are well described by the model calculations for the central value of the pQCD charm cross section. Since the rapidity distributions for open charm production are rather wide \[14\], no visible narrowing of the calculated $J/\psi$ rapidity distributions is observed, in contrast to predictions within the kinetic model \[11\]. Obviously, the agreement observed depends sensitively on the magnitude and rapidity dependence of the open charm cross section and a direct measurement of these quantities is very important.

Next we focus on the rapidity and centrality dependence of the nuclear modification factor $R_{AA}$ which has recently been calculated also in the statistical hadronization model \[17\]. For this purpose, $R_{AA}$ is defined as

$$R_{AA}^{J/\psi} = \frac{dN_{J/\psi}^{AuAu}/dy}{N_{coll} \cdot dN_{J/\psi}^{pp}/dy}$$

(2)

and relates the charmonium yield in nucleus-nucleus collisions to that expected for a superposition of independent nucleon-nucleon collisions. Here, $dN_{J/\psi}/dy$ is the rapidity density of the $J/\psi$ yield integrated over transverse momentum and $N_{coll}$ is the number of binary collisions for a given centrality class. This definition of the modification factor is essentially equivalent to the $J/\psi$ modification factor employed previously by the NA50 collaboration at top SPS energy \[18\].

Important in the evaluation of the nuclear modification factor are also data on $J/\psi$ production in pp collisions. For experiments at RHIC energy ($\sqrt{s_{NN}}=200$ GeV)
we use the recently released data by the PHENIX experiment \[19\]. For LHC energy we extrapolate the cross section for \(J/\psi\) production in \(\bar{p}p\) collisions measured at the Tevatron \[20\].

![Figure 4. Rapidity dependence of \(R_{\text{AA}}^{J/\psi}\) for two centrality classes. The data (symbols with errors) are compared to calculations (lines). For the data \[16\], the error bars show the statistical and uncorrelated systematic errors added in quadrature, while the correlated systematic errors are represented by the boxes. Note that a global systematic error of the order of 10% has to be additionally applied. The dashed lines denote the error of the gaussian width of the \(J/\psi\) distribution in pp collisions (see text).](image)

In Fig. 4 we present the calculated rapidity dependence of \(R_{\text{AA}}^{J/\psi}\) along with the PHENIX experimental results \[16\]. For this calculation, we have fitted the pp measurements \[19\] with a gaussian, with a resulting width in rapidity \(\sigma_y = 1.63 \pm 0.05\) (\(\chi^2/N_{\text{df}}=4.5/8\)). As an aside, we note that the fitted gaussian is very close to the shape of the rapidity distribution of the pQCD charm cross section \[14\]. Our calculations reproduce quantitatively the \(R_{\text{AA}}^{J/\psi}\) data, including the observed larger suppression away from midrapidity. We note that this trend is opposite to that expected from the melting model \[1, 2\], where \(R_{\text{AA}}^{J/\psi}\) is constant or exhibits a minimum at midrapidity. Destruction of charmonia by co-moving hadrons \[21, 22\] should similarly also lead to the largest suppression at mid-rapidity and, hence, this mechanism produces results in conflict with the PHENIX data.

The maximum of \(R_{\text{AA}}^{J/\psi}\) at midrapidity is in our model due to the enhanced charmonium production yield at the phase boundary, determined by the rapidity dependence of the charm production cross section with its maximum at mid-rapidity. In this sense, the above result constitutes the first unambiguous evidence for the statistical
production of $J/\psi$ at chemical freeze-out. In details, our model is in very good agreement with the data for the central bin (0-20%), while predicting for the mid-central (20-40%) centrality class a somewhat flatter shape than observed in the data. The error $\sigma_y$ of the pp data [19] used in our model plays a rather minor role, as denoted by the dashed lines in Fig. 4. On the other hand, the systematic errors of the data including the not exhibited scale error of the order of 12 % [16] should be taken into account in a detailed comparison. Since the expected shape in rapidity of the open charm production cross section at LHC energy is probably even flatter compared to that at RHIC energy, we expect less variation with rapidity of the nuclear modification factor for charmonia production as the energy is increased. On the other hand, $R_{AA}^{J/\psi}$ contains both the pp and AA data, so one should be open for surprises. In any case, the rapidity dependence of $R_{AA}^{J/\psi}$ will be measured in the ALICE experiment [23] in the rapidity range $-1 < y < 4$ with precision so that this issue will be addressed in the near future.

![Figure 5](image-url)  

**Figure 5.** Centrality dependence of the nuclear modification factor $R_{AA}^{J/\psi}$ for RHIC and LHC energies. For details see text.

The centrality dependence of $R_{AA}^{J/\psi}$ at midrapidity is shown in Fig. 5. Our calculations approach the value in pp collisions around $N_{part}=50$, which corresponds to a minimal volume for the creation of QGP of 400 fm$^3$ [6]. The model predictions reproduce very well the decreasing trend versus centrality seen in the RHIC data [16]. We have not included in our calculations the smearing in $N_{part}$ due to finite resolution in the experimental centrality selection. This effect would lead to a better agreement with data for peripheral collisions. Note that in the statistical hadronization model
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the centrality dependence of the nuclear modification factor is a consequence of the still rather moderate rapidity density of initially produced charm quark pairs \( \left( dN_{c\bar{c}}/dy=1.6 \right) \) at top RHIC energy, implying that canonical thermodynamics has to be used to compute the charm quark fugacity factor in the charm balance equation [6].

\[ \sqrt{s_{NN}} = 5.5 \text{ TeV} \]

\[ \frac{d\sigma}{d_{cc}} = 0.64 \text{ mb} \]

\[ \frac{d\sigma}{d_{cc}} = 1.28 \text{ mb} \]

**Figure 6.** Expected centrality dependence of the nuclear modification factor \( R_{AA}^{J/\psi} \) for the nominal charm production cross section and for a cross section enhanced by a factor of 2 compared with current pQCD calculations.

In contradistinction, at the much higher LHC energy, \( \sqrt{s_{NN}} = 5.5 \) TeV, the charm production cross section is expected to be about an order of magnitude larger [15, 6]. In this case, the canonical correction is sizable only for peripheral collisions. As a result, a totally opposite trend as a function of centrality is predicted, see Fig. 5 with \( R_{AA} \) exceeding 1 for central collisions. A significantly larger enhancement of 2 is obtained if the charm production cross section is a factor 2 larger than presently assumed, as is exhibited in Fig. 6.

In summary, we have presented a brief discussion of the various mechanisms currently proposed to understand charmonium production in ultra-relativistic nucleus-nucleus collisions. The main emphasis of this paper is on the statistical hadronization model. This model has been further developed recently [6, 17] to include charmonium rapidity and transverse momentum distributions and a description of the nuclear modification factor \( R_{AA}^{J/\psi} \). By an analysis of the rapidity dependence of this nuclear modification factor, for which data were recently published by the PHENIX collaboration, we have identified, for the first time, a clear signal for production of
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Charmonia due to statistical hadronization at the phase boundary. Predictions using this model also describe well the measured decrease with centrality of $R_{AA}^{J/\psi}$ at RHIC energy. Extrapolation to LHC energy leads, contrary to the observations at RHIC, to a $J/\psi$ nuclear modification factor increasing with collision centrality and exceeding 1 for central collisions. While the exact amount of enhancement will depend on the precise energy dependence of the open charm production cross section, the trend is a robust prediction of the model. If the predicted centrality and rapidity dependence is observed, this would be a striking fingerprint for the deconfinement of heavy quarks in the QGP. Data from the LHC will be decisive in settling this important issue and all three large experiments (ALICE, ATLAS, CMS) are planning to measure charmonium production in the first heavy ion run of the LHC.

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