Interpretations of $J/\psi$ suppression

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Abstract. We review the two main interpretations of $J/\psi$ suppression proposed in the literature. The phase transition (or deconfining) scenario assumes that below some critical value of the local energy density (or of some other geometrical quantity which depends both on the colliding systems and on the centrality of the collision), there is only nuclear absorption. Above this critical value the absorptive cross-section is taken to be infinite, i.e. no $J/\psi$ can survive in this hot region. In the hadronic scenario the $J/\psi$ dissociates due both to nuclear absorption and to its interactions with co-moving hadrons produced in the collision. No discontinuity exists in physical observables. We show that an equally good description of the present data is possible in either scenario.

1. Introduction

Charmonium suppression due to Debye screening in a deconfined medium was proposed in 1986 by Matsui and Satz [1] and found experimentally by the NA38 collaboration [2]. However, it was claimed very soon [3, 4, 5] that this phenomenon, which is also present in $pA$ collisions, could be due to the absorption of the pre-resonant $c\bar{c}$ pair in the colliding nuclei. It is nowadays known [6, 7] that the data on $pA$ and on $AB$ collisions with a light projectile can indeed be described by nuclear absorption with an absorptive cross-section $\sigma_{abs} = 7.3 \pm 0.6$ mb [6].

Recently the NA50 collaboration has found an anomalous $J/\psi$ suppression in $PbPb$ collisions, i.e. a suppression which is substantially stronger than the one obtained from nuclear absorption with the above value of $\sigma_{abs}$ [7, 8]. Two different interpretations of this anomalous suppression have been proposed in the literature. One is a conventional hadronic interpretation in which there is an extra

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$J/\psi$ suppression due to final state interaction of the resonant $J/\psi$ state with co-moving hadrons \cite{1, 11, 12, 13}. The other interpretation \cite{3, 13, 14, 15} assumes that when the local hadronic energy density is larger than some critical value (taken to be around the one reached in a central $SU$ collision), there is a discontinuity in the $J/\psi$ survival probability. (See also \cite{16} for ideas based on percolation of strings.)

2. Nuclear absorption

Nuclear absorption is present in all interpretations. We describe it in the probabilistic model of Ref. \cite{4}. Let us consider first proton-nucleus collisions. In this model, the pre-resonant $c\bar{c}$ pair is produced at some point $z$ inside the nucleus and scatters with nuclei on its path at $z' > z$, with an absorptive cross-section $\sigma_{abs}$. This produces a change in the $A$ dependence of the $J/\psi$ inclusive cross-section. For nucleus-nucleus collisions this change is given \cite{4} by

$$S_{abs}^2(b, s) = \frac{1 - \exp(-A T_A(s) \sigma_{abs})[1 - \exp(-B T_B(b - s) \sigma_{abs})]}{A B T_A(s) T_B(b - s) \sigma_{abs}^2}.$$  \hspace{1cm} (1)

Here $T_A$ and $T_B$ are the nuclear profile functions, determined from a standard Saxon-Woods density, and $\sigma_{abs}$ is the absorptive cross-section. In the following we take $\sigma_{abs} = 7.3 \pm 0.6$ mb which gives the best fit to the $pA$ data \cite{6}. Note that $S_{abs}^2 = 1$ for $\sigma_{abs} = 0$. Expression (1) has the meaning of a survival probability of the $J/\psi$ due to nuclear absorption.

Since we are aiming at a quantitative analysis it should be emphasized that the probabilistic formula, with its longitudinal ordering in $z$, can only be true in the low energy limit. Therefore it is important to evaluate the uncertainty resulting from using this formula at $\sqrt{s} \sim 20$ GeV. In a recent paper \cite{17} the equivalent of Eq. (1) has been derived in a field theoretical approach. The obtained formula is valid at all energies and coincides exactly with (1) in the low energy limit. In the asymptotic limit we find \cite{17}

$$S_{\sqrt{s} \to \infty}^2(b, s) = \exp \left[ -\frac{1}{2} \tilde{\sigma} T_A(s) \right] \exp \left[ -\frac{1}{2} \tilde{\sigma} B T_B(b - s) \right],$$  \hspace{1cm} (2)

where $\tilde{\sigma}$ is the $c\bar{c} - N$ total cross-section. At asymptotic energies, the results obtained from Eqs. (1) and (2) differ only by 8%. It is amazing that at $\sqrt{s} = 20$ GeV the
difference between the result obtained with the exact formula, valid at all energies, and the one obtained from Eq. (1) is less than 1 %.

3. Phase transition scenario

The anomalous $J/\psi$ suppression observed by the NA50 collaboration in $PbPb$ collisions came as a surprise. Indeed, it was believed that the energy densities in $SU$ and $PbPb$ collisions were comparable - the larger energies reached in $PbPb$ being compensated by a larger interaction transverse area. However, it was soon realized that the local energy density (i.e. the energy per unit of transverse area $d^2s$) is larger by about 30 % in central $PbPb$ than in central $SU$ collisions [13]. More precisely, let us consider the well known geometrical factors [18, 19]

$$
m_{A(B)}(b, s) = A(B) T_{A(B)}(s) \left[ 1 - \exp \left( -\sigma_{pp} B(A) T_{B(A)}(b - s) \right) \right]. \quad (3)
$$

The average number of participants is obtained as

$$
\bar{n}_A + \bar{n}_B = \frac{1}{\sigma_{AB}} \int d^2b \int d^2s N_w(b, s), \quad (4)
$$

where

$$
N_w(b, s) = m_A(b, s) + m_B(b, b - s). \quad (5)
$$

In Ref. [13], the quantity in Eq. (5) is taken as a measure of the energy per unit transverse area at each impact parameter. It is found [13] that the maximum value reached in $SU$ collisions at $b = 0$ is $n_c = 3.3 \text{ fm}^{-2}$ (see Fig. 1). The model of Ref. [13] can then be formulated as follows: For $N_w(b, s) < n_c$, one assumes nuclear absorption alone with a standard value of $\sigma_{abs}$ (see Section 2). For $N_w(b, s) \geq n_c$, one puts $\sigma_{abs} = \infty$, i.e. one assumes that none of the $J/\psi$'s produced in this hot region can survive. This model gives the maximal suppression that can be obtained in $PbPb$ collisions when one imposes that, up to central $SU$ collisions, there is only nuclear absorption. The interesting result is that with this simple model one approximately obtains the suppression observed experimentally in central $PbPb$ collisions. In Ref. [6] a more detailed analysis of the data has been performed in a similar framework.
More precisely, instead of the local energy density $N_w(b, s)$, the authors of Ref. [6] consider the quantity

$$\kappa(b, s) = \frac{N_c(b, s)}{N_w(b, s)},$$

(6)

where

$$N_c(b, s) = AB T_A(s) T_B(b - s) \sigma_{pp}.$$  

(7)

The quantity (6) gives the average number of collisions per participant at fixed $b$ and $s$. It increases with the centrality of the collision. The value of $\kappa(b, s)$ determines the onset of deconfinement in Ref. [6]. More precisely, at a given impact parameter $b$, the absorptive cross-section is assumed to be infinite for $\kappa(b, s)$ larger than some critical value $\kappa_c$, while for $\kappa(b, s) < \kappa_c$ it takes the standard value $\sigma_{abs} = 7.3 \pm 0.6$ mb discussed in Section 2. Actually in Ref. [6] one has two distinct values of $\kappa_c$. One is for $\chi$’s and is taken to be equal to the maximum value of $\kappa(b, s)$ in a central $SU$ collision, i.e.

$$\kappa_c^\chi = [\kappa(b = 0, s = 0)]_{SU} \approx 2.3.$$  

(8)

The second one is for direct $J/\psi$ and is taken as a free parameter satisfying $\kappa_c^\psi > \kappa_c^\chi$. The overall $J/\psi$ survival probability is then obtained by combining 40 % $\chi$ suppression with 60 % suppression of direct $J/\psi$.

In this way a reasonable description of $J/\psi$ suppression is obtained. The results for $PbPb$ are shown in Fig. 2.

Finally in Ref. [14] one combines nuclear absorption, deconfinement and absorption by co-movers (see Section 4). The quantity which determines the onset of deconfinement depends not only on $b$ and $s$ but also on the longitudinal coordinate $z$. When some critical value of this quantity is reached the involved cross-sections present a discontinuity but their values remain finite.
4. Absorption by co-moving hadrons

The survival probability of the $J/\psi$ due to absorption with co-moving hadrons is given by (see [6, 9, 10, 12] and references therein)

$$S_{\text{co}}(b,s) = \exp \left[ -\sigma_{\text{co}} N_{y}^{\text{co}}(b,s) \ln \left( \frac{N_{y}^{\text{co}}(b,s)}{N_{f}} \right) \theta\left(N_{y}^{\text{co}}(b,s) - N_{f}\right) \right].$$  \hspace{1cm} (9)

Here $N_{y}^{\text{co}}(b,s)$ is the density of hadrons per unit transverse area $d^{2}s$ and per unit rapidity at impact parameter $b$. $N_{f}$ is the density at freeze-out that we take to be universal. The argument of the log is the interaction time of the $J/\psi$ with co-moving hadrons. The $\theta$-function is numerically irrelevant (see Section 5). $\sigma_{\text{co}}$ is the co-mover cross-section properly averaged over the momenta of the colliding particles (the relative velocity of the latter is included in its definition). We treat $\sigma_{\text{co}}$ as a free parameter [20, 21]. All species of hadrons are included in $N_{y}^{\text{co}}$. This quantity has been computed in the dual parton model (DPM) [22]. It is expressed as a linear combination of the geometrical quantities defined in Eqs. (5) and (7) [12].

Note that $S_{\text{co}}^{(b,s)} = 1$ for $\sigma_{\text{co}} = 0$. The effects of the co-movers in proton-nucleus collisions turn out to be negligibly small (see Section 5).

The inclusive cross-section for $J/\psi$ production in nuclear collisions is then given by

$$I_{\psi}^{\text{AB}}(b) = \frac{I_{\psi}^{\text{NN}}}{\sigma_{pp}} \int d^{2}s \ N_{c}(b,s) \ S_{\text{abs}}(b,s) \ S_{\text{co}}(b,s),$$  \hspace{1cm} (10)

where $N_{c}$ is given by (7). We see that for Drell-Yan pair production ($\sigma_{\text{abs}} = \sigma_{\text{co}} = 0$), $I_{\psi}^{\text{DY}} = I_{\psi}^{\text{DY}}$ AB. We take $\sigma_{pp} = 30$ mb.

The results [12] are presented for three sets of parameters. Set I: $\sigma_{\text{abs}} = 7.3$ mb, $\sigma_{\text{co}} = 0$; Set II: $\sigma_{\text{abs}} = 6.7$ mb, $\sigma_{\text{co}} = 0.6$ mb, $N_{f} = 1.15$ fm$^{-2}$; and Set III: $\sigma_{\text{abs}} = 7.3$ mb, $\sigma_{\text{co}} = 1.0$ mb, $N_{f} = 2.5$ fm$^{-2}$.

The results for $J/\psi$ suppression versus $AB$ are presented in Fig. 3. In Fig. 4 we show the ratio $J/\psi$ over DY versus $E_{T}$ and in Fig. 5 we show the same ratio versus $L$. This variable, defined in Refs. [2, 8], is a measure of the centrality of the collision. We see that nuclear absorption alone (Set I) fails very badly, whereas Sets II and III give a reasonable description of the data.
5. Proton-nucleus collisions

Let us first discuss the role of the $\theta$-function in Eq. (9). This function looks like a discontinuity in the co-mover contribution. However, numerically it has practically no effect in our results for $SU$ and $PbPb$ collisions - especially with the parameters of Set II. Indeed, the value $N_f = 1.15\, \text{fm}^{-2}$ in this Set (which is the same used in Ref. [3]) is just the average density of co-movers in $pp$ (given by $[1/(\pi R_p^2)]dN/dy$). Therefore the argument of the log is always larger than one (except for values of the integration variables where the argument of the exponent is very close to zero) and the $\theta$-function is irrelevant. With Eq. (9), the effect of co-movers is rather small in $SU$ (see Figs. 3 and 4) and negligible in $pA$.

In Ref. [10] a different expression for the argument of the log was introduced. Using it in Eq.(9) for $AB$ collisions our results are practically unchanged. However, the effect of the co-movers in $pA$, although small, is then non-negligible. When discussing the $\psi'/DY$ ratio this effect can be compensated by a decrease of $\sigma_{abs}$. However, an effect is left in the ratio $\psi'/\psi$, which will decrease by roughly 10% between $pp$ and $pPb$.

6. $\psi'$ suppression

There is a rather general consensus that (most of) the observed $\psi'$ suppression in $SU$ and $PbPb$ collisions is due to co-mover interactions. Even the authors [3], who strongly support the deconfinement scenario for $J/\psi$ suppression, do interpret in that way the $\psi'$ over Drell-Yan ratio in all systems (including $PbPb$). Let me discuss this ratio within Set II. Here the value of $N_f$ is the same used in Ref. [3] and the analysis therein is essentially unchanged in our approach. More precisely, in $pA$ collisions this ratio is constant both in Ref. [3] and in our formalism (Eq. (9)). In $SU$ collisions one can choose the value of $\sigma_{co}^{\psi'} > \sigma_{co}^{\psi}$ such as to reproduce [3, 10] the ratio $\psi'/DY$. In the formalism of Ref. [3] one then gets a good description of $PbPb$ using this value of $\sigma_{co}^{\psi'}$. In our case, the value for the last bin of $PbPb$ is too small. However, this discrepancy is at the level of two standard deviations, and, therefore,
one has to wait for better data†.

Let me discuss now the effect of deconfinement on \( \psi' \) suppression. In Ref. \[23\] it is shown that deconfinement produces a sharp decrease of the ratio \( \psi'/\psi \) at the critical value of the \( \psi' \) deconfining phase transitions (taken to be the same as for \( \chi' \)’s, Eq. (8)). At the time Ref. \[23\] was published, it was assumed that this deconfinement would take place after \( pPb \). Thus, the decrease of the ratio \( \psi'/\psi \) observed in \( SU \) was regarded as a qualitative success of the phase transition scenario. Nowadays, we know that this phase transition can only take place after the last \( E_T \) bin of \( SU \) (Eq. (8)). No sharp decrease of the \( \psi'/\psi \) ratio is observed here. Therefore the experimental behaviour of the ratio \( \psi'/\psi \) (or \( \psi'/DY \)) does not confirm the qualitative expectations of the phase transition scenario.

7. The inverse kinematic experiment

Perturbative QCD calculations yield a very small value of the co-mover cross-section, i.e. of the cross-section of a bound \( J/\psi \) with hadrons near threshold \[20\]. When non-perturbative effects are introduced, a much larger value is obtained \[21\]. In order to settle this important question Kharzeev and Satz have proposed to measure the \( J/\psi \) suppression in \( pA \) collisions in the backward hemisphere (or \( A \) on \( p \) in the forward one). When the \( J/\psi \) is slow in the rest system of the nucleus it will be produced inside the nucleus and if its interaction cross-section is very small there will be no \( J/\psi \) suppression. The problem, however, is that it may be experimentally very difficult to distinguish a cross-section of, say, less than 0.1 mb \[20\] from the moderate values (0.5 to 1.5 mb) needed in the co-mover scenario.

Perhaps a more interesting possibility would be to consider \( SU \) in the backward hemisphere (or \( U \) on \( S \) in the forward one). Indeed, in the co-mover scenario the decrease of the absorptive cross-section discussed above may be over-compensated by an increase of absorption due to an increase of the density of co-movers when one moves in rapidity towards the maximum of \( dN/dy \). The observation of a maximum in the \( J/\psi \) suppression at this value of \( y \) would support the co-mover scenario.

† In Ref. \[10\] this discrepancy was taken seriously and solved by introducing the exchange reactions \( \psi + \pi \to \psi' + X \) and \( \psi' + \pi \to \psi + X \).
A further advantage of this proposal is that it can be done in the rapidity range 
\(0 < y_{cm} < 1\) covered by the present NA50 experimental set up. The calculation 
of this effect is, of course, possible in the co-mover scenario but it requires a 
hyothesis on the energy dependence of \(\sigma_{abs}\). It should be stressed, however, that 
the observation of such a maximum does not rule out the phase transition scenario. 
Indeed, the \(J/\psi\) environment at \(-1 < y_{cm} < 0\) in \(SU\) (or at \(0 < y_{cm} < 1\) in \(US\)) 
is hotter than the one in \(SU\) at \(0 < y_{cm} < 1\), and therefore deconfinement can be 
present there. This shows that the geometrical criteria for deconfinement used in 
Refs. [3, 13] can only be appropriate for a flat rapidity density of hadrons. When 
this is not the case the critical value of the local energy density has to be a function 
of \(y\). It also shows the difficulty to disentangle the co-mover scenario from the 
deconfining one.

8. Discussion and conclusions

The main difference between color deconfinement and co-mover absorption is the 
presence in the former of a sudden change in the \(J/\psi\) survival probability, whereas 
all changes are smooth in the latter. However, this discontinuity is assumed to take 
place in a variable (the local energy density) which is not directly observable.

As for the number of free parameters, in the deconfinement approach of Ref. 
[13] there is (apart from \(\sigma_{abs}\) which is present in all approaches) only the value of 
\(n_c\) (the critical value of the local energy density). Moreover, one has chosen a value 
of \(\sigma_{abs} = \infty\) above the critical density. In Ref. [3] there is an extra parameter since 
one takes two distinct critical values for \(\chi\)’s and for direct \(J/\psi\) deconfinement.

In the co-mover scenario there are two free parameters: \(\sigma_{co}\) and \(N_f\). The \(E_T\) (or 
\(L\)) dependence in \(PbPb\) is controlled by both quantities. However, we see in Figs. 
3, 4 and 5 that changing \(N_f\) by a factor 2 has very little effect on the results, since 
this change is compensated by a corresponding change in the value of \(\sigma_{co}\). Because 
the effects of these two parameters are strongly correlated, it is not possible in the 
simple co-mover approach of Refs. [3, 11, 12] to reproduce the structure in the \(E_T\) 
(or \(L\)) dependence of the \(PbPb\) data. Taking a mixture of \(\chi\)’s and direct \(J/\psi\) with 
distinct parameters, as done in Ref. [4], would improve the situation. However, one
should make sure that such a structure is not due to a statistical fluctuation.

The success of the co-mover model is due to the fact that, when a couple \((N_f, \sigma_{co})\) is chosen in such a way to reproduce the \(E_T\) (or \(L\)) dependence in \(PbPb\), the corresponding effect of the co-movers in \(SU\) turns out to be rather small and does not spoil the success of the nuclear absorption model. Moreover, the dependence on centrality of the local density of co-movers is stronger in \(PbPb\) than in \(SU\) collisions. This produces the change in the \(L\) slope between the two systems, seen in Fig. 5.

In conclusion, to distinguish the deconfinement scenario involving a phase transition (or discontinuity) from the co-mover scenario turns out to be a quantitative rather than a qualitative issue. The present data can be reasonably well described in both approaches with a comparable (and small) number of free parameters. So far no experiment has been suggested which would allow to disentangle these two mechanisms.

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Figure 1. The density $N_w(b, s)$ in Eq. (5) for $s$ along the direction of the impact parameter, for various values of the impact parameter $b = 0, 2, 4, \ldots$ fm. The origin is at a distance $b/(1 + R_B/R_A)$ from the center of nucleus $A$. Left: $SU$ collision; right: $PbPb$ collision. The horizontal dashed line corresponds to the largest density achieved in the $SU$ system, $n_c = 3.3$ fm$^{-2}$. 
Figure 2. The experimental $J/\psi$ survival probability over $DY$ ratio divided by the deconfinement suppression in $PbPb$ collisions, with $\kappa_\bar{c}^\chi = 2.3$ and $\kappa_\bar{c}^\psi = 2.9$.

Figure 3. $J/\psi$ suppression versus $AB$: Set I (dotted line), Set II (solid line) and Set III (dashed line) compared to the experimental data. Note that the calculations have been performed only for those nuclei where data exist. The obtained values have been joined by straight lines. For clarity of the figure, the results of Set III are shown only for $SU$ and $PbPb$. 
Figure 4. $J/\psi$ over $DY$ ratio versus $E_T$: Set I (dotted line), Set II (solid line) and Set III (dashed line) compared to the experimental data [8].

Figure 5. Same as in Fig. 4 plotted versus $L$ [2, 8].