A QUANTITATIVE REANALYSIS OF CHARMONIUM SUPPRESSION IN NUCLEAR COLLISIONS

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Abstract

We present a quantitative description of $J/\psi$ and $\psi'$ suppression in proton-nucleus and nucleus-nucleus collisions at CERN energies. We use a conventional hadronic framework based on nuclear absorption plus final state interaction of the $J/\psi$ or $\psi'$ with co-moving hadrons.
Charmonium suppression due to Debye screening in a deconfined medium was proposed in 1986 by Matsui and Satz \cite{1} and found experimentally by the NA38 Collaboration \cite{2}. However, it was claimed very soon \cite{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 \cite{6, 7} that the $J/\psi$ 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.

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 $\sigma_{abs}$ \cite{7, 8}. Two different interpretations of this anomalous suppression have been proposed in the literature. One is a scenario in which there is an extra suppression of the $J/\psi$ due to interactions with co-moving hadrons (co-movers) \cite{9, 10, 11}. The other interpretation \cite{12, 13, 14} assumes that when the local energy density is larger than some critical value (taken to be around the maximal one reached in a central $SU$ collision), there is a discontinuity in the $J/\psi$ survival probability. (See also \cite{15} for ideas based on percolation of strings.)

In recent papers Kharzeev, Louren\c{c}o, Nardi and Satz \cite{6} and Vogt \cite{16} have claimed that a quantitative analysis of the data allows to conclude that the co-mover model cannot describe the data, whereas a quark-gluon plasma interpretation describes them well. In the present work we re-examine this point by reanalyzing all available data, using the final 1995 NA50 results \cite{8}, in the conventional co-mover scenario mentioned above (see also \cite{17}).

**Nuclear absorption:** 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 nucleons on its path at \( z' > z \), with an absorptive cross-section \( \sigma_{\text{abs}} \). This produces a change in the \( A \) dependence of the \( J/\psi \) inclusive cross-section. For nucleus-nucleus collisions this change, at impact parameter \( b \) and transverse position \( s \), is given \cite{4} by

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

Here \( T_A \) and \( T_B \) are the nuclear profile functions normalized to unity, determined from a standard Saxon-Woods density \( \rho(r) = \rho_0 / (1 + \exp [(r - R_A)/a]) \), with \( R_A = 1.14 A^{1/3} \) fm and \( a = 0.545 \) fm \cite{8}. \( \sigma_{\text{abs}} \) is the absorptive cross-section. In the following we take \( \sigma_{\text{abs}} = 7.3 \pm 0.6 \) mb which gives the best fit to the \( pA \) data \cite{1}. Note that in Refs. \cite{7, 8} a smaller value, \( \sigma_{\text{abs}} = 6.2 \pm 0.7 \) mb, has been obtained. This is due to the fact that the approximate expression of nuclear absorption in Ref. \cite{7} was used, instead of Eq. (1). Also note that \( S_{\text{abs}} = 1 \) for \( \sigma_{\text{abs}} = 0 \), so 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{19} 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. It is amazing that the differences between the results obtained with this exact formula and the ones obtained from Eq. (1) are less than 1 %.

**Absorption by co-moving hadrons:** The survival probability of the \( J/\psi \) due to absorption with co-moving hadrons is given by (see \cite{5} and references therein)
\[
S^{\text{co}}(b, s) = \exp \left[ -\sigma_{\text{co}} N_{y}^{\text{co}}(b, s) \ln \left( \frac{N_{y}^{\text{co}}(b, s)}{N_{f}} \right) \theta(N_{y}^{\text{co}}(b, s) - N_{f}) \right].
\]  

(2)

This formula is obtained assuming longitudinal boost invariance of hadronic densities and isoentropic longitudinal expansion (i.e. a decrease of densities with proper time in \(1/\tau\)). Transverse expansion is neglected. \(N_{y}^{\text{co}}(b, s)\) is the density of hadrons per unit transverse area \(d^{2}s\) and per unit rapidity at impact parameter \(b\). All species of hadrons are included in \(N_{y}^{\text{co}}\). (If we consider only the process \(\psi + \rho \rightarrow D + \bar{D} + \cdots\) as in Ref. [9], the value of \(N_{y}^{\text{co}}(b, s)\) has to be decreased and that of \(\sigma_{\text{co}}\) increased by the same percentage amount.)

In order to have a smooth onset of the co-movers and to avoid any threshold effect, it is natural to take for \(N_{f}\) the density of hadrons per unit rapidity in a \(pp\) collision, i.e. \(N_{f} = \left[ 3/(\pi R_{p}^{2}) \right] dN^{-}/dy(y^{*} = 0) \simeq 1.15 \text{ fm}^{-2}\). This coincides with the value introduced in Ref. [3]. Because of this choice of \(N_{f}\), the \(\theta\)-function in Eq. (2) is irrelevant; we have checked it numerically. Thus, \(N_{f}\) cannot be regarded just as a free parameter. Moreover, small changes in the value of \(N_{f}\) can be compensated by smaller changes in \(\sigma_{\text{co}}\), without spoiling the quantitative comparison to the data. The argument of the log is the interaction time of the \(J/\psi\) with co-moving hadrons. In Ref. [10] a different expression for the interaction time based on interferometry radii was used. The results obtained with the two expressions are practically identical. More precisely the expression (7) in Ref. [10], with the initial time \(\tau_{0} = 1 \text{ fm/c}\) used there, gives practically the same results as our Eq. (2) with \(N_{f} = 1.15 \text{ fm}^{-2}\).

\(\sigma_{\text{co}}\) 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) and over the different species of secondaries. Unfortunately, the value of \(\sigma_{\text{co}}\) is not known experimentally. This is, of course, the main limitation of the co-mover scenario. Different theoretical cal-
Calculations of the $J/\psi$-hadron cross-section based on the multipole expansion in QCD \cite{20} differ from those which include other non-perturbative effects \cite{21} by at least a factor 20 for $\sqrt{s} \sim 5$ GeV. Other references \cite{22} obtain values for the $J/\psi$-$N$ cross-section at high energy of $4 \div 6$ mb and a ratio $\sigma^{J/\psi-N}/\sigma^{J/\psi-N} \sim 3 \div 4$ in agreement with geometrical considerations. Our value $\sigma^{\psi_c}/\sigma^{\psi_c} = 10$ (see below) is much larger than its asymptotic value. This is consistent with the very different behaviour of the two cross-sections near threshold. Note, however, that Eq. (2) is the result of an integration from time $\tau_0$ to freeze-out. For times close to $\tau_0$, one is dealing with a dense interacting parton system and thus the precise relation between $\sigma_c$ and the $J/\psi(\psi')$-hadron cross-section is not established. In this situation, inverse kinematic experiments could help to determine the actual rôle of co-movers in $J/\psi$ suppression. Phenomenologically, the value of $\sigma_c$ obtained here allows to make predictions at other energies, in particular for RHIC \cite{23}.

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

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

\begin{equation}
I^\psi_{AB}(b) = \frac{I^\psi_{NN}}{\sigma_{pp}} \int d^2 s \ m(b, s) \ S^{abs}(b, s) \ S^{co}(b, s) \ , \tag{3}
\end{equation}

where

\begin{equation}
m(b, s) = AB \ \sigma_{pp} \ T_A(s) \ T_B(b - s) \ . \tag{4}
\end{equation}

We use $\sigma_{pp} = 30$ mb. From Eqs. (3) and (4) we see that for Drell-Yan pair production ($\sigma_{abs} = \sigma_{co} = 0$), $I^{DY}_{AB} = AB \ I^{DY}_{NN}$.

In the dual parton model (DPM), $N^{co}_y(b, s)$ is given by \cite{24, 25}

\begin{equation}
N^{co}_y(b, s) = [N_1 \ m_A(b, s) + N_2 \ m_B(b, b - s) + N_3 \ m(b, s)] \ \theta(m_B(b, b - s) - m_A(b, s)) \ .
\end{equation}
\[ + [N'_1 m_A(b, s) + N'_2 m_B(b, b - s) + N'_3 m(b, s)] \theta (m_A(b, s) - m_B(b, b - s)) \] . \tag{5} 

Here \( m \) is given by Eq. (4) and \( m_A, m_B \) are the well known geometric factors \[25, 26\] 

\[ m_{A(B)}(b, s) = A(B) T_{A(B)}(s) \left[ 1 - \exp \left( -\sigma_{pp} B(A) T_{B(A)}(b - s) \right) \right] \] . \tag{6} 

The coefficients \( N_i \) and \( N'_i \) are obtained in DPM by convoluting momentum distribution functions and fragmentation functions \[24\]. Their values (per unit rapidity) for the rapidity windows and energies of the NA38 and NA50 experiments are given in Table 1. 

The rapidity density of hadrons is given by 

\[ \frac{dN^{co}}{dy} = \frac{1}{\sigma_{AB}} \int d^2 b \int d^2 s N^co_y(b, s) \] , \tag{7} 

with \( \sigma_{AB} = \int d^2 b \left[ 1 - \exp \left( -\sigma_{pp} A B T_{A(B)}(b) \right) \right], T_{A(B)}(b) = \int d^2 s T_A(s) T_B(b - s) \). The obtained densities of negative hadrons at \( y^* = 0 \) for \( pp, SS, SAu \) and \( PbPb \) are compared in Table 2 with available data \[27, 28, 29\], using in each case the centrality criteria (in percentage of total events) given by the experimentalists. At this point we would like to comment on the differences between DPM and the scaling in the number of participants known as wounded nucleon model (WNM, for a review see e.g. \[30\]). The former gives a multiplicity that increases faster with centrality. This is due to the presence of strings of type quark-antiquark \[24\]. Since these strings contribute only at midrapidity, the difference between the two models is maximal at \( y^* \sim 0 \), where the NA38/NA50 spectrometer is located, and quite small at the negative values of \( y^* \) of the NA50 \( E_T \) calorimeter. The data of the NA35 \[28\] and NA49 \[29\] Collaborations on the rapidity distribution of negatives in central \( SA \) and \( PbPb \) interactions show an agreement with the WNM in the fragmentation region and an excess of \( 20 \div 30 \% \) at \( y^* \sim 0 \), as expected from DPM. We have checked \[23\] that the correlation between \( E_T \) and \( E_{ZDC} \)
(the energy in the NA50 zero degree calorimeter) in PbPb has a small concavity in DPM, resulting in a fit to the measured correlation which is at least as good as the straight line obtained in the WNM.

**E_T dependence:** To determine the $E_T$ dependence we need the $E_T - b$ correlation, i.e. the $E_T$ distribution at each impact parameter $P(E_T, b)$. The $E_T$-dependence of the ratio $J/\psi$ over Drell-Yan is given by

$$R(E_T) = \frac{\int d^2b \ P(E_T, b) \ I_{AB}^{J/\psi}(b)}{\int d^2b \ P(E_T, b) \ I_{AB}^{DY}(b)},$$

(8)

where $I_{AB}^\psi(b)$ is given by Eq. (3) and $I_{AB}^{DY}(b)$ is obtained (up to a normalization constant) from Eq. (3) with $\sigma_{abs} = \sigma_{co} = 0$.

It is clear from the discussion below Eq. (7) that, in the region of the NA50 calorimeter, $P(E_T, b)$ in DPM is very similar to the WNM one [6, 31]. However, for consistency, we are going to use the DPM distribution:

$$P(E_T, b) = \frac{1}{\sqrt{2\pi q^2 a N_{co}^y(b)}} \ exp \left[ -\frac{(E_T - qN_{co}^y(b))^2}{2q^2 a N_{co}^y(b)} \right],$$

(9)

where $q$ and $a$ are free parameters and $N_{co}^y(b) = \int d^2s \ N_{co}^y(b, s)$ is obtained from (5) with the coefficients $N_i$ and $N'_i$ obtained in DPM. They correspond to the density of neutral particles in the rapidity windows of the NA38 (SU) and NA50 (PbPb) calorimeters. The parameters $q$ and $a$ are obtained from a fit of the $E_T$ distributions for dimuon pair production above the $J/\psi$ mass. The resulting fits are quite good [23] and give: $q = 0.65$ GeV, $a = 1.5$ for $SU$ and $q = 0.78$ GeV, $a = 1.5$ for PbPb. It is interesting to note that the value of $q$ for PbPb is identical from the one obtained from the best fit to the $E_T - E_{ZDC}$ correlation. The value of $a$ is poorly determined but affects very little the results below. A value $a = 1$ [3] is also consistent with the data. Our value $a = 1.5$ is the one expected from a Poissonian distribution of clusters (resonances) with an average
cluster multiplicity of 1.5. This value agrees with the one obtained when clusters are identified with a realistic mixture of known resonances and direct particles [32].

**Numerical results:** We present the results for $J/\psi$ and $\psi'$ suppression obtained with two sets of parameters. Set I corresponds to nuclear absorption alone: $\sigma_{abs} = 7.3$ mb and $\sigma_{co} = 0.0$ mb. Set II contains the effect of the co-movers: $\sigma_{abs} = 6.7$ mb, $\sigma_{co} = 0.6$ mb and $\sigma_{co} = 6.0$ mb ($N_f = 1.15$ fm$^{-2}$ as discussed previously). The absolute normalization (corresponding to $\sigma_{pp}$ in $(J/\psi)/AB$ and to $\sigma_{pp}^{V(t)} / \sigma_{pp}^{DY}$ in $\psi^{(t)}/DY$, in the acceptance of the NA38 and NA50 experiments), is a free parameter which, for each Set, has been determined from a best fit to the data.

The results for $J/\psi$ suppression versus $AB$ are presented in Fig. 1. Nuclear absorption alone, Set I, gives a $\chi^2/dof = 1.1$; although this value is quite good, the experimental $PbPb$ point lies well below the theoretical curve for this Set (by $\sim 3$ standard deviations). However, Set II gives a satisfactory description ($\chi^2/dof = 0.2$) of all points. We also see that the effect of co-movers is much smaller in $SU$ than in $PbPb$.

We turn next to the $E_T$ dependence. Using Eqs. (8) and (9) we compute the ratio $R(E_T)$ for $SU$ and $PbPb$ in the five $E_T$ intervals of the NA38 and NA50 experiments. In order to exhibit all the results in the same figure we plot the ratio $R$ versus $L$. This variable is a measure of the centrality of the collision. The average value of $L$ in each $E_T$ bin is given in the experimental papers [8]. However, the value of $L$ is largely irrelevant since we are comparing the measured suppression in specific $E_T$ bins with the model calculations in the same $E_T$ bins; it only provides a scale for the horizontal axes. For consistency, we have to take, for each $E_T$, the same value of $L$ used by the experimentalists. Note that the first calculations of $L$ by NA50 [7] used a sharp-surface approximation for the nuclear density. More recent calculations [8] are based on
a Saxon-Woods density and are in better agreement with other calculations available in
the literature (e.g. [33]).

The results for Sets I and II for $J/\psi$ suppression ($(J/\psi)/DY$) are given in Fig. 2 for
all $pA$ and $AB$ data as a function of $L$. In Fig. 3 the same results for $SU$ and PbPb are
presented as a function of $E_T$ in the form of a continuous line (not as the average in each
$E_T$ bin as in Figs. 2 and 4). Set I gives a $\chi^2/dof = 27.9$ for all $pA$, $SU$ and PbPb data,
indicating that nuclear absorption alone fails very badly. On the contrary, without the
$PbPb$ data the best fit with Set I gives $\chi^2/dof = 0.9$. Set II gives $\chi^2/dof = 2.7$ with
only $pA$ and $SU$ data. So without the $PbPb$ data it is hardly possible to decide whether
co-movers are present or not – although the $\chi^2/dof$ is better without co-movers. When
$PbPb$ data are included Set II gives $\chi^2/dof = 4.3$. What prevents this value of being
smaller is the peculiar $L$ or $E_T$ shape of the $PbPb$ data which cannot be reproduced in
our simple approach.

The results for $\psi'$ suppression ($\psi'/DY$) are presented in Fig. 4. Set I gives $\chi^2/dof =
14.3$ and Set II $\chi^2/dof = 1.3$ for all $pA$, $SU$ and PbPb data.

The treatment of the co-movers presented above is similar to the one in Ref. [3].
However, it differs from it and from previous treatments [3, 11] in that we use the DPM
expression for the density of hadrons, Eq. (5), instead of assuming it to be proportional
to either the number of participants or to $E_T$. Another difference resides in the nuclear
densities. In the present work (and also in [12]) calculations have been done with the
nuclear density described after Eq. (1), whereas in [3, 16] the 3-parameter Fermi distri-
bution of Ref. [34] is used. Using the latter and keeping all other parameters as above,
we have obtained a $J/\psi$ suppression between the first and the last $E_T$ bins which is 7 %
larger in $SU$ and 4 % larger in $PbPb$.

In conclusion, the data on both $J/\psi$ and $\psi'$ suppression can be described in a co-
mover approach with a small number of free parameters, which take reasonable values. In this approach there is no discontinuity in any observable. One obtains a monotonic decrease of the $J/\psi$ and $\psi'$ over Drell-Yan ratios from the most peripheral to the most central collisions. A clear departure from such a behaviour would rule out the co-mover description of $J/\psi$ and $\psi'$ suppression presented above. It is also important to compute the $J/\psi$ suppression at RHIC in the two approaches using the parameters determined at SPS. This suppression is expected to be quite large and will possibly be wildly different in the two scenarios.

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Note added: A mistake in the evaluation of the experimental errors of both $SU$ and $PbPb$ data has been reported by A. Romana (NA50 Collaboration) at the XXXIIIrd Rencontres de Moriond (Les Arcs, France, March 1998). The statistical errors of $SU$ ($PbPb$) have to be multiplied by a factor 3 (1.4). This reduces significantly our $\chi^2/dof$ for ($(J/\psi)/DY$), which, for Set I (II), are now 0.6 (1.4) for $pA$ and $SU$ and 8.1 (1.9) for all systems ($pA$, $SU$ and $PbPb$) together.
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Table captions:

Table 1. Coefficients (per unit rapidity) in Eq. (5) in the rapidity windows of the electromagnetic calorimeters (corresponding to neutral multiplicity) and dimuon detector (corresponding to multiplicity of charged plus neutrals) and at energies of the NA38 and NA50 experiments. When using these values in Eq. (5) one should put $A = A_{\text{projectile}}$ and $B = A_{\text{target}}$.

Table 2. Negative particle densities at midrapidity obtained with Eqs. (5) and (7) $(th)$, compared to experimental data [27, 28, 29] $(exp)$. Percentages of total events (given in the experimental papers), and corresponding impact parameters considered, are shown.
Figure captions:

**Figure 1.** $J/\psi$ suppression versus $AB$: Set I (dotted line) and Set II (solid line) compared to the experimental data [8]. The normalization factors are 2.01 nb/nucleon$^2$ for Set I and 2.08 nb/nucleon$^2$ for Set II. Note that the calculations have been performed only for those nuclei where data exist. The obtained values have been joined by straight lines.

**Figure 2.** Ratio $(J/\psi)/DY$ (Eq. (8)) versus $L$ (fm): Set I (dotted line) and Set II (solid line) compared to the experimental data [8]. Results obtained as an average over each experimental $E_T$ bin have been joined by straight lines. The normalization factors for the theoretical lines (giving the $\chi^2/dof$ indicated in the text for all $pA$, $SU$ and $PbPb$ data included in the fit) are 38.32 for Set I and 45.50 for Set II.

**Figure 3.** Ratio $(J/\psi)/DY$ (Eq. (8)) versus $E_T$ (GeV) compared to the experimental data [8], in the form of a continuous line (not as an average over each $E_T$ bin as in Figs. 2 and 4), for $SU$ (upper figure) and $PbPb$ (lower figure). Conventions and normalizations are the same as in Fig. 2.

**Figure 4.** Ratio $\psi'/DY$ (Eq. (8)) versus $L$ (fm): Set I (dotted line) and Set II (solid line) compared to the experimental data [8]. Results obtained as an average over each experimental $E_T$ bin have been joined by straight lines. The normalization factors for the theoretical lines (giving the $\chi^2/dof$ indicated in the text for all $pA$, $SU$ and $PbPb$ data included in the fit) are 0.299 for Set I and 0.723 for Set II.
Table 1

| Reaction                | $N_1$ | $N_2$ | $N_3$ | $N'_1$ | $N'_2$ | $N'_3$ |
|-------------------------|-------|-------|-------|--------|--------|--------|
| SU ($-1.2 < y^* < 1.2$) | 0.2096| 0.2746| 0.1598| 0.2827 | 0.2015 | 0.1598 |
| PbPb ($-1.8 < y^* < -0.6$) | 0.3549| 0.0548| 0.0946| 0.3198 | 0.0899 | 0.0946 |
| SU ($0.0 < y^* < 1.0$) | 0.8433| 0.6003| 0.4995| 1.0854 | 0.3582 | 0.4995 |
| PbPb ($0.0 < y^* < 1.0$) | 0.5891| 0.8086| 0.4248| 0.3685 | 1.0292 | 0.4248 |

Table 2

| Reaction               | $dN^-/dy|_{y^*=0}$ | $dN^-/dy|^{exp}_{y^*=0}$ |
|------------------------|----------------|---------------------|
| $pp$                   | 0.73           | 0.76 ± 0.04         |
| $SS$ (11 %, $b \leq 2.7$ fm) | 19.3           | 19.0 ± 1.5         |
| $SAu$ (1.3 %, $b \leq 1.3$ fm) | 56.3           | 59.0 ± 3.0         |
| $PbPb$ (5 %, $b \leq 3.4$ fm) | 207            | 195 ± 15           |
Figure 1

![Figure 1](image_url)
Figure 2

![Graph showing data points and lines](image-url)
Figure 3

Graph showing the ratio $B_{\phi}/C_{\phi}$ in $\sqrt{s} = 2.7-4.5$ GeV for different $E_T$ values for SU and PbPb conditions.
Figure 4