J/ψ AND ψ’ SUPPRESSION IN HEAVY ION COLLISIONS

by

A. Capella, A. Kaidalov*, A. Kouider Akil
Laboratoire de Physique Théorique et Hautes Energies **
Université de Paris XI, bâtiment 211, 91405 Orsay cedex, France

C. Gerschel
Institut de Physique Nucléaire
Université de Paris XI, bâtiment 100, 91406 Orsay cedex, France

Abstract

We study the combined effect of nuclear absorption and final state interaction with co-moving hadrons on the J/ψ and ψ’ suppression in proton-nucleus and nucleus-nucleus collisions. We show that a reasonable description of the experimental data can be achieved with theoretically meaningful values of the cross-sections involved and without introducing any discontinuity in the J/ψ or ψ’ survival probabilities.

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* Permanent address : ITEP, B. Cheremushkinskaya 25, 117259 Moscow, Russia
** Laboratoire associé au Centre National de la Recherche Scientifique - URA D0063
In 1986 Matsui and Satz [1] proposed $J/\psi$ suppression in heavy ion collisions as a signal of quark gluon plasma (QGP) formation. This suppression results from Debye screening in a medium of deconfined quarks and gluons. Shortly afterwards, the NA38 collaboration tested this idea and found that in $O-U$ and $S-U$ collisions the ratio $J/\psi$ over di-muon continuum decreases with increasing centrality [2]. However, very soon, two alternative explanations involving conventional physics - i.e. no phase transition - were proposed. In the first one, known as nuclear absorption [3] [4], the $c\bar{c}$ pair wave packet produced inside the nucleus, is modified by nuclear collisions in such a way that it does not project into $J/\psi$ but into open charm. It was shown that the absorptive cross-section $\sigma_{abs}$ needed to explain the $A$-dependence of $J/\psi$ production in $pA$ collisions also does explain the suppression found in nucleus-nucleus. This cross-section turns out to be about 6 mb. In the second explanation, known as interaction with co-movers, the $J/\psi$ produced outside the nucleus is surrounded by a dense system of hadrons (mainly pions) and converts into open charm due to interactions in the medium [5]. This interaction takes place at low energies - which, however, have to be large enough to overcome threshold effects. Reliable theoretical calculations of the corresponding cross-section $\sigma_{co}^{\psi}$ show that it increases very slowly with energy from threshold [6]. In view of that, the second interpretation has been progressively abandoned in favor of nuclear absorption [7].

Very recent data for $Pb Pb$ collisions obtained by the NA50 collaboration show an anomalous $J/\psi$ suppression [8]. The ratio $J/\psi$ over Drell-Yan (DY) is two times smaller than the extrapolation of the $O-U$ and $SU$ data based on nuclear absorption - the statistical significance of this discrepancy being of nine standard deviations. These data provide a most exciting hint of QGP formation and some interpretations in this context have been presented at the QM’96 conference [9]. In them a discontinuity in the $J/\psi$ survival probability is assumed when some threshold of local energy density is reached.

In this note we present an attempt to describe the observed $J/\psi$ suppression using the combined effect of nuclear absorption and interaction with co-movers - without introducing
any discontinuity in the survival probability [10]. For the nuclear absorption we adopt the formalism of refs. [3, 4]. For simplicity, we use the exponential form of the $J/\psi$ suppression given in ref. [4] and used in the experimental papers, namely

$$S_1 = \exp(-\rho L \sigma_{abs})$$

(1)

where $\rho = 0.138$ nucleon/fm$^3$ is the nuclear density and $L$ is the length of nuclear matter crossed by the $c\bar{c}$ pair. The more involved formalism of ref. [3] gives results very similar to those obtained from (1).

We turn next to the final state interaction with produced hadrons (co-movers). A rigourous treatment of this interaction is very complicated and is not available in the literature. We use the simple treatment proposed in refs. [11]. The decrease in the spatial density of $J/\psi$ at point $x$ due to the interaction $\psi-h$ is given by [12]

$$\Delta \frac{dN^\psi}{d^4x} = \rho^\psi(x) \rho^h(x) \sigma_{co}^\psi$$

(2)

with $d^4x = \tau d\tau dy d^2s$, where $\tau$ is the proper time, $y$ the space-time rapidity (to be later on identified with the usual rapidity) and $d^2s$ an element of transverse area. $\sigma_{co}^\psi$ is the part of the $\psi-h$ cross-section which does not contain the $J/\psi$ in the final state, averaged over the momentum distribution of the colliding particles. The effect of thresholds will be taken into account in an effective way through the value of $\sigma_{co}^\psi$. Assuming longitudinal boost invariance and a dilution of the densities $\rho^\psi$ and $\rho^h$ of the type $1/\tau$ (i.e. neglecting transverse expansion), we get from (2)

$$\left. \frac{dN^\psi}{dy} \right|_{\tau_0 + \Delta \tau} = \int d^2s \frac{dN^\psi}{dy d^2s} \frac{dN^h}{dy d^2s} \sigma_{co}^\psi \ell_n \left. \frac{\tau_0 + \tau}{\tau_0} \right|$$

(3)

where $\tau_0$ is the formation time and $\tau$ is the duration of the hadronic phase.

We want to express the densities $dN/dy d^2s$ in terms of the observables $dN/dy$. We have [11]

$$\int d^2s \frac{dN^\psi}{dy d^2s}(b) \frac{dN^h}{dy d^2s}(b) = G(b) \frac{dN^\psi}{dy}(b) \frac{dN^h}{dy}(b)$$

(4)
where $b$ is the impact parameter of the collision and the geometrical factor $G(b)$ is given by

\[
G(b) = \int d^2 s \frac{T_A^2(s) T_B^2(b-s)}{T_{AB}^2(b)} ,
\]

which has an obvious geometrical interpretation. For the nuclear profile $T_A(b)$ we use standard Saxon-Woods. For the proton we use a Gaussian profile with $R_p = 0.6$ fm. Using (3)-(5) we have:

\[
\frac{dN^\psi}{dy}(b) \bigg|_{\tau_0 + \Delta \tau} = \frac{dN^\psi}{dy}(b) \left[ 1 - \sigma_{co}^\psi G(b) \ell n \frac{\tau_0 + \Delta \tau}{\tau_0} \right] \frac{dN^h}{dy}(b)
\]

and, for a finite time interval,

\[
\frac{dN^\psi}{dy}(b) = \frac{dN^\psi}{dy}(b) \exp \left[ -\sigma_{co}^\psi G(b) \ell n \frac{\tau_0 + \tau(b)}{\tau_0} \right] \frac{dN^h}{dy}(b) \equiv \frac{dN^\psi}{dy}(b) S_2(b) .
\]

We have now to specify the duration time of the interaction $\tau(b)$. This time is not well known. We use the following ansatz [11]. In the case of Gaussian profiles one has

\[
G = \frac{1}{2\pi} \left[ \frac{2}{3} \frac{R_A^2 \cdot R_B^2}{R_A^2 + R_B^2} \right]
\]

where $R$ are the rms radii. In ref. [13] it was found that the quantity in brackets in (8) is precisely the geometrical HBT squared transverse radius. Following the arguments of [14] we take it as a measure of the duration of interaction and therefore use

\[
\tau(b) = [2\pi G(b)]^{-1/2}
\]

For the formation time $\tau_0$ we take $\tau_0 = 1$ fm [14]. Of course our results depend on the value of $\tau_0$. However, this dependence can, to a large extent, be compensated by a small change of $\sigma_{co}^\psi$. Finally $dN^h(b)/dy$ is a measurable quantity. In order to avoid model estimates we use the experimental value of $E_T$ as a measure of the hadronic activity. More precisely, for $SU$ collisions, where the NA38 calorimeter covers a range $-1.3 < \eta_{cm} < 1.1$ not far from the one of the dimuon $(0 < \eta < 1)$, we take

\[
\frac{dN^h}{dy}(b) = \frac{3E_T(b)}{\Delta \eta < p_T >} ,
\]
where $E_T$ is the average energy of neutrals measured by the calorimeter in each centrality bin, $\Delta \eta = 2.4$, and $<p_T> = 0.35$ GeV. Note, however, that our results depend only on the product $\sigma_{co} dN^h/dy$. The value of $b$ in each bin is determined from the NA38 code [15]. Unfortunately, in $Pb Pb$ collisions, the calorimeter does not have the same acceptance as in $SU$ and, moreover, is not located at mid-rapidities. Due to these differences the $E_T$ measured in $Pb Pb$ has to be multiplied by a factor $2.35 \pm 0.15$ [16] in order to be comparable to the $E_T$ measured in $SU$. Finally for a $pA$ collision we take

$$\frac{dN^{pA\rightarrow h}}{dy} (b) = \frac{3}{2}(\bar{\nu} + 1) \frac{dN^{NN\rightarrow h^{-}}}{dy} ,$$  

where $\bar{\nu}$ is the average number of collisions. From (1) and (7) we obtain the combined result of nuclear absorption and destruction of the $J/\psi$ via interactions with co-moving hadrons, as

$$\frac{dN^{\psi}}{dy} (b) = \frac{dN^{\psi}}{dy} \bigg|_{\tau_0} (b) S_1 (b) S_2 (b)$$  

Note that $dN^{\psi}/dy$ at $\tau_0$ is close but not identical to $AB$ times the corresponding value in $pp$ collisions. This is due to the fact that, contrary to $S_1$, $S_2 \neq 1$ for $pp$. Therefore it has to be determined from

$$\frac{dN}{dy} \bigg|_{\tau_0}^{AB\rightarrow \psi} (b) = AB \frac{dN^{pp\rightarrow \psi}}{dy} S_{2}^{pp} (b) .$$  

We can now compute the absolute yield of $J/\psi$ in any reaction - or the ratio $J/\psi$ over DY since, in the latter case, $S_1 = S_2 = 1$. The results, which depend on two parameters $\sigma_{abs}$ and $\sigma_{co}^{\psi}$, are presented in Fig. 1 and compared with the NA38 and NA50 data. The agreement with experiment is reasonably good. In particular the strong suppression between $SU$ and $Pb Pb$ is obtained with no discontinuity in the parameters. However, our $L$-dependence is somewhat too weak in $pA$ collisions and too strong in $SU$. It is important that the values of the parameters

$$\sigma_{abs} = 4.1 \text{ mb} \quad \text{,} \quad \sigma_{co}^{\psi} = 0.46 \text{ mb}$$  

(14)
are very reasonable. Had we needed a much larger value of $\sigma_{co}^{\psi}$ our interpretation of the $J/\psi$ suppression should be dismissed on theoretical grounds [6].

So far we have considered, besides nuclear absorption, all the destruction channels $h + \psi \rightarrow D + \bar{D} + X$, ..., with cross-section $\sigma_{co}^{\psi}$. Likewise, in order to study $\psi'$ suppression we have to consider the channels $h + \psi' \rightarrow D + \bar{D} + X$, ..., which do not involve $\psi'$ in the final state. The corresponding cross-section will be denoted $\sigma_{co}^{\psi'}$. Due to the different geometrical sizes, $\sigma_{co}^{\psi'}$ is larger than $\sigma_{co}^{\psi}$ at very high energies. Their difference is even bigger at low energies due to the dramatic differences in the energy behaviour of these two cross-sections near threshold [6]. With this sole extra parameter at our disposal, it is not possible to reproduce the $\psi'/\psi$ ratio in both $SU$ and $Pb Pb$ systems. If we choose $\sigma_{co}^{\psi'}$ such as to reproduce the $SU$ data, the result for central $Pb Pb$ is an order of magnitude too low. However, in this case the above destruction channels are not the only relevant ones. One has also to consider the exchange channels

$$
\psi + \pi \rightarrow \psi' + X, \quad \psi' + \pi \rightarrow \psi + X
$$

with cross-sections $\sigma_{ex}^{\psi}$ and $\sigma_{ex}^{\psi'}$ respectively. Asymptotically, $\sigma_{ex}^{\psi} = \sigma_{ex}^{\psi'}$. However, at low energies $\sigma_{ex}^{\psi'}$ is expected to be much larger than $\sigma_{ex}^{\psi}$ due to the different thresholds.

The presence of these channels has little effect on the $J/\psi$ over DY ratio but it changes considerably the $\psi'/\psi$ one and allows to cure the problem mentioned above. Indeed, for central $Pb Pb$ collisions, when the $\psi'/\psi$ ratio becomes very small, channels (15) produce a feeding of $\psi'$ at the expense of $\psi$, thereby increasing the ratio $\psi'/\psi$.

Let us now discuss the combined effect of all destruction and exchange channels. The destruction channel for the $\psi'$ is treated in the same way as for the $\psi$ - with $\sigma_{co}^{\psi}$ replaced by $\sigma_{co}^{\psi'}$ ($\sigma_{co}^{\psi'} > \sigma_{co}^{\psi}$). For the exchange channels (15), there is a gain of $\psi'$ due to $\psi \rightarrow \psi'$ conversion and a loss of $\psi$ due to the inverse reaction. The net gain of $\psi'$ is

$$
\Delta(b) = \left. \frac{dN_{\psi}}{dy} \right|_{\tau_0} (b) \left[ \frac{\sigma_{ex}^{\psi} - \sigma_{ex}^{\psi'} R(b)}{\tau_0} \right] G(b) \ell n \left( \frac{\tau_0 + \Delta \tau}{\tau_0} \right) \frac{dN_{h}}{dy}(b)
$$

(16)
where $R(b)$ is the ratio of $\psi'$ over $\psi$ rapidity densities at time $\tau_0$. The net gain of $\psi$ is obviously given by the same eq. (16) with opposite sign.

Combining (1), (6) and (16) we have

$$
\left. \frac{dN^\psi}{dy} \right|_{\tau_0+\Delta \tau} (b) = \left[ \left. \frac{dN^\psi}{dy} \right|_{\tau_0} (b) \exp \left[ -\sigma_{co}^\psi G(b) \ell n \left| \frac{\tau_0 + \Delta \tau}{\tau_0} \right| \frac{dN^h}{dy} (b) \right] - \Delta(b) \right] S_1(b) \quad (17)
$$

and

$$
\left. \frac{dN^{\psi'}}{dy} \right|_{\tau_0+\Delta \tau} (b) = \left[ \left. \frac{dN^{\psi'}}{dy} \right|_{\tau_0} (b) \exp \left[ -\sigma_{co}^{\psi'} G(b) \ell n \left| \frac{\tau_0 + \Delta \tau}{\tau_0} \right| \frac{dN^h}{dy} (b) \right] + \Delta(b) \right] S_1(b) . \quad (18)
$$

Contrarily to (6), eqs. (17) (18), have to be solved numerically, because, not only $\frac{dN^\psi}{dy}$ changes with increasing $\tau$, but also $R(b)$. Therefore, it is not possible to get a close formula at freeze-out time $\tau$ - but only the variation during an infinitesimal interval $\Delta \tau$. One has to solve the problem numerically, dividing the total $\ell n \tau$ interval into a very large number of subintervals, and using as initial condition in each subinterval the result obtained at the end of the previous one.

The results for the ratios $J/\psi$ over DY and $\psi'/\psi$ are given in Figs. 1 and 2. We have used the following values of the parameters

$$
\sigma_{abs} = 4.1 \text{ mb} , \quad \sigma_{co}^\psi = 0.40 \text{ mb} , \quad \sigma_{co}^{\psi'} = 2.6 \text{ mb} , \quad \sigma_{ex}^\psi = 0.1 \text{ mb} , \quad \sigma_{ex}^{\psi'} = 0.65 \text{ mb} \quad (19)
$$

The result presented in Fig. 1 for the $J/\psi$ over DY ratio is not changed by the introduction of the exchange channels (15) (within 1%). More precisely, a small change in $\sigma_{co}^{\psi'}$ from 0.46 (14) to 0.40 mb (19) has compensated for their effect. The value of $\sigma_{co}^{\psi'}$ is basically determined from the data on $\psi'/\psi$ for SU. Finally, the value of $\sigma_{ex}^{\psi'}$ is determined in such a way to get enough feeding of $\psi'$ from $\psi$ in $Pb Pb$. Due to the smallness of $R(b)$, our results are rather unsensitive to the ratio $\sigma_{ex}^{\psi'}/\sigma_{ex}^\psi$, and, in order to decrease the number of parameters, we have taken it equal to $\sigma_{ex}^{\psi'}/\sigma_{ex}^\psi = 6.5$. (A ratio $\sigma_{ex}^{\psi'}/\sigma_{ex}^\psi = 1$ with $\sigma_{ex}^\psi = 0.06$ also gives acceptable results). Although we have not attempted a best fit of the data we
describe the $\psi'/\psi$ ratio reasonably well. In particular, we have a mild decrease of this ratio both in $pA$ and $Pb Pb$ collisions and a faster decrease in $SU$. This striking feature is also present in the experimental data. However, our $\psi'/\psi$ ratio in $pA$ collisions decreases somewhat faster than the experimental one.

Before concluding it should be noted that the values of $E_T$ measured in $Pb Pb$ collisions, relative to those measured in $SU$, are 20 to 30% larger than expected from scaling in the number of participant nucleons and from Monte Carlo codes. At present this point is not well understood either theoretically or experimentally. If the $E_T$ values in $Pb Pb$ were to be decreased by such an amount, the values of the ratio $\psi'/\psi$ in $Pb Pb$ would increase without spoiling the agreement with experiment. However, the ratio $J/\psi$ over DY for $Pb Pb$ collisions would increase (by as much as 20% in the most central bin of $Pb Pb$) as shown in Fig. 1. In this case, the mechanism described above would not reproduce entirely the NA50 data.

Note also that an important part of the effect of the co-movers comes from the region of $\tau$ near $\tau_0$ where the densities are very high and one can wonder whether such a dense system can be regarded as a hadronic one. In any case our mechanism of $J/\psi$ suppression is different from Debye screening.

In conclusion, combining nuclear absorption and final state interaction with co-moving hadrons, we have obtained a reasonable description of the $J/\psi$ and $\psi'$ data. This description is better for $SU$ and $Pb Pb$ collisions than for $pA$. It has been achieved with theoretically meaningful values of the cross-sections involved and without introducing any discontinuity in the $J/\psi$ or $\psi'$ survival probabilities.

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References

[1] T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.

[2] NA38 collaboration : C. Baglin et al, Phys. Lett. B201 (1989) 471 ; Phys. Lett. B255 (1991) 459.

[3] A. Capella, J. A. Casado, C. Pajares, A.V. Ramallo and J. Tran Thanh Van, Phys. Lett. B206 (1988) 354.
A. Capella, C. Merino, C. Pajares, A. V. Ramallo and J. Tran Thanh Van, Phys. Lett. B230 (1989) 149.

[4] C. Gerschel and J. Høfner, Phys. Lett. B207 (1988) 253 ; Z. fØr Phys. C56 (1992) 71.

[5] J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D39 (1989) 232.
S. Gavin, M. Gyulassy and A. Jackson, Phys. Lett. 207 (1988) 194.
J. Ftacnik, P. Lichard and J. Pitsut, Phys. Lett. B207 (1988) 194.
R. Vogt, M. Parakash, P. Koch and T. H. Hansson, Phys. Lett. B207 (1988) 263.
S. Gavin and R. Vogt, Nucl. Phys. B345 (1990) 1104.
S. Gavin, H. Satz, R. Thews and R. Vogt, Z. Phys. C61 (1994) 351.

[6] G. Bhanot and M. E. Peskin, Nucl. Phys. B156 (1979) 365.
A. Kaidalov and P. Volkovitsky, Phys. Rev. Lett. 69 (1992) 3155.
A. Kaidalov, Proceedings XXVIII Rencontres de Moriond (1993), ed. J. Tran Thanh Van.
JM. Luke et al, Phys. Lett. B288 (1992) 355.
D. Kharzeev and H. Satz, Phys. Lett. B306 (1994) 155.

[7] D. Kharzeev and H. Satz, Phys. Lett. B366 (1996) 316.
B. Kopeliovich and J. Høfner, Phys. Rev. Lett. 76 (1996) 192.

[8] NA50 collaboration : P. Bordaló et al, Proceedings XXI Rencontres de Moriond (1996), ibid ; M. Gonin et al, Proceedings Quark Matter 96, to be published in Nucl. Phys. A.

[9] J.P. Blaizot and J.Y. Ollitrault, Proceedings Quark Matter 96, ibid and Saclay preprint 1996.
C.Y. Wong, Proceedings Quark Matter 96, ibid.
D. Kharzeev and H. Satz, Proceedings QM’96, ibid.
Preliminary results of this work were presented by A. Capella during the discussion session in the QM’96 conference. For a contribution based on a similar approach, see S. Gavin and R. Vogt, Proceedings of QM’96 ibid.

A. Capella, Phys. Lett. B364 (1995) 175.
A. Capella, A. Kaidalov, A. Kouider Akil, C. Merino and J. Tran Thanh Van, Z. Phys. C70 (1996) 507.
P. Koch, U. Heinz, J. Pitsut, Phys. Lett. B243 (1990) 149.
A. Capella and A. Krzywicki, Z. Phys. C41 (1989) 659.
NA35 collaboration : G. Roland, Nucl. Phys. A566 (1994) 527c.
D. Ferenc, Proceedings XXIX Rencontres de Moriond (1994) ibid.
NA38 collaboration : C. Baglin et al, Phys. Lett. B251 (1990) 472.
NA50 collaboration : private communication.

Figure Captions

Fig. 1 The ratio $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$ versus the interaction length $L$ in the final state for $pp$, $pA$, $SU$ and $Pb Pb$ collisions. The data are from ref. [8]. The theoretical values are obtained from eq. (17) with the values of the parameters in (19). The same result (within 1%) is obtained from eq. (12) with the values of the parameters in (14). The straight line corresponds to nuclear absorption alone (eq. (1)), with $\sigma_{abs} = 6.2$ mb.

Fig. 2 The ratio $B_{\mu\mu}\sigma(\psi')/B_{\mu\mu}\sigma(J/\psi)$ versus $L$ in $pp$, $pA$, $SU$ and $Pb Pb$ collisions. The data are from ref. [8]. The theoretical values are obtained from eq. (18), with the values of the parameters in (19).
$B_{\mu\nu} \sigma(J/\psi) / \sigma(Drell-Yan)_{2.9-4.5}$

- $p(450^* \text{GeV}/c) - A (A = p,d)$ (NA51)
- $p(200 \text{GeV}/c) - A (A = W,U)$ (NA38)
- $^{32}\text{S}(32 \times 200 \text{GeV}/c) - U$ (NA38)
- $^{208}\text{Pb}(208 \times 158^* \text{GeV}/c) - \text{Pb}$ (NA50)
- Theory $p-A$
- Theory $S-U$
- Theory $\text{Pb-Pb}$
- Theory $\text{Pb-Pb ET}/1.25$

* rescaled to 200 GeV/c
\[ \frac{B_{\mu \mu} \sigma(\psi)}{B_{\mu \mu} \sigma(J/\psi)} \]

- \( \star \) p(450 GeV/c) - A (A = C, Al, Cu, W) (NA38)
- \( \star \) p(200 GeV/c) - A (A = W, U) (NA38)
- \( \star \) p(450 GeV/c) - A (A = H₂, D₂) (NA51)
- \( \square \) \( ^{32} \text{S} \)(32 x 200 GeV/c) - U (NA38)
- \( \bigcirc \) \( ^{208} \text{Pb} \)(208 x 158 GeV/c) - Pb (NA50)
- \( \star \) Theory p - A
- \( \blacksquare \) Theory S - U
- \( \blacktriangle \) Theory Pb - Pb

L (fm)