J/ψ Suppression in Pb+Pb Collisions: A New Look at Hadrons vs. Plasma

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Abstract

A reexamination of hadronic comover scattering indicates that this mechanism cannot explain the observed J/ψ suppression in Pb+Pb interactions. The possibility of quark-gluon plasma formation is then plausible. We present calculations in which the χ_c and ψ' are suppressed by the plasma while the J/ψ itself is not.

1 Introduction

Ever since it was realized that the J/ψ suppression by quark-gluon plasma formation predicted by Matsui and Satz [1] could be mimicked by hadronic means, the source of the observed J/ψ suppression [2] has remained controversial. Recent debate has focussed on whether or not the data can be consistently described by hadronic means [3, 4, 5, 6, 7, 8]. In this paper we readdress this question in light of a reanalysis of our previous work [3]. We briefly recall parts of the data analysis pertinent to our discussion. Then, in light of these points, we reexamine the agreement of purely hadronic mechanisms with the data and suggest a quark-gluon plasma origin of newly observed apparent thresholds in the latest Pb+Pb data [9].

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The NA38/NA50/NA51 data \cite{2,10,11} has been adjusted for isospin, continuum mass, projectile energy and phase space so that all the $J/\psi$, $\psi'$ and Drell-Yan data can be compared on the same level \cite{2}. At Quark Matter ’96 \cite{2}, the data were adjusted to 200 GeV in the rapidity interval, $0 < y_{cm} < 1$, and in the angular interval $|\cos \theta_{CS}| < 0.5$. The Drell-Yan cross sections were all reported in the mass interval $2.9 < M < 4.5$ GeV and isospin adjusted to the $pp$ cross section using the GRV LO \cite{12} parton distributions. The isospin correction depend on the parton distribution functions. The GRV LO set suggests an isospin correction in Pb+Pb collisions of $pp/Pb+Pb \approx 1.3$ at $\sqrt{s} = 19.4$ GeV and $2.9 < M < 4.5$ GeV while the GRV 94 LO set \cite{13}, adjusted to fit the NA51 $\overline{7}/\pi$ flavor asymmetry \cite{11}, indicates a correction of 1.03.

The original S+U data \cite{14} was compared to the “continuum” in the range $1.7 < M < 2.7$ GeV. This continuum included $D\overline{D}$ decays and an intermediate mass enhancement \cite{15}. The continuum was later fit for $M \geq 2.9$ GeV, where only Drell-Yan pairs are expected to be important, and then extrapolated to the mass interval $1.5 < M < 5.5$ GeV \cite{10,15}. Finally, after the Pb+Pb data was analyzed in the interval $2.9 < M < 4.5$ GeV, the S+U data was adjusted to this range \cite{2,16}.

Since $J/\psi$ production is dominated by gluons, it is insensitive to isospin. Parameterizations of the $J/\psi$ cross section \cite{7,17} are in generally good agreement at this energy as well as with next-to-leading order calculations \cite{18}. Alternatively, the $pp$ production cross section can be inferred from a fit to the $pA$ data for a given value of $\alpha$, or $\sigma_{\psi N}$, when comovers are neglected.

Finally, model calculations of $J/\psi$ and Drell-Yan production are angle-integrated and must be adjusted to the reported region. Muon pairs from $J/\psi$ decays are isotropic \cite{19} so that a factor of two is needed to adjust the model $J/\psi$ cross section from $|\cos \theta_{CS}| < 1$ to $|\cos \theta_{CS}| < 0.5$. However, the Drell-Yan cross section is proportional to $1 + \cos^2 \theta_{CS}$ \cite{20}, resulting in an adjustment by a factor of 2.46.

## 2 Hadronic Models

We first note that the most simplistic assumptions of $J/\psi$ suppression by hadronic interactions lead to the same $A$ dependence of absorption and secondary scatterings. Then we discuss the implications for the $E_T$ dependence.
2.1 A Dependence

Let us assume for the moment that the J/ψ may suffer interactions with both nucleons and secondaries in hadron-nucleus, hA, collisions before it can escape the target. The combined effect of nuclear absorption and comover scattering on J/ψ production is [21]

\[ \sigma_{hA \rightarrow \psi} = \sigma_{hN \rightarrow \psi} \int d^2b T_A^{\text{eff}}(b) S(b) , \]  

(1)

where \( b \) is the impact parameter, \( T_A^{\text{eff}}(b) \) is the effective nuclear profile

\[ T_A^{\text{eff}}(b) = \int_{-\infty}^{\infty} dz \rho_A(b, z) \exp \left\{ -\int_{z}^{\infty} dz' \rho_A(b, z') \sigma_{\psi N}(z' - z) \right\} \]  

(2)

and \( \sigma_{\psi N} \) is the cross section for \( \psi \) absorption by nucleons. The comover survival probability is [21]

\[ S \approx \exp \left\{ -\int d\tau \langle \sigma_{\psi co} v \rangle n(\tau, b) \right\} , \]  

(3)

where \( \sigma_{\psi co} \) is the J/ψ–comover absorption cross section, \( v \approx 0.6 \) is the relative velocity of the J/ψ with the comovers, and \( n(\tau, b) \) is the density of comovers at time \( \tau \) and impact parameter \( b \). Integrating over time \( \tau \) and relating the initial density of the system to the final hadron rapidity density by scaling [22] with \( n_0 \tau_0 = (\pi R_h^2)^{-1}(dN/dy) \), one finds [21]

\[ \langle \sigma_{\psi co} v \rangle \int d\tau n(\tau, b) \approx \frac{\langle \sigma_{\psi co} v \rangle}{\pi R_h^2} \sigma_{hN} T_A(b) \ln \left( \frac{\tau_f}{\tau_0} \right) \frac{dN}{dy} \bigg|_{y=0} , \]  

(4)

where \( dN/dy \big|_{y=0} \), the central rapidity density in an \( hp \) collision, is scaled up to \( hA \) interactions by \( \sigma_{hN} T_A(b) \), the number of participants. Since \( \pi R_h^2 \approx \sigma_{hN} \), these two factors cancel. The effective proper lifetime \( \tau_f \) over which the comovers, formed at time \( \tau_0 \), interact with the J/ψ is \( \tau_f \sim R_h/v \).

Expanding the exponentials in \( T_A^{\text{eff}} \) and \( S \) to terms linear in cross section, integrating eq. (1) and re-exponentiating, the ratio of the \( \psi \) production cross sections is [21]

\[ \frac{\sigma_{hA \rightarrow \psi}}{A \sigma_{hN \rightarrow \psi}} \approx \exp \left\{ -\frac{9A^{1/3}}{16\pi R_h^2} \left[ \sigma_{\psi N} + \frac{1}{2} \langle \sigma_{\psi co} v \rangle \ln \left( \frac{\tau_f}{\tau_0} \right) \frac{dN}{dy} \bigg|_{y=0} \right] \right\} \]  

(5)

\[ = \exp \left\{ -A^{1/3} (\eta + \beta) \right\} . \]  

(6)
For large targets with $A > 50$, $A^{1/3} \approx \ln A$ so that

$$\frac{\sigma_{hA \to \psi}}{\sigma_{hN \to \psi}} = A^{1-\eta-\beta} = A^\alpha. \quad (7)$$

Thus comover interactions do not introduce any unusual $A$ dependence. Depending on the values of $\langle \sigma_{\psi_{\text{co}}} v \rangle$, $\tau_0$, $\tau_f$ and $dN/dy$, the comover contribution to $\alpha$ could be significant, perhaps even as large as the suppression due to nuclear absorption if $\sigma_{\psi_{\text{co}}}$ is not a strong function of energy. This was first pointed out in Ref. [21], but has been neglected in the most recent analyses [3, 4, 6, 7, 23] because $\psi$-hadron interaction cross sections may be strongly reduced at low energies [24] although hadron mass corrections are large [24].

Unfortunately the identical nature of the two contributions to eq. (7) suggests that they may be inextricably intertwined. Experimental constraints on the absorption and comover interactions are clearly valuable. Exclusive $J/\psi$ production in near threshold $pA$ interactions [26] and an inverse kinematics experiment [27], which would measure $J/\psi$ production in a region where more absorption has been implied [28], albeit with low statistics, would clarify $\sigma_{\psi N}$. A measurement of $dN/dy$ associated with $J/\psi$ production as a function of energy could place limits on the comover interactions.

### 2.2 $E_T$ Dependence

The production cross section of muon pairs in nuclear collisions as a function of the transverse energy, $E_T$, is

$$\frac{d\sigma_{AB-\mu\mu}}{dE_T} = \sigma_{pp-\mu\mu} \int d^2 b \int d^2 s T_A(b) T_B(|b - \vec{s}|) p(E_T; b), \quad (8)$$

where $p(E_T; b)$ is a Gaussian with mean $\overline{E_T}(b) = \epsilon_N N_{AB}(b)$ proportional to the number of participants and standard deviation $\sigma^2(b) = \omega \epsilon_N \overline{E_T}(b)$ [21]. The parameters $\epsilon_N$, the energy per participant, and $\omega$, the fluctuation measure, are chosen to agree with the NA38/NA50 neutral $E_T$ distributions. In $S+U$ interactions $\epsilon_N = 0.74$ GeV while in $Pb+Pb$ interactions $\epsilon_N = 0.4$ GeV. A smaller $\epsilon_N$ is needed for $Pb+Pb$ because the calorimeter acceptance has been reduced to $1.1 < \eta < 2.3$ [2] from $1.7 < \eta < 4.1$ [10]. The value $\omega = 3.2$ is used in both cases. In Fig. 1 the Drell-Yan $E_T$ distributions for $S+U$ and $Pb+Pb$ interactions calculated with eq. (8) are shown normalized to the $pp$ cross section at 200 GeV.
The $E_T$ dependence of the $J/\psi$ is modified from eq. (8) by the survival probabilities given in eq. (1) so that \cite{21}

$$\frac{d\sigma_{AB-\psi}}{dE_T} = \sigma_{pp-\psi} \int d^2b \int d^2s T_A^{\text{eff}}(b) T_B^{\text{eff}}(|\vec{b} - \vec{s}|) S(E_T; b) p(E_T; b) . \quad (9)$$

Two ansätze have been used for the comover survival probability, both starting with the scaling solution of eq. \cite{20, 21},

$$S(E_T; b) = \exp \left\{ -\langle \sigma_{\text{co}}v \rangle n_{\text{co}}\tau_0 \ln \left( \frac{\tau_f}{\tau_0} \right) \right\} . \quad (10)$$

In Refs. \cite{3, 23} the density of comovers was assumed to be directly proportional to $E_T$, $n_{\text{co}} = \pi E_T/E_T(0)$. The comover formation time and the system lifetime were assumed constant, $\tau_0 \approx 2$ fm and $\tau_f \approx R_A/v$. The proportionality to $E_T$ is reasonable for central S+U collisions because although the projectile is engulfed in the target when $b < R_S$, $E_T$ still rises due to fluctuations. However, the approximation breaks down in symmetric systems where complete overlap is never achieved. Therefore, the impact parameter
dependence of $\tau_0$ and $\tau_f$ are retained in eq. (10) and $n_{co}$ is left as a constant parameter. The formation time,

$$\tau_0(b) = 1 + \frac{L_A(b)}{\gamma_A(b)} + \frac{L_B(b)}{\gamma_B(b)},$$

is $\sim 2$ fm in central collisions and $\sim 1$ in the most peripheral collisions. Note that $\tau_0(b)$ depends on the path length, $L$. The comovers interact with the $J/\psi$ only if $\tau_f(b) > \tau_0(b)$ where

$$\tau_f(b) = \begin{cases} R_A/v & b < R_B - R_A \\ (R_A + R_B - b)/(2v) & R_B - R_A < b < R_B + R_A \end{cases}.$$

Figure 2 shows the $\psi/DY$ ratios for $\sigma_{\psi N} = 4.8$ mb and 7.3 mb. Comovers are included in the solid curves, calculated with $\sigma_{\psi N} = 4.8$ mb and $\sigma_{\psi co} \approx 2\sigma_{\psi N}/3 = 3.2$ mb from quark counting and $n_{co} = 0.4/fm^3$. The $J/\psi$ cross section in $pp$ interactions is fit to the $A$ dependence given each value of $\sigma_{\psi N}$: $\sigma_{pp \rightarrow \psi} = 2.08$ nb for $\sigma_{\psi N} = 4.8$ mb and $\sigma_{pp \rightarrow \psi} = 2.29$ nb for $\sigma_{\psi N} = 7.3$ mb. The Drell-Yan $pp$ cross sections are obtained from a leading order calculation with the GRV LO [12] parton densities given the NA50 same $K$ factor, rapidity and angular interval. The comover density is now smaller than that used previously [3, 23] because the $\psi/DY$ ratio at $E_T \approx 0$, corresponding to production in $pp$ interactions, has changed to better reflect the NA50 adjustments [3].

The conclusions that can be drawn from Fig. 2 lend support to the results of Kharzeev et al. [4] and differ from those obtained in Ref. [3]. The difference between the S+U calculations shown here and those in Refs. [3, 21, 23], besides in the specific $E_T$ dependence of the comovers lies in the adjustment of the S+U continuum from $1.7 < M < 2.7$ GeV to $2.9 < M < 4.5$ GeV. The isospin and angular corrections to the Drell-Yan contribution may have been incompletely handled in [3]. Agreement with the most recent NA38 S+U data achieved with the comover model as given here is at least as good if not better than before with the smaller comover density of $n_{co} = 0.4/fm^3$ compared to $n = 0.8/fm^3$ [3, 23]. However, when this new value of $n_{co}$ is used in Pb+Pb collisions, the result now falls short of the Pb+Pb data but agrees with [4]. (See also [5].) Although assuming that $\sigma_{\psi N} = 4.8$ mb still leads one to the earlier conclusion that comovers are necessary to explain the S+U data [21, 23], the Pb+Pb results now show that the total suppression
Figure 2: The $\psi$/DY ratio is given in S+U (a) and Pb+Pb (b) interactions. The solid curve shows $\sigma_{\psi N} = 4.8$ mb and $\sigma_{\psi co} = 3.2$ mb with $n_{co} = 0.4/fm^3$. The dashed and dot-dashed curves show the effect of absorption alone with $\sigma_{\psi N} = 4.8$ mb and $\sigma_{\psi N} = 7.3$ mb, respectively.

is inconsistent with a comover explanation alone. Other recent calculations with comover interactions [6, 7] claim to achieve simultaneous agreement between the two systems within dynamical models of secondary production. More realistic models of production and interactions of secondaries than the simple model used here are clearly needed.

The $\psi'$ has also been measured in S+U and Pb+Pb interactions. The $\psi$ and $\psi'$ are assumed to interact with nucleons while in $|\bar{c}g\rangle$ color octet states [31]. The $\psi'$-comover cross section is left as a free parameter. Since the $\psi'$ mass is much closer to the $D\overline{D}$ threshold, only a 50 MeV excitation is needed to break up a $\psi'$, compared to the nearly 650 MeV needed to excite a $J/\psi$ above the $D\overline{D}$ threshold. Thus, as argued in Ref. [4], even if the $\psi$ interaction with comovers is negligible, the $\psi'$ can be easily broken up by secondary scatterings. The $\psi'/\psi$ ratios are shown in Fig. 3. To reproduce the magnitude of the observed suppression, $\sigma_{\psi'co} \approx 21-26$ mb. The larger cross section is needed for absorption and comovers with $\sigma_{\psi N} = 4.8$ mb, the
Figure 3: The $\psi'/\psi$ ratio is given in S+U (a) and Pb+Pb (b) interactions. The solid curve shows $\sigma_{\psi N} = \sigma_{\psi' N} = 4.8$ mb, $\sigma_{\psi co} = 3.2$ mb, $\sigma_{\psi' co} = 25$ mb and $n_{co} = 0.4$/fm$^3$. Similar results are found with $\sigma_{\psi N} = \sigma_{\psi' N} = 7.3$ mb and $\sigma_{\psi' co} = 21$ mb. The horizontal line corresponds to no secondary interactions.

smaller value is needed when $\sigma_{\psi N} = 7.3$ mb. The flattening of $\psi'/\psi$ at large $E_T$ in S+U interactions corresponds to collisions with $b < R_S$, as also noted by Wong [5]. In light of these revised results, one can then ask what kind of QGP model could explain the $J/\psi$ suppression.

3 Plasma Screening?

We use the model of charmonium break-up due to color screening in combination with the finite formation time of the bound states ([32]) to obtain the properties of the charmonium states at break-up. At zero temperature, the charmonium states can be described by a nonrelativistic potential model,

$$V(r,0) = \sigma r - \frac{\alpha}{r},$$

(13)
where $r$ is the separation between the $c$ and $\bar{c}$. The potential is modified at finite temperatures by the screening mass $\mu(T)$,

$$V(r, T) = \frac{\sigma}{\mu(T)} (1 - e^{-\mu(T)r}) - \frac{\alpha}{r} e^{-\mu(T)r}.$$  \hspace{1cm} (14)

The range of the potential decreases with $\mu(T)$, making the binding less effective. For $\mu(T)$ above the critical value, $\mu_D$, the screening prevents the formation of the resonance at temperature $T_D$ where $\mu(T_D) = \mu_D$. The values are $\mu_D^\psi = 0.699$ GeV, $\mu_D^{\psi'} = 0.357$ GeV and $\mu_D^{\chi_c} = 0.342$ GeV [32].

If the screening mass is proportional to $gT$ [33],

$$\mu(T) = \sqrt{1 + n_f/6} g(T) T,$$  \hspace{1cm} (15)

where $g$ is the temperature-dependent running coupling constant,

$$g^2(T) = \frac{24\pi^2}{(33 - 2n_f) \ln[(19T_c/\Lambda_{\overline{MS}})(T/T_c)]}.$$  \hspace{1cm} (16)

In SU(3) gauge theory, $T_c/\Lambda_{\overline{MS}} = 1.78 \pm 0.03$ [22]. When $n_f = 3$ and $T_c = 150$ MeV, the charmonium states break up at $T_D^\psi = 413$ MeV, $T_D^{\psi'} = 191$ MeV, and $T_D^{\chi_c} = 182$ MeV.

Suppression is possible when the energy density is above both that needed to break up the bound state, $\epsilon > \epsilon_D$, and the critical energy density for plasma production, $\epsilon > \epsilon_c$. In an ideal gas, the energy density is proportional to the number of degrees of freedom in the plasma $\gamma_P$, $\epsilon \propto \gamma_P T^4$ When $n_f = 3$, $\gamma_P = 47.5$, and $T_c = 150$ MeV, $\epsilon_c \approx 1$ GeV/fm$^3$. The energy density at resonance break-up is then $\epsilon_D^{\chi_c} = 2.23$ GeV/fm$^3$ and $\epsilon_D^{\psi'} = 2.7$ GeV/fm$^3$. The $\psi$ itself cannot break up unless the initial temperature is much higher than expected at the SPS. In Fig. 4(a) we show $S(\epsilon)$ at $p_T \approx 0$. The step functions are the result if all the mesons disappear at the break-up density while the smooth curves show calculations with the finite size of the plasma taken into account [34]. At this value of $p_T$, the transverse area of the plasma is a very small effect. However, for finite $p_T$, the charmonium states are more likely to escape, increasing the survival probability of these states in the plasma.

Although $\epsilon$ is not directly observable, it is proportional to the average number of subcollisions per area in a nucleus-nucleus collision [4, 8, 29],

$$n(E_T) = \frac{\int d^2b d^2s T_A(s) T_B(|\vec{b} - \vec{s}|) [T_A(s) + T_B(|\vec{b} - \vec{s}|)] p(E_T; b)}{\int d^2b d^2s T_A(s) T_B(|\vec{b} - \vec{s}|) p(E_T; b)},$$  \hspace{1cm} (17)
as well as the path length, \( L(E_T) = n(E_T)/2\rho_0 \). (See [29] and references therein for a more detailed discussion of \( L \) and its relation to the transverse momentum dependence.) We use the same prescription as NA50 to calculate \( \epsilon \) for Pb+Pb collisions within the NA38 acceptance, \( \epsilon \approx 3\epsilon_N n(E_T)/\Delta\eta\tau_0 \). When the energy density is calculated this way, the break-up energy densities correspond to values of \( E_T \) approximately 15% lower than the apparent thresholds in the data [9], as shown in Fig. 4(b).

Even if the \( \psi \) itself is not suppressed directly, the contribution to the \( \psi \) yield from \( \chi_c \) and \( \psi' \) decays vanishes, resulting in an indirect \( \psi \) suppression. In Fig. 4(b) we show the \( \psi/DY \) ratio when the \( \sim 30\% \chi_c \) decay contribution [35] and \( \sim 12\% \psi' \) contribution are taken into account. Definite thresholds appear if the suppression is assumed to be total above \( \epsilon_{\chi_c} \) and \( \epsilon_{\psi'} \). However, when the gradual suppression due to the finite size of the plasma is included, the thresholds are smoothed out, resulting in the dashed line. The curves and data are normalized to 200 GeV, to change to 158 GeV, they should be multiplied by a factor of 1.25.

The \( \psi'/\psi \) ratio is shown in Fig. 4(c). In this case, if the suppression is assumed to be total, the \( \psi'/\psi \) ratio vanishes above \( \epsilon_{\psi'} \). The sharp threshold would also make an apparent sudden enhancement of the \( \psi'/\psi \) ratio, somewhat unexpected. An intriguing explanation of \( \psi' \) suppression, the excitation of \( \psi \) into \( \psi' \) via \( \psi\pi \rightarrow \psi'\pi \) near the chiral phase transition has recently appeared [36]. This could explain why the suppression is not total even if all the initially produced \( \psi \)’s disappear.

Models which include a phase transition [5, 8] have already been suggested to describe the Pb+Pb data. In these models, above a certain critical energy density, QGP formation further suppresses the \( J/\psi \) or \( \chi_c \) and \( J/\psi \) [4]. A nonlinear increase of multiple gluon scattering has also been introduced [37] although no \( E_T \) dependence has been calculated. These models do not suggest any threshold effect due plasma production.

4 Summary

There now seems to be a general consensus that comover interactions cannot explain the effects seen by the NA50 collaboration in Pb+Pb interactions [4]. Indeed, the new results from NA50 are an intriguing and surprising indication of apparently total \( \chi_c \) and \( \psi' \) suppression. Since finite-size effects
of the plasma are expected to be important, the results are even more striking.

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Figure 4: The survival probability as a function of $\epsilon$ is shown in (a) for the $\psi'$ (dashed) and $\chi_c$ (dot-dashed). The suppression pattern with plasma production included are shown in (b) for the $\psi$/DY ratios and in (c) for the $\psi'/\psi$ ratios. The solid curves show the results assuming total suppression at $\epsilon_D$ in the comover model, $\sigma_{\psi N} = \sigma_{\psi' N} = 4.8$ mb, $\sigma_{\psi co} = 3.2$ mb, $\sigma_{\psi' co} = 25$ mb and $n_{co} = 0.4$/fm$^3$ while the dot-dashed curves show the same calculations with $\sigma_{\psi N} = \sigma_{\psi' N} = 7.3$ mb, $\sigma_{\psi co} = 21$ mb and $n_{co} = 0.4$/fm$^3$. The dashed curve shows the comover result with the spatial dependence of the suppression included.