Charmonium Suppression in Nuclear Collisions

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Measurements of $\psi$ and $\psi'$ production from experiment NA50 at the CERN SPS are compared to calculations based on a hadronic model of charmonium suppression developed previously. Data on centrality dependence and total cross sections are in good accord with these predictions. Uncertainties in theoretical quantities such as NA50’s $L$ parameter are discussed.

1. Introduction

Has the quark gluon plasma been discovered at the CERN SPS? Experiment NA50 has reported an abrupt decrease in $\psi$ production in Pb+Pb collisions at 158 GeV per nucleon [1]. Specifically, the collaboration presented a striking ‘threshold effect’ in the $\psi$–to–continuum ratio by plotting it as a function of a calculated quantity, the mean path length of the $\psi$ through the nuclear medium, $L$, as shown in fig. 1a. This apparent threshold has sparked considerable excitement as it may signal deconfinement in the heavy Pb+Pb system [2].

In this talk I report on work with Ramona Vogt in ref. [3] comparing Pb results to predictions [4, 5] using a hadronic model of charmonium suppression. We first demonstrate that the behavior in the NA50 plot, fig. 1a, is not a threshold effect but, rather, reflects the approach to the geometrical limit of $L$ as the collisions become increasingly central. When plotted as a function of the measured neutral transverse energy $E_T$ as in fig. 1b, the data varies smoothly as in S+U measurements in fig. 3b below [1, 6, 7, 8, 9]. The difference between S+U and Pb+Pb data lies strictly in the relative magnitude. To assess this magnitude, we compare $\psi$ and $\psi'$ data to expectations based on the hadronic comover model [4, 5]. The curves in fig. 1 represent our calculations using parameters fixed earlier in Ref. [5]. Our result is essentially the same as the Pb+Pb prediction in [3].

Our primary intention is to demonstrate that there is no evidence for a strong discontinuity between $pA$, S+U and Pb+Pb data. However, to quote Maurice Goldhaber, “… absence of evidence is not evidence of absence.” Our secondary goal is to show that our model predictions agree with the new Pb+Pb data. The consistency of these predictions is evident from the agreement of our old $pA$ and S+U calculations with more recent NA38 and NA51 data. Nevertheless, the significance

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of this result must be weighted by the fact that all pA and AB data are preliminary and at different beam energies.

In this work, we do not attempt to show that our comover interpretation of the data is unambiguous – this is certainly impossible at present.

2. Nucleons and Comovers

The hadronic contribution to charmonium suppression arises from scattering of the nascent $\psi$ with produced particles – the comovers – and nucleons [4, 5]. To determine the suppression from nucleon absorption of the $\psi$, we calculate the probability that a $c\bar{c}$ pair produced at a point $(b, z)$ in a nucleus survives scattering with nucleons to form a $\psi$. The standard result is

$$S_A = \exp\{-\int_{-\infty}^{z} dz \rho_A(b, z)\sigma_{\psi N}\}$$

(1)

where $\rho_A$ is the nuclear density, $b$ the impact parameter and $\sigma_{\psi N}$ the absorption cross section for $\psi$–nucleon interactions. One can estimate $S_A \sim \exp\{-\sigma_{\psi N} \rho_0 L_A\}$, where $L_A$ is the path length traversed by the $c\bar{c}$ pair.

Suppression can also be caused by scattering with mesons that happen to travel along with the $c\bar{c}$ pair (see refs. in [4]). The density of such comovers scales roughly as $E_T$. The corresponding survival probability is

$$S_{co} = \exp\{-\int d\tau n\sigma_{co}v_{rel}\},$$

(2)
where \( n \) is the comover density and \( \tau \) is the time in the \( \psi \) rest frame. We write \( S_{\text{co}} \sim \exp\{-\beta E_T\} \), where \( \beta \) depends on the scattering frequency, the formation time of the comovers and the transverse size of the central region, \( R_T \), cf. eq. (8).

To understand the saturation of the Pb data with \( L \) in fig. 1a, we apply the schematic approximation of Ref. [10] for the moment to write

\[
\frac{\sigma^{AB}(E_T)}{\sigma^{AB}_{\mu^+\mu^-}(E_T)} \propto \langle S_A S_B S_{\text{co}} \rangle \sim e^{-\sigma_{\psi N} L e^{-\beta E_T}},
\]

where the brackets imply an average over the collision geometry for fixed \( E_T \) and \( \sigma(E_T) \equiv \frac{d\sigma}{dE_T} \). The path length \( L \equiv \langle L_A + L_B \rangle \) and transverse size \( R_T \) depend on the collision geometry. The path length grows with \( E_T \), asymptotically approaching the geometric limit \( R_A + R_B \). Explicit calculations show that nucleon absorption begins to saturate for \( b < R_A \), where \( R_A \) is the smaller of the two nuclei, see fig. 4 below. On the other hand, \( E_T \) continues to grow for \( b < R_A \) due, e.g., to fluctuations in the number of \( NN \) collisions. Equation (2) falls exponentially in this regime because \( \beta \), like \( L \), saturates.

In fig. 1b, we compare the Pb data to calculations of the \( \psi \)–to–continuum ratio that incorporate nucleon and comover scattering. The contribution due to nucleon absorption indeed levels off for small values of \( b \), as expected from eq. (3). Comover scattering accounts for the remaining suppression.

These results are predictions obtained using the computer code of Ref. [4] with parameters determined in Ref. [5]. However, to confront the present NA50 analysis [1], we account for changes in the experimental coverage as follows:

- Calculate the continuum dimuon yield in the new mass range \( 2.9 < M < 4.5 \) GeV.
- Adjust the \( E_T \) scale to the pseudorapidity acceptance of the NA50 calorimeter, \( 1.1 < \eta < 2.3 \).

The agreement in fig. 1 depends on these updates.

3. \( J/\psi \) Suppression

We now review the details of our calculations, highlighting the adjustments as we go. For collisions at a fixed \( b \), the \( \psi \)–production cross section is

\[
\sigma_{\psi}^{AB}(b) = \sigma_{\psi}^{NN} \int d^2s dz \rho_A(s,z) \rho_B(b-s,z') S,
\]

where \( S \equiv S_A S_B S_{\text{co}} \) is the product of the survival probabilities in the projectile \( A \), target \( B \) and comover matter. The continuum cross section is

\[
\sigma_{\mu^+\mu^-}^{AB}(b) = \sigma_{\mu^+\mu^-}^{NN} \int d^2s dz \rho_A(s,z) \rho_B(b-s,z').
\]

The magnitude of (4,5) and their ratio are fixed by the elementary cross sections \( \sigma_{\psi}^{NN} \) and \( \sigma_{\mu^+\mu^-}^{NN} \). We calculate \( \sigma_{\psi}^{NN} \) using the phenomenologically–successful color evaporation model [4]. The continuum in the mass range used by NA50, \( 2.9 <\)
\[ M < 4.5 \text{ GeV}, \] is described by the Drell–Yan process. To confront NA50 and NA38 data in the appropriate kinematic regime, we compute these cross sections at leading order following [11, 12] using GRV LO parton distributions with a charm \( K \)-factor \( K_c = 2.7 \) and a color evaporation coefficient \( F_\psi = 2.54\% \) and a Drell–Yan \( K \)-factor \( K_{DY} = 2.4 \). Observe that these choices were fixed by fitting \( pp \) data at all available energies [13]. Computing \( \sigma^{NN}_{\mu^+\mu^-} \) for \( 2.9 < M < 4.5 \text{ GeV} \) corresponds to the first update.

To obtain \( E_T \) dependent cross sections from eqs. (4) and (5), we write

\[ \sigma^{AB}(E_T) = \int d^2b \, P(E_T, b) \sigma^{AB}(b). \] (6)

The probability \( P(E_T, b) \) that a collision at impact parameter \( b \) produces transverse energy \( E_T \) is related to the minimum–bias distribution by

\[ \sigma_{\min}(E_T) = \int d^2b \, P(E_T, b). \] (7)

We parametrize \( P(E_T, b) = C \exp\{-(E_T - \overline{E}_T)^2/2\Delta^2\} \), where \( \overline{E}_T(b) = \epsilon N(b) \), \( \Delta(b) = \omega \overline{E}_T(b) \), \( C(b) = (2\pi\Delta(b))^{-1} \) and \( N(b) \) is the number of participants (see, e.g., Ref. [4]). We take \( \epsilon \) and \( \omega \) to be phenomenological calorimeter–dependent constants.

We compare the minimum bias distributions for total hadronic \( E_T \) calculated using eq. (7) for \( \epsilon = 1.3 \) GeV and \( \omega = 2.0 \) to NA35 \( S+S \) and NA49 \( Pb+Pb \) data [13]. The agreement in fig. 2a builds our confidence that eq. (7) applies to the heavy \( Pb+Pb \) system. Figure 2b shows the distribution of neutral transverse energy calculated using eqs. (5) and (6) to simulate the NA50 dimuon trigger. We take \( \epsilon = 0.35 \) GeV, \( \omega = 3.2 \), and \( \sigma^{NN}_{\mu^+\mu^-} \approx 37.2 \) pb as appropriate for the dimuon–mass range \( 2.9 < M < 4.5 \text{ GeV} \). The \( E_T \) distribution for \( S+U \rightarrow \mu^+\mu^- + X \) from NA38 was described [3] using \( \epsilon = 0.64 \) GeV and \( \omega = 3.2 \) – the change in \( \epsilon \) corresponds roughly to the shift in particle production when the pseudorapidity coverage is changed from \( 1.7 < \eta < 4.1 \) (NA38) to \( 1.1 < \eta < 2.3 \) (NA50).

Taking \( \epsilon = 0.35 \) GeV for the NA50 acceptance is the second update listed earlier. We now apply eqs. (1,2,4) and (5) to charmonium suppression in \( Pb+Pb \) collisions. To determine nucleon absorption, we used \( pA \) data to fix \( \sigma_{\psi N} \approx 4.8 \) mb in Ref. [5]. This choice is in accord with the latest NA38 and NA51 \( pA \) data, see fig. 3a. To specify comover scattering [3], we assumed that the dominant contribution to \( \psi \) dissociation comes from exothermic hadronic reactions such as \( \rho + \psi \rightarrow D + \overline{T} \). We further took the comovers to evolve from a formation time \( \tau_0 \sim 2 \text{ fm} \) to a freezeout time \( \tau_F \sim R_T/v_{\text{rel}} \) following Bjorken scaling, where \( v_{\text{rel}} \sim 0.6 \) is roughly the average \( \psi - \rho \) relative velocity. The survival probability, eq. (2), is then

\[ S_{co} = \exp\{-\sigma_{co} v_{\text{rel}} n_0 \tau_0 \ln(R_T/v_{\text{rel}} \tau_0)\} \] (8)

where \( \sigma_{co} \approx 2\sigma_{\psi N}/3 \), \( R_T \approx R_A \) and \( n_0 \) is the initial density of sufficiently massive \( \rho, \omega \) and \( \eta \) mesons. To account for the variation of density with \( E_T \), we take \( n_0 = \pi_0 E_T/E_T(0) \) [4]. A value \( \pi_0 = 0.8 \text{ fm}^{-3} \) was chosen to fit the central \( S+U \) datum. Since we fix the density in central collisions, this simple \textit{ansatz} for \( S_{co} \) may be
Figure 2: Transverse energy distributions from eq. (7). The S–Pb comparison (a) employs the same parameters.

inaccurate for peripheral collisions. [Densities \( \sim 1 \text{ fm}^{-3} \) typically arise in hadronic models of ion collisions, e.g., refs. [15]. The internal consistency of hadronic models at such densities demands further study.]

We expect the comover contribution to the suppression to increase in Pb+Pb relative to S+U for central collisions because both the initial density and lifetime of the system can increase. To be conservative, we assumed that Pb and S beams achieve the same mean initial density. Even so, the lifetime of the system essentially doubles in Pb+Pb because \( R_T \sim R_A \) increases to 6.6 fm from 3.6 fm in S+U. The increase in the comover contribution evident in comparing figs. 1b and 3b is described by the seemingly innocuous logarithm in eq. (8), which increases by \( \approx 60\% \) in the larger Pb system.

In Ref. [5], we pointed out that comovers were necessary to explain S+U data from the NA38 1991 run [13]. Data just released [1] from their 1992 run support this conclusion. The ’91 \( \psi \) data were presented as a ratio to the dimuon continuum in the low mass range \( 1.7 < M < 2.7 \text{ GeV} \), where charm decays are an important source of dileptons. On the other hand, the ’92 \( \psi \) data [1, 2] are given as ratios to the Drell–Yan cross section in the range \( 1.5 < M < 5.0 \text{ GeV} \). That cross section is extracted from the continuum by fixing the \( K \)–factor in the high mass region [14]. To compare our result from Ref. [5] to these data, we scale the ’92 data by an empirical factor. This factor is \( \approx 10\% \) larger than our calculated factor \( \sigma_{DY}^{NA50}(92)/\sigma_{cont.}^{NA49}(91) \approx 0.4 \); these values agree within the NA38 systematic errors. [NA50 similarly scaled the ’92 data to the high–mass continuum to produce fig. 1a.] Because our fit is driven by the highest \( E_T \) datum, we see from fig. 3b that a fit to the ’92 data would not appreciably change our result. Note that a uniform decrease of the ratio would
increase the comover contribution needed to explain S+U collisions.

NA50 and NA38 have also measured the total ψ-production cross section in Pb+Pb and S+U reactions. To compare to that data, we integrate eqs. (4, 6) to obtain the total \((\sigma/AB)_{\psi} = 0.95 \text{ nb in S+U at 200 GeV and } 0.54 \text{ nb for Pb+Pb at 158 GeV in the NA50 spectrometer acceptance, } 0.4 > x_F > 0 \text{ and } -0.5 < \cos \theta < 0.5 \) (to correct to the full angular range and \( 1 > x_F > 0 \), multiply these cross sections by \( \approx 2.07 \)). The experimental results in this range are \( 1.03 \pm 0.04 \pm 0.10 \) nb for S+U collisions and \( 0.44 \pm 0.005 \pm 0.032 \) nb for Pb+Pb reactions. Interestingly, in the Pb system we find a Drell–Yan cross section \((\sigma/AB)_{DY} = 37.2 \) pb while NA50 finds \((\sigma/AB)_{DY} = 32.8 \pm 0.9 \pm 2.3 \) pb. Both the ψ and Drell–Yan cross sections in Pb+Pb collisions are somewhat above the data, suggesting that the calculated rates at the NN level may be \( \sim 20-30\% \) too large at 158 GeV. This discrepancy is within ambiguities in current pp data near that low energy. Moreover, nuclear effects on the parton densities omitted in eqs. (4,5) can affect the total S and Pb cross sections at this level.

We remark that if one were to neglect comovers and take \( \sigma_{\psi N} = 6.2 \) mb, one would find \((\sigma/AB)_{\psi} = 1.03 \) nb in S+U at 200 GeV and 0.62 nb for Pb+Pb at 158 GeV. The agreement with S+U data is possible because comovers only contribute to the total cross section at the \( \sim 18\% \) level in the light system. This is expected, since the impact–parameter integrated cross section is dominated by large \( b \) and the distinction between central and peripheral interactions is more striking for the asymmetric S+U system. As in Ref. [5], the need for comovers is evident
4. Saturation and the Definition of $L$

To see why saturation occurs in Pb+Pb collisions but not in S+U, we compare the NA50 $L(E_T)$ [1] to the average impact parameter $\langle b \rangle (E_T)$ in fig. 4. To best understand fig. 1a, we show the values of $L(E_T)$ computed by NA50 for this figure. We use our model to compute $\langle b \rangle = \langle b_{T_{AB}} \rangle / \langle T_{AB} \rangle$, where $\langle f(b) \rangle \equiv \int d^2b P(E_T, b) f(b)$ and $T_{AB} = \int d^2s dz' \rho_A(s, z) \rho_B(b - s, z')$. [Note that NA50 reports similar values of $\langle b \rangle (E_T)$ [1].] In the $E_T$ range covered by the S experiments, we see that $\langle b \rangle$ is near $\sim R_S = 3.6$ fm or larger. In this range, increasing $b$ dramatically reduces the collision volume and, consequently, $L$. In contrast, in Pb+Pb collisions $\langle b \rangle \ll R_{Pb} = 6.6$ fm for all but the lowest $E_T$ bin, so that $L$ does not vary appreciably.

To understand the sensitivity of fig. 1a to the definition of the path length, we now estimate $L(E_T)$ [16]. We identify (3) with the exact expression formed from the ratio of (4) and (5). Expanding in $\sigma_{\psi N}$ and neglecting comovers, we find:

$$L(E_T) = \left\{2 \rho_0(T_{AB})\right\}^{-1} \left\{ \int d^2s \left[ T_A(s)^2 T_B(b - s) + [T_B(b - s)]^2 T_A(s) \right] \right\},$$

(9)

where $T_A(s) = \int \rho_A(s, z)dz$. In fig. 5 we compare the NA50 $L(E_T)$ to the path length calculated using two assumptions for the nuclear density profile: our realistic three-parameter Fermi distribution and the sharp-surface approximation $\rho = \rho_0 \Theta(R_A - r)$. NA38 [17] obtained $L$ for S+U using the empirical prescription of ref. [10], while NA50 calculated $L$ assuming the sharp-surface approximation [18].
Figure 5: NA50 $L(E_T)$ [1] (points) compared to calculations for realistic nuclear densities (solid), as used here, and for a sharp–surface approximation (dot-dashed).

Figure 6: NA50 data replotted with a realistic $L(E_T)$ from (9).
Indeed, we see that the NA50 Pb+Pb values agree with our sharp–surface result, while the NA38 S+U values are nearer to the realistic distribution.

To see how the value of the path length can affect the appearance of fig. 1a, we replot in fig. 6 the NA50 data using $L(E_T)$ from (9) with the realistic density. We learn that the appearance of fig. 1a is very sensitive to the definition of $L$.

Furthermore, with a realistic $L$, one no longer gets the impression given by the NA50 figure [1] of Pb+Pb data “departing from a universal curve.” Nevertheless, the saturation phenomena evident in fig. 1a does not vanish. Saturation is a real effect of geometry.

5. $\psi'$ Suppression

To apply eqs. (4-6) to calculate the $\psi'$–to–$\psi$ ratio as a function of $E_T$, we must specify $\sigma_{\psi'N}^N$, $\sigma_{\psi'N}$, and $\sigma_{\psi'co}$. Following Ref. [1], we use $pp$ data to fix $B_0\sigma_{\psi'N}^N / B_0\sigma_{\psi'N} = 0.02$ (this determines $F_{\psi'}$). The value of $\sigma_{\psi'N}$ depends on whether the nascent $\psi'$ is a color singlet hadron or color octet as it traverses the nucleus. In the singlet case, one expects the absorption cross sections to scale with the square of the charmonium radius. Taking this ansatz and assuming that the $\psi'$ forms directly while radiative $\chi$ decays account for 40% of $\psi$ production, one expects $\sigma_{\psi'} \approx 2.1\sigma_\psi$ for interactions with either nucleons or comovers [3]. For the octet case, we take $\sigma_{\psi'N} \approx \sigma_{\psi'N}$ and fix $\sigma_{\psi'co} \approx 12$ mb to fit the S+U data. In fig. 7a, we show that the singlet and octet extrapolations describe $pA$ data equally well.

Our predictions for Pb+Pb collisions are shown in fig. 8. In the octet model, the entire suppression of the $\psi'$–to–$\psi$ ratio is due to comover interactions. In view of the schematic nature of our approximation to $S_{co}$ in eq. (8), we regard the agreement with data of singlet and octet extrapolations as equivalent.
6. Summary

In summary, the Pb data [1] cannot be described by nucleon absorption alone. This is seen in the NA50 plot, fig. 1a, and confirmed by our results. The saturation with $L$ but not $E_T$ suggests an additional density–dependent suppression mechanism. Earlier studies pointed out that additional suppression was already needed to describe the S+U results [2]; recent data [2] support that conclusion (see, however, [3]). Comover scattering explains the additional suppression. Nevertheless, it is unlikely that this explanation is unique. SPS inverse-kinematics experiments ($B < A$) and AGS $pA$ studies near the $\psi$ threshold can help pin down model uncertainties.

After the completion of [3], several cascade calculations [15] have essentially confirmed our conclusions. This confirmation is important, because such calculations do not employ the simplifications (e.g. $n_0 \propto E_T$) needed to derive (8). In particular, these models calculate $E_T$ and the comover density consistently. Some of these authors took $\sigma_{\psi N} \sim 6 \text{ mb}$ (instead of $\sim 5 \text{ mb}$) to fit the NA51 data in fig. 3a somewhat better.

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References

1. M. Gonin et al. (NA50), Proc. Quark Matter ’96, Heidelberg, Germany, P. Braun-Munzinger et al., eds. (1996).
2. J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. Lett. 77 (1996) 1703; D. Kharzeev, hep-ph/9609260 (1996).
3. S. Gavin and R. Vogt, LBL-37980 (1996), hep-ph/9606460.
4. S. Gavin and R. Vogt, Nucl. Phys. B345 (1990) 104.
5. S. Gavin, H. Satz, R. L. Thews, and R. Vogt, Z. Phys. C61 (1994) 351; S. Gavin, Nucl. Phys. A566 (1994) 383c.
6. O. Drapier et al. (NA38) Nucl. Phys. A544 (1992) 209c.
7. C. Baglin et al. (NA38) Phys. Lett. B270 (1991) 105.
8. C. Baglin et al. (NA38) Phys. Lett. B345 (1995) 617; S. Ramos et al. Nucl. Phys. A590 (1995) 117c.
9. C. Lourenco (NA38/NA50), Europhysics Conf. on High Energy Physics - EPS-HEP, Brussels (1995).
10. C. Gerschel and J. H"ufner, Z. Phys. C56 (1992) 171.
11. R. Gavai et al., Int. J. Mod. Phys. A10 (1995) 3043.
12. S. Gavin et al., Int. J. Mod. Phys. A10 (1995) 2961.
13. S. Margetis et al. (NA49), Phys. Rev. Lett. 75 (1995) 3814.
14. M. C. Abreu et al., Nucl. Phys. A566 (1994) 77c.
15. W. Cassing and C. M. Ko, nucl-th/9609023 (1996); D. Kahana, S. H. Kahana and Y. Pang, in progress; L. Gerland et al., in progress.
16. S. Gavin and R. Vogt, in progress.
17. A. Borhani, NA38, Ph. D. Thesis, l’Ecole Polytechnique (1996).
18. C. Gerschel, NA50, private communications.