

Charmonium Suppression by Comover Scattering in Pb + Pb Collisions

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The first reports of ψ and ψ' production from experiment NA50 at the CERN Super Proton Synchrotron 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. [S0031-9007(97)02336-3]

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Experiment NA50 has reported an abrupt decrease in ψ production in Pb + Pb collisions at 158 GeV per nucleon [1]. Specifically, the collaboration presented a striking “threshold effect” in the ψ -to-continuum ratio by plotting it as a function of a calculated quantity, the mean path length of the ψ through the nuclear medium, L , as shown in Fig. 1(a). This apparent threshold has sparked considerable excitement as it may signal the formation of quark-gluon plasma in the heavy Pb + Pb system [2].

Our aim is to study the Pb results in the context of a hadronic model of charmonium suppression [3,4]. We first demonstrate that the behavior in the NA50 plot, Fig. 1(a), 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. 1(b), the data vary smoothly as in S + U measurements in Fig. 3(b) below [1,5–8]. The difference between S + U and Pb + Pb data lies strictly in the relative magnitude. To assess this magnitude, we compare ψ and ψ' data to expectations based on the hadronic comover model [3,4]. The curves in Fig. 1 represent our calculations using parameters fixed earlier in Ref. [4]. Our result is essentially the same as the Pb + Pb prediction in [3].

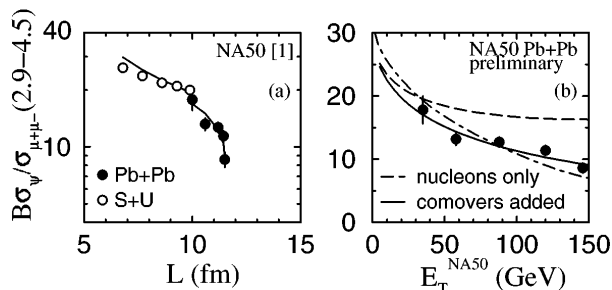


FIG. 1. (a) The NA50 [1] comparison of ψ production in Pb + Pb and S + U collisions as a function of the average path length L ; see Eq. (3). B is the $\psi \rightarrow \mu^+ \mu^-$ branching ratio. (b) Transverse energy dependence of Pb + Pb data. Curves in (a) and (b) are computed using Eqs. (4)–(6). Dot-dashed curve shows sensitivity to comover E_T and b dependence.

The hadronic contribution to the suppression arises from scattering of the nascent ψ with produced particles—the comovers—and nucleons [3,4]. To determine the suppression from nucleon absorption of the ψ , 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 ψ . The standard [4,9] result is

$$S_A = \exp\left\{-\int_z^\infty dz \rho_A(b, z) \sigma_{\psi N}\right\}, \quad (1)$$

where ρ_A is the nuclear density, b the impact parameter, and $\sigma_{\psi N}$ the absorption cross section for ψ -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 references in [3]). The density of such comovers scales roughly as E_T . The corresponding survival probability is

$$S_{co} = \exp\left\{-\int d\tau n \sigma_{co} v_{rel}\right\}, \quad (2)$$

where n is the comover density and τ is the time in the ψ rest frame. We write $S_{co} \sim \exp\{-\beta E_T\}$, where β 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. 1(a), we apply the schematic approximation of Ref. [9] for the moment to write

$$\frac{\sigma_{\psi}^{AB}(E_T)}{\sigma_{\mu^+\mu^-}^{AB}(E_T)} \propto \langle S_A S_B S_{co} \rangle \sim e^{-\sigma_{\psi N} \rho_0 L} e^{-\beta E_T}, \quad (3)$$

where the brackets imply an average over the collision geometry for fixed E_T and $\sigma(E_T) \equiv d\sigma/dE_T$. 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 β , like L , saturates.

In Fig. 1(b), we compare the Pb data to calculations of the ψ -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. [3] with parameters determined in Ref. [4]. However, to confront the present NA50 analysis [1], we account for changes in the experimental coverage as follows:

- (i) Calculate the continuum dimuon yield in the new mass range $2.9 < M < 4.5$ GeV.
- (ii) 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.

We now review the details of our calculations, highlighting the adjustments as we go. For collisions at a fixed b , the ψ -production cross section is

$$\sigma_{\psi}^{AB}(b) = \sigma_{\psi}^{NN} \int d^2s dz dz' \rho_A(s, z) \rho_B(b - s, z') S, \quad (4)$$

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

$$\sigma_{\mu^+\mu^-}^{AB}(b) = \sigma_{\mu^+\mu^-}^{NN} \int d^2s dz dz' \rho_A(s, z) \rho_B(b - s, z'). \quad (5)$$

The magnitude of (4) and (5) and their ratio are fixed by the elementary cross sections σ_{ψ}^{NN} and $\sigma_{\mu^+\mu^-}^{NN}$. We calculate σ_{ψ}^{NN} using the phenomenologically successful color evaporation model [10]. The continuum in the mass range used by NA50, $2.9 < M < 4.5$ 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 [10,11] 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 [10]. Computing $\sigma_{\mu^+\mu^-}^{NN}$ for $2.9 < M < 4.5$ GeV corresponds to the first update.

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

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

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

$$\sigma_{\text{min}}(E_T) = \int d^2b P(E_T, b). \quad (7)$$

We parametrize $P(E_T, b) = C \exp\{-(E_T - \bar{E}_T)^2/2\Delta\}$, where $\bar{E}_T(b) = \epsilon \mathcal{N}(b)$, $\Delta(b) = \omega \epsilon \bar{E}_T(b)$, $C(b) = [2\pi\Delta(b)]^{-1}$, and $\mathcal{N}(b)$ is the number of participants (see, e.g., Ref. [3]). We take ϵ and ω 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 [12]. The agreement in Fig. 2(a) builds our confidence that Eq. (7) applies to the heavy Pb + Pb system.

Figure 2(b) 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 $\sigma_{\mu^+\mu^-}^{NN} \approx 37.2$ pb as appropriate for the dimuon-mass range $2.9 < M < 4.5$ GeV. The E_T distribution for $S + U \rightarrow \mu^+\mu^- + X$ from NA38 was described [4] using $\epsilon = 0.64$ GeV and $\omega = 3.2$ —the change in ϵ 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. [4]. This choice is in accord with the latest NA38 and NA51 pA data; see Fig. 3(a). The survival probability for comover scattering, Eq. (2), is

$$S_{\text{co}} = \exp\{-\sigma_{\text{co}} v_{\text{rel}} n_0 \tau_0 \ln(\tau_F/\tau_0)\}, \quad (8)$$

where $\sigma_{\text{co}} \approx 2\sigma_{\psi N}/3$ and n_0 is the initial density of sufficiently massive ρ , ω , and η mesons; we take $\tau_0 \sim 2$ fm, $\tau_F \sim R_T/v_{\text{rel}}$, and $v_{\text{rel}} \sim 0.6$ as in [3]. To account for the variation of density with E_T , we take $n_0 = \bar{n}_0 E_T/\bar{E}_T(0)$ for the solid curves in Figs. 1(b) and 3(b) [3]. A value $\bar{n}_0 = 0.8 \text{ fm}^{-3}$ was chosen to fit the central $S + U$ datum. To test the sensitivity to this ansatz, we employ an alternative equally schematic ansatz in which the number of comovers scales with E_T but the volume scales with the transverse area of the overlap region as a function of b ; see the dot-dashed curves. Both ansätze may be inaccurate for peripheral collisions.

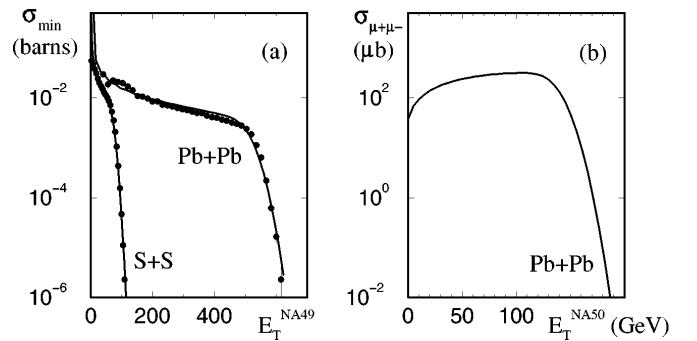


FIG. 2. Transverse energy distributions from Eq. (7). The S-Pb comparison (a) employs the same parameters.

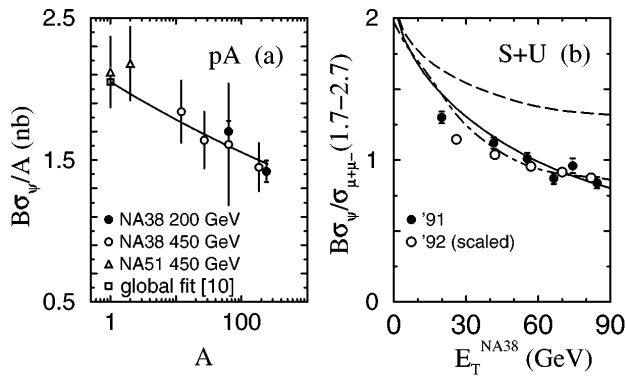


FIG. 3. (a) pA cross sections [1] in the NA50 acceptance and (b) $S + U$ ratios from 1991 [6] and 1992 [1] runs. The 1992 data are scaled to the 1991 continuum. The dashed line indicates the suppression from nucleons alone. The pp cross section in (a) is constrained by the global fit to pp data in Ref. [10]. Dot-dashed curve shows sensitivity to comover E_T and b dependence.

(Densities $\sim 1 \text{ fm}^{-3}$ typically arise in hadronic models of ion collisions, e.g., Refs. [13]. 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. 1(b) and 3(b) is described by the seemingly innocuous logarithm in Eq. (8), which increases by $\approx 60\%$ in the larger Pb system.

In Ref. [4], we pointed out that comovers were necessary to explain $S + U$ data from the NA38 1991 run [5]. Data just released [1] from their 1992 run support this conclusion. The 1991 ψ 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 1992 ψ data [1,8] 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. [4] to these data, we scale the 1992 data by an empirical factor. This factor is $\approx 10\%$ larger than our calculated factor $\sigma_{DY}^{NN}(92)/\sigma_{cont}^{NN}(91) \approx 0.4$; these values agree within the NA38 systematic errors. [NA50 similarly scaled the 1992 data to the high-mass continuum to produce Fig. 1(a).] Because our fit is driven by the highest E_T datum, we see from Fig. 3(b) that a fit to the 1992 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.

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. 1(a), 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 $T_{AB} = \int d^2s dz dz' \rho_A(s, z) \rho_B(b - s, z')$. [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 $\sim R_S = 3.6 \text{ fm}$ or larger. In this range, increasing b dramatically reduces the collision volume and, consequently, L . In contrast, in $Pb + Pb$ collisions $\langle b \rangle \ll R_{Pb} = 6.6 \text{ fm}$ for all but the lowest E_T bin, so that L does not vary appreciably.

NA50 and NA38 have also measured the total ψ -production cross section in $Pb + Pb$ [1] and $S + U$ reactions [6]. To compare to that data, we integrate Eqs. (4) and (6) to obtain the total $(\sigma/AB)_\psi = 0.95 \text{ nb}$ in $S + U$ at 200 GeV and 0.54 nb for $Pb + Pb$ at 158 GeV in the NA50 spectrometer acceptance, $0.4 > x_F > 0$ and $-0.5 < \cos \theta < 0.5$ (to correct to the full angular range and $1 > x_F > 0$, multiply these cross sections by ≈ 2.07). The experimental results in this range are $1.03 \pm 0.04 \pm 0.10 \text{ nb}$ for $S + U$ collisions [5] and $0.44 \pm 0.005 \pm 0.032 \text{ nb}$ for $Pb + Pb$ reactions [1]. Interestingly, in the Pb system we find a Drell-Yan cross section $(\sigma/AB)_{DY} = 37.2 \text{ pb}$ while NA50 finds $(\sigma/AB)_{DY} = 32.8 \pm 0.9 \pm 2.3 \text{ pb}$. 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 [10].

We remark that if one were to neglect comovers and take $\sigma_{\psi N} = 6.2 \text{ mb}$, one would find $(\sigma/AB)_\psi = 1.03 \text{ nb}$ 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

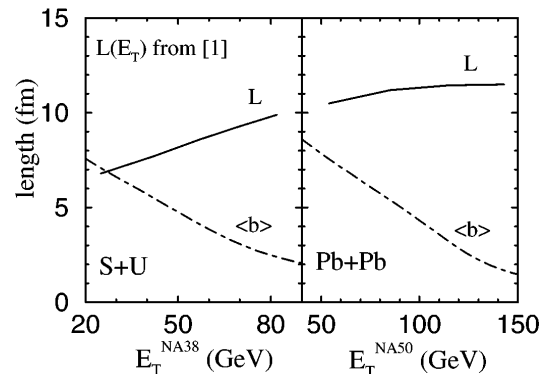


FIG. 4. E_T dependence of L (solid line) used by NA50 [1] [see Fig. 1(a)] and the average impact parameter $\langle b \rangle$ (dot-dashed line). The solid line covers the measured E_T range.

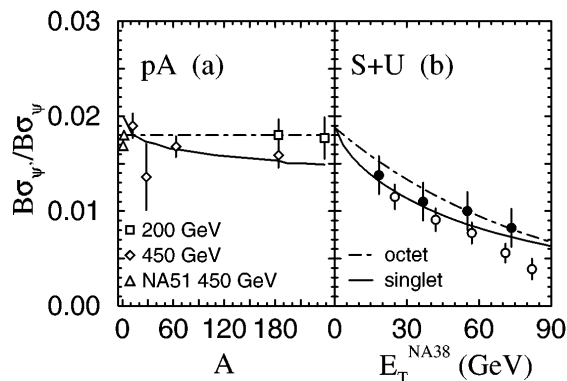


FIG. 5. Comover suppression of ψ' compared to (a) NA38 and NA51 pA data [1,8] and (b) NA38 $S + U$ data [7] (filled points) and preliminary data [1].

dominated by large b and the distinction between central and peripheral interactions is more striking for the asymmetric $S + U$ system. As in Ref. [4], the need for comovers is evident for the E_T -dependent ratios, where central collisions are singled out.

To apply Eqs. (4)–(6) to calculate the ψ' -to- ψ ratio as a function of E_T , we must specify $\sigma_{\psi'N}^{NN}$, $\sigma_{\psi'N}$, and $\sigma_{\psi'co}$. Following Ref. [10], we use pp data to fix $B\sigma_{\psi'}^{NN}/B\sigma_{\psi}^{NN} = 0.02$ (this determines $F_{\psi'}$). The value of $\sigma_{\psi'N}$ depends on whether the nascent ψ' is a color singlet hadron or color octet $c\bar{c}$ 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 ψ' forms directly while radiative χ decays account for 40% of ψ production, one expects $\sigma_{\psi'} \sim 2.1\sigma_{\psi}$ for interactions with either nucleons or comovers [4]. 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. 5(a), we show that the singlet and octet extrapolations describe pA data equally well.

Our predictions for $Pb + Pb$ collisions are shown in Fig. 6. In the octet model, the entire suppression of the ψ' -to- ψ 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.

In summary, the Pb data [1] cannot be described by nucleon absorption alone. This is seen in the NA50 plot, Fig. 1(a), 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 [4]; recent data [1] support that conclusion (see, however, [2]). Comover

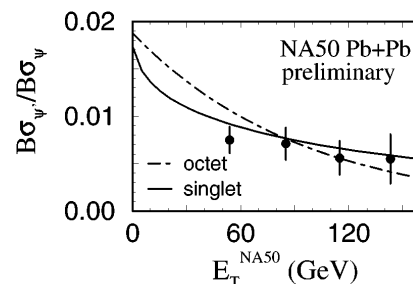


FIG. 6. Comover suppression in $Pb + Pb \rightarrow \psi' + X$.

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 ψ threshold can help pin down model uncertainties.

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Note added.—After completing this manuscript, we learned of cascade calculations [13] that confirm our conclusions. Such calculations do not employ the simplifications (e.g., $n_0 \propto E_T$) needed to derive (8). Some of these authors took $\sigma_{\psi N} \sim 6$ mb (instead of ~ 5 mb) to fit the NA51 data in Fig. 3(a) somewhat better.

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