Charmonium Suppression

(*Sean Gavin and Ina Sarcevic*)

Charmonium suppression remains among the most exciting and tantalizing problems in relativistic heavy ion physics. At the Quark Matter '96 meeting, CERN Collaboration NA50 reported the first measurement of ψ and ψ' production in Pb+Pb collisions. Controversy developed as many asked if the data signaled quark gluon plasma formation [1]. At the meeting, Gavin and Vogt showed that the data agreed with predictions based on their comover model of charmonium suppression in nuclear collisions [2]. However, at the Quark Matter '97 meeting, NA50 reported results from a much more extensive data set. While the overall trend of this data is consistent with the '96 data, the new data may show one or perhaps two abrupt changes in the suppression. While data is as yet preliminary, even one such feature would be inconsistent with a model in which comovers are treated as hadrons.

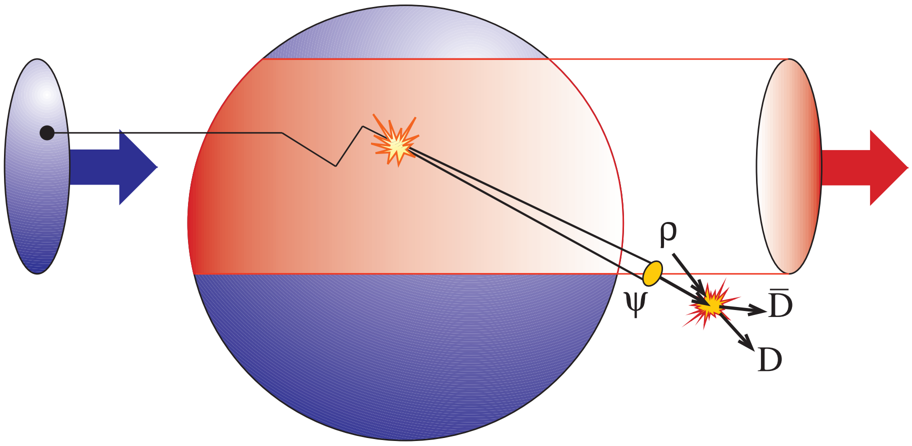

Figure 1: Conventional wisdom on charmonium suppression is summarized in this figure. The charm-anticharm pair is produced in a hard process as the projectile nucleus crashes through the target. Before that process, initial state scattering can occur broadening transverse momentum and possibly leading to energy loss. After formation, the pair can scatter in the nucleus or with comovers.

Charmonium production provides a probe of the densities achieved in nucleus–nucleus collisions that is also sensitive to quark gluon plasma production. However, Gavin, Gyulassy, and Jackson [7] were the first to point out that scattering with hadronic comovers can explain data with light nuclear projectiles, $A < 32$. We know know that the plasma suppression occurs amid a host of background effects: initial state parton scattering, nucleon absorption, comover scattering, and nuclear dependence of the parton distributions (shadowing and EMC effects). Careful systematic studies of hadron–nucleus, hA, and nucleus–nucleus, AA, data are needed to distinguish these effects. Using with the latest hA and AA data on ψ and ψ' production from CERN, the comover model implies that Pb+Pb collisions achieve densities greater than ten times that of ordinary nuclear matter – if we ignore the discontinuities. Conventional nucleon–absorption alone cannot consistently describe the Pb data, constituting evidence of an additional high–density suppression mechanism such as scattering with co–moving mesons.

Agreement with Pb data would support our hadronic explanation, but would not rule out a contribution from plasma formation. The possible appearance of discontinuous behavior is exciting. Nevertheless, it is worthwhile to look for other systematic discrepancies with hadronic models. In [6] we predict the transverse momentum dependence of charmonium and Drell–Yan dimuon production. Deviations from these predictions, if any, can reveal plasma contributions to the suppression. However, we expect this contribution to be small at the low SPS energy, ~ 20 GeV per nucleon in the center of mass. More likely, the answer to the fundamental question — what gave rise to the suppression — awaits the completion of RHIC at 200 GeV per nucleon.

The hadronic contribution to the suppression arises from scattering of the nascent ψ with produced particles – the comovers – and nucleons [9, 10]. 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 [10] result is

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

where ρ_A is the nuclear density, b the impact parameter and $\sigma_{\psi N}$ the absorption cross section for ψ–nucleon interactions. Suppression can also be caused by scattering with mesons that happen to travel along with the $c\bar{c}$ pair (see refs. in [9]). The corresponding survival probability is

$$S_{\rm co} = \exp\{-\int d\tau n\, \sigma_{\rm co} v_{\rm rel}\}, \tag{2}$$

where n is the comover density and τ is the time in the ψ rest frame.

For collisions at a fixed b, the ψ–production cross section is

$$\sigma_\psi^{AB}(b) = \sigma_\psi^{NN} \int d^2s dz dz'\, \rho_A(s,z)\rho_B(b-s,z')\, S, \tag{3}$$

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

$$\sigma_{\mu^+\mu^-}^{AB}(b) = \sigma_{\mu^+\mu^-}^{NN} \int d^2s dz dz'\, \rho_A(s,z)\rho_B(b-s,z'). \tag{4}$$

We calculate σ_ψ^{NN} using the phenomenologically–successful color evaporation model [11]. 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 [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 [11].

To obtain E_T dependent cross sections, we write

$$\sigma^{AB}(E_T) = \int d^2b\, P(E_T, b)\sigma^{AB}(b). \tag{5}$$

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

$$\sigma_{\min}(E_T) = \int d^2b \, P(E_T, b). \tag{6}$$

We parametrize $P(E_T, b) = C \exp\{-(E_T - \overline{E}_T)^2/2\Delta\}$, where $\overline{E}_T(b) = \epsilon\mathcal{N}(b)$, $\Delta(b) = \omega\epsilon\overline{E}_T(b)$, $C(b) = (2\pi\Delta(b))^{-1}$ and $\mathcal{N}(b)$ is the number of participants (see, *e.g.*, Ref. [9]). We take ϵ and ω to be phenomenological calorimeter–dependent constants.

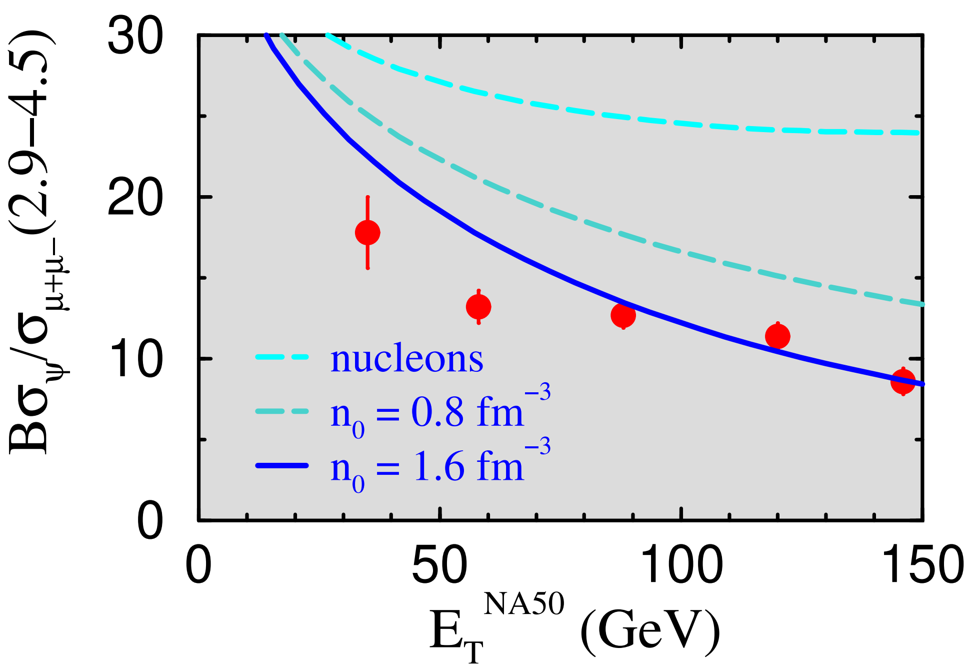

Figure 2: Suppression in Pb+Pb after changing normalization [5] and doubling the density. Data is from QM '96.

We now calculate 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. [10]. This choice is in accord with the latest NA38 and NA51 pA data. A value of $\sigma_{\psi N} \approx 7.2$ mb yields better agreement with peripheral data in both S+U and Pb+Pb. The survival probability for comover scattering is

$$S_{\rm co} = \exp\{-\sigma_{\rm co} v_{\rm rel} n_0 \tau_0 \ln(\tau_F/\tau_0)\} \tag{7}$$

where $\sigma_{\rm co} \approx 2\sigma_{\psi N}/3$ and n_0 is the initial density of sufficiently massive ρ, ω and η mesons; we take $\tau_0 \sim 2$ fm, $\tau_F \sim R_T/v_{\rm rel}$ and $v_{\rm rel} \sim 0.6$ as in [9].

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 in [2] that Pb and S beams achieve the *same* mean initial density. With the information then in hand, we found agreement with data. However, Vogt has recently computed the Drell Yan cross section at NNLO in QCD, incorporating detailed knowledge of the NA50 muon acceptance [5]. She now finds results that fall above the data for the S+U density[2]. To bring the comover model into agreement, we must increase the value of $\beta = \sigma_{\rm co} v_{\rm rel} n_0 \tau_0 \ln(\tau_F/\tau_0)$ by a factor of two in Pb+Pb relative to S+U. We can achieve this by one or all of the following:

- Increase the initial comover density. A value of n_0 for Pb+Pb that is the same as S+U is in fact too small to explain NA49 Pb+Pb data.
- Increase the fraction of resonances to prompt pions in the hadron gas. One would expect the ρ abundance to increase due to $\pi\pi$ scattering in the comover gas.
- Increase the system lifetime τ_F to a value larger than R/v to allow for collective transverse flow.

Any combination of these adjustments that increases β by a factor of two would bring the model into better agreement. I show the effect of varying β in the figure below.

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Interpreting SPS and RHIC J/ψ Experiments

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Much detailed work is needed to understand the very precise new data reported by NA50 and to make high-quality predictions for RHIC. It is sobering to observe that all of the analyses [1, 2, 4, 3] are based on work in ref. [5], a paper that is seven years old. We have learned a lot about heavy ion collisions since then.

There is currently a dispute over whether or not one can tune parameters to obtain further agreement [1, 2]. We find the agreement with peripheral data can be improved compared to the accompanying figure (and also for S+U) by using a value $\sigma_{\psi N} = 7.2$ mb following ref. [4]. For these parameters, however, we would have to take the comover density to be zero in S+U and over 1 fm^{-3} in Pb+Pb. This is unreasonable in the context of hadronic comovers. However, there are many nuclear effects mandated by pA, eA, and AB data that are omitted in current models [3, 4]. These features are:

1. Nuclear parton-distribution effects, such as shadowing, EMC and fermi smearing. These effects vary with impact parameter and, consequently transverse energy, and can be different for gluon and quark distributions (see, *e.g.*, Huang, Lu and Sarcevic in this proposal).

2. Baryon stopping, measured at CERN but ignored by Glauber approximations, can add to the suppression. Slow baryons contribute to comover suppression with a low threshold via $\rho N \to \overline{D}\Lambda_c$.

3. Transverse flow of the comover fluid.

4. Different absorption of color-singlet and color-octet $c\overline{c}$ pairs.

5. Elastic scattering of the J/ψ by pions at energies below the threshold for $\pi\psi \to D\overline{D}$.

6. Chemical reactions such as $\rho\psi \to \chi\pi$.

7. Quantum effects in J/ψ formation from the $c\overline{c}$ boundstate.

8. Charm contribution to the continuum, which complicates the fitting procedure used by NA50 to extract the "Drell Yan" cross section.

9. Puzzling behavior of CERES and NA50 dilepton data may indicate that there are additional affects of unknown origin that enhance the continuum below – and perhaps *underneath* – the J/ψ.

Any of these effects can alter the pattern of suppression at the $\sim 10\%$ level in AB collisions relative to pA. In sum, these effects could account for the rather minute discrepancies between calculations and data.

The more important question is how seriously one should take the rapid shift in transverse energy shown by the latest QM '97 data. If one interprets the abrupt change at $E_T = 50$ GeV, then there is no point in tuning a hadronic model. While we will be in a better position to assess the need for further work when details concerning the new data are published, it is interesting to consider the possibility that novel behavior has been seen.

We observe that a sharp discontinuity in transverse energy is difficult to understand on the basis of a bulk [6], local equilibrium phase transition in a system where finite-size effects are

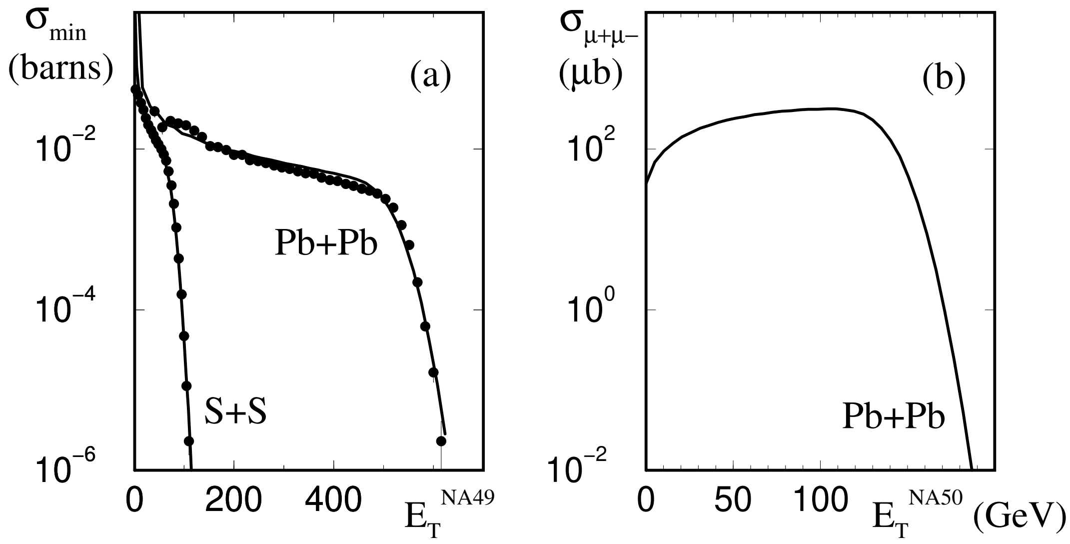

Figure 3: Where to look for plasma – comparison of transverse energy distributions for a) NA49 and b) NA50. NA50 sees a rapid drop in J/ψ production at $E_T \sim 50$ GeV.

appreciable. In addition to the obvious effect of dispersion in the relation between impact parameter and E_T, any post-transition effects tend to obscure the relationship between E_T and the local energy density within an inhomogeneous collision volume [7]. Perhaps a two dimensional dynamical percolation transition of color strings into flux tubes is a more plausible alternative [8], since the order parameter for such a transition is the number of strings per unit transverse area. This variable is more closely related to E_T than the energy density. Such a transition would have broad implications for many observables. For example, flux tube or 'color rope' formation has been proposed to account for the measured production of strange hyperons and anti-hyperons. The figure shows the relation between the E_T distributions for NA49, which measures hyperons, and NA50. We intend to estimate the change in other observables such as Strangeness and HBT that would accompany flux tube percolation [10].

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Perturbative Contribution to J/ψ Suppression

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J/ψ production is a complex process that begins with the hard production of a $c\bar{c}$ pair, predominantly through gluon fusion. Gluon fusion is a hard process, with momentum transfer $Q \sim M_\psi \sim 3$ GeV and can be described using perturbative QCD. The $c\bar{c}$ can then form a 3_1^S J/ψ bound state in two ways: a) if the $c\bar{c}$ is color singlet, it can form a P-wave χ meson, which can emit a photon and become a J/ψ, or b) if the $c\bar{c}$ is color octet, it can radiate gluons and become a J/ψ. Data at the SPS shows production through χ decay accounts for 30% of the production. In J/ψ *suppression*, much of the discussion has focused on the octet channel. There, most authors regard the $c\bar{c}$ as a strongly interacting object that can be absorbed in nucleon interactions with a cross section perhaps as large as 7 mb. However, the question of the singlet contribution has not been addressed.

In this work we use perturbative QCD to explore the production and absorption of the singlet channel for J/ψ in high-energy γA and pA collisions in the region of high x_F. This channel can be probed experimentally by measuring the associated photon from the $\chi \to \gamma + J/\psi$ decay. For photoproduction at high x_F, two nuclear effects are possible:

- Gluon shadowing of the target gluon distribution,
- Nucleon absorption of the J/ψ.

We apply the partonic picture developed by Huang, Lu and Sarcevic to estimate both of these effects. That shadowing is important at high x_F is well known — HLS simply gives us a model that can be used to calculate gluon shadowing. That absorption can have a role is a surprising consequence of the HLS picture, and violates the conventional wisdom CW [3, 2] for J/ψ suppression.

This work can also have implications for J/ψ suppression at SPS energy, where very precise new data for S+U and Pb+Pb collisions is soon to be published. Various authors confront these data with models that ignore shadowing and absorption of the color singlet component, because these effects are small. Some find discrepancies at the 30-40% level. Before one draws conclusions from such small discrepancies, one must have a very precise understanding of all contributions.

In the CW picture of J/ψ suppression [3, 2], the absorption of a high energy color singlet $c\bar{c}$ pair as it traverses the nucleus is taken to be negligible. The reason for this is that the pair is regarded as pointlike at the point of its creation, with a spatial extent on the order of $\sim 1/M_{c\bar{c}}$. In the rest frame of the pair, it then takes a time $\tau_F \sim 1$ fm for the pair to expand to the size of a χ meson. But in the nuclear frame, this formation time is dilated to

$\sim E\tau_F/M_{c\bar{c}}$, where E is the energy of the pair. A pair with energy $E \gg M_{c\bar{c}}R_A/\tau_F \sim 18$ GeV will barely have time to reach its bound state radius before it escapes a lead-sized nucleus of $R_A = 6$ fm. If we then follow CW and take the absorption cross section to scale as the classical geometrical size of the pair, then this cross section can be very small for high energy pairs.

To see how CW breaks down in the large x_F region, we use perturbative QCD to calculate the interaction of a nucleon with a $q\overline{q}$ pair of transverse separation r_t in the double logarithm approximation [7]:

$$\sigma_{q\overline{q}N} \propto r_t^2 \alpha_s x g_{DLA}(x, r_t^{-2}) \tag{8}$$

where g_{DLA} is the gluon distribution inside the nucleon for gluons of scale $Q \sim r_t^{-1}$ and momentum fraction x. Observe that for x_F large, the target x is small; E772 measured J/ψ production in 800 GeV pA for up to $x_F \sim 0.64$ and down to $x \sim 10^{-2}$ [8]. For large Q and moderate x, the cross section indeed vanishes roughly as $Q^{-2} \sim r_t^2$.

At small $x < 10^{-2}$ the nucleon structure function exhibits a strong scaling violation in the semihard region 0.9 GeV$< Q < 3$ GeV^2. In general, scaling violations cause the gluon density to grow $xg \propto (Q^2)^\gamma$ as Q increases for fixed x, where γ is the anomalous dimension. At small x, γ can exceed unity, so that the growth of the parton density can compensate the smallness of r_t^2. We write

$$\sigma_{q\overline{q}N} \propto r_t^{2(1-\gamma)}. \tag{9}$$

This effect has been used by Huang, Lu, and Sarcevic to describe shadowing. Here, we see that scaling violations can compensate for the smallness of the size of the $c\overline{c}$ pair.

Future plans: We intend to apply the lessons learned from this analysis to calculate the perturbative contribution to J/ψ suppression at RHIC and LHC energies. At high energies a substantial fraction of the $c\overline{c}$ interactions may occur at hard scales where we can apply perturbative QCD. The expected dominance of hard scales at high energies has driven attempts to apply parton cascade models to describe RHIC and LHC phenomenology. When the predominant interactions occur at the parton level, the picture of spacetime evolution differs strongly from that at SPS energy. It is not meaningful to distinguish between nucleon absorption and comover scattering – all interactions of the $c\overline{c}$ are essentially with comoving quarks and gluons produced as minijets, starting from a very early time $\tau_0 \sim 0.1$ fm. These interactions may then be calculated using perturbation theory. At RHIC and particularly LHC, typical midrapidity partons are formed from interactions at very small x. If we are phenomenologically successful in describing the high x_F region at FNAL, we will be able to apply our techniques to describe the major contributions to charmonium production and suppression at higher energies:

- Primary production of $c\overline{c}$ through hard scattering.
- Gluon shadowing of the target gluon distribution takes place.
- Secondary production of $c\overline{c}$ can now occur through semihard parton-parton scattering.
- Interactions of the $c\overline{c}$ with semihard comover partons can now be described using perturbative QCD.

We remark that the interactions of octet $c\overline{c}$ in the medium at high energies are also perturbative. Reactions with surrounding gluons can easily change octet pairs into singlet pairs without resolving the individual c and $\overline{c}$. We suspect that even for an octet pair, the gluon must resolve either the quark or antiquark to dissociate the pair. Therefore, the cross section for dissociation of an octet may also depend on size as above, albeit with a larger charge.

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