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Theoretical Status of J/ψ Suppression

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ABSTRACT

Evidence of high densities in nucleus-nucleus collisions is extracted by comparing hadron-nucleus and nucleus-nucleus measurements of J/ψ suppression.

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ABSTRACT

Evidence of high densities in nucleus-nucleus collisions is extracted by comparing hadron-nucleus and nucleus-nucleus measurements of J/ψ production.

High energy heavy ion collisions are expected to produce hadron densities far beyond the density in nuclei,[1] $\rho_0 = 0.16\,\text{fm}^{-3}$. Remarkably, no single measurement from the AGS and SPS light ion programs with projectiles $A \leq 32$ stands out as unambiguous evidence of these extreme densities.[2] To separate the high density signals from the background effects that result, *e.g.* from scattering with primary nucleons, careful systematic studies of hadron-nucleus, hA, and nucleus-nucleus, AB, data are needed.

In this talk I survey the ongoing systematic study of the most notorious case in point — J/ψ suppression. In principle, measurements of J/ψ suppression provide a probe of the densities obtained in AB collisions that is also sensitive to quark gluon plasma production.[3] The latest results from SPS experiment NA38 reported by A. Romana in these proceedings show that the ratio of cross sections in the dimuon channel $B_{\mu\mu}\sigma_\psi/\sigma_{\rm cont}$ is reduced by a factor 0.50 ± 0.05 in central S+U compared to minimum bias pU collisions at 200 AGeV.[4,5] This is precisely the sort of suppression that one expects if high densities are obtained. On the other hand, a target-mass dependence suggestive of this suppression is found in hA collisions[6,7] where high densities are not expected. At 200 GeV, NA38 finds that $B_{\mu\mu}\sigma_\psi/\sigma_{\rm cont}$ falls to 0.84 ± 0.08 in pU compared to pCu. The hA suppression in this kinematic regime is likely due to a combination of nuclear effects:[8,9] nucleon absorption[10–12] and shadowing.[13,14]

To interpret the AB data as evidence of high densities, one must determine the contribution of these nuclear effects. Following a brief discussion of the NA38 results, I consider the nucleon absorption contribution to J/ψ suppression in detail. Satz, Thews, Vogt and myself have estimated the maximum contribution of nucleon absorption to J/ψ suppression in AB. In a comparative study of pA and AB data, we have demonstrated that nucleon absorption alone cannot account for all of the measured suppression. Next, I list other nuclear effects that can influence J/ψ production, and consider the case for high density matter at the SPS. For other reviews that treat different aspects of J/ψ suppression, see Refs. 15 and 16.

NA38 measures J/ψ production in the rapidity range $2.8 < y < 4$ via its decay to $\mu^+\mu^-$ pairs. These pairs appear as a resonance peak at $M_{\mu^+\mu^-} \approx 3.1$ GeV above a continuum largely due to the Drell Yan process. In addition, there is an experimental background of false coincidences from semileptonic π, K and D decays that can, in principle, be subtracted by measuring $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs. Fischer and Geist have pointed out that a substantial fraction of the $\mu^+\mu^-$ continuum comes from the simultaneous semileptonic decay of $D\overline{D}$ pairs.[17,18]

To gauge the centrality of the event that produced the J/ψ, NA38 also operates a electromagnetic calorimeter. Transverse energy E_T is correlated with centrality because more energy is diverted from the beam in central than in peripheral collisions. The calorimeter covers the pseudorapidity range $1.7 < \eta < 4.1$, and measures the E_T of neutral hadrons with a small contamination from charged hadrons. NA38 now presents spectra as a functions of a neutral E_T^0 corrected for this charged contamination.

To exhibit the suppression effect in O+U and S+U collisions, NA38 presents the cross section ratio

$$\frac{B_{\mu\mu}\sigma_\psi}{\sigma_{\rm cont}} \equiv \frac{B_{\mu\mu}\left(d\sigma/dE_T^0\right)_\psi^{AB}}{\left(d\sigma/dE_T^0\right)_{\rm cont}^{AB}}, \tag{1}$$

where the $\mu^+\mu^-$ continuum cross section consists of pairs in the mass range $1.7 < M < 2.7$ GeV. While different choices of the continuum mass range and the E_T scale have been given in publications referenced in Ref. 4, the overall trend has consistently been that the J/ψ-to-continuum ratio is reduced in central collisions by roughly a factor of two. This effect is truly a suppression of the J/ψ rather than an enhancement of the continuum, since the E_T integrated continuum cross section[3] varies with the target mass as $A^{1.01\pm0.04}$.

Empirically,[6,7] the production of J/ψ in hA is known to increase with the target mass as A^α with $\alpha \sim 0.93$, in contrast to Drell Yan dilepton production, which grows as A. The traditional explanation of this suppression is nucleon absorption — a J/ψ can be dissociated by scattering with a nucleon as it traverses the target nucleus. The cross section for $\psi N \to D\overline{D} + X$ is essentially unknown, although scaling from other hadronic cross sections suggests that it is roughly $\sigma_{\psi N} \sim 4$ mb. Let me assume for the moment that the J/ψ hadron is formed instantaneously, so that it can interact with the hadronic cross section $\sigma_{\psi N}$ inside the target. I also take the nucleus to be undisturbed by the hA collision, so that its density is $\rho_A \approx \rho_0$. Following Ref. 12, I will start by investigating the phenomenological implications of these traditional approximations, and then consider how more realistic assumptions can modify the results.

In a high energy hA collision the probability of the J/ψ's survival is

$$S = \exp\left\{-\int dz\, \rho_A\left(z,\vec{b}\right)\sigma_{\psi N}\right\}, \tag{2}$$

where $\vec{b}$ is the impact parameter, z is the longitudinal distance, and ρ_A is the nuclear density. The standard expressions for the cross sections of J/ψ and continuum production are then

$$\sigma_\psi^{pA} = \sigma_\psi^{NN} \int d^2b dz \, \rho_A S \qquad \text{and} \qquad \sigma_{\rm cont}^{pA} = \sigma_{\rm cont}^{NN} A. \tag{3}$$

To draw quantitative conclusions from data one must numerically integrate σ_ψ^{pA} using Fermi density distributions. However, by taking the density $\rho_A \approx \rho_0 \equiv 3/4\pi r_0^3$ and the nuclear radius $R \approx r_0 A^{1/3}$, one can estimate $\sigma_{pA}/A \sim \exp\{-3\rho_0 R \sigma_{\psi N}/4\}$. The traditional power law $\sigma_{pA} \sim A^\alpha$ for $\alpha \sim 1-3\sigma_{\psi N}/4$ follows from the numerical coincidence $A^{1/3} \approx \log A$.

For AB collisions of a given impact parameter b, the differential cross section for J/ψ production is

$$\left(\frac{d\sigma}{d^2b}\right)_\psi^{AB} = \sigma_\psi^{NN} \int d^2s dz dz' \, \rho_A(s,z) \, \rho_B(b-s,z') \; S_A S_B, \tag{4}$$

where $S_{A,B}$ are the survival probabilities (2) for the target A and projectile B. The continuum cross section is

$$\left(\frac{d\sigma}{d^2b}\right)_{\rm cont}^{AB} = \sigma_{\rm cont}^{NN} \int d^2s dz dz' \, \rho_A(s,z) \, \rho_B(b-s,z'). \tag{5}$$

The E_T^0 dependent cross sections in (1) are then

$$\left(\frac{d\sigma}{dE_T^0}\right)_{\psi,\,{\rm cont}}^{AB} = \int d^2b \, P\left(E_T^0, b\right) \left(\frac{d\sigma}{d^2b}\right)_{\psi,\,{\rm cont}}^{AB}, \tag{6}$$

where $P(E_T^0, b)$ is the probability that an AB collision of impact parameter b produces transverse energy E_T^0 in NA38's acceptance from Refs. 8 and 9. To demonstrate that $P(E_T^0, b)$ describes the correlation between E_T and centrality correctly, we compare our calculations to the measured S-U continuum in Fig. 1.

Can nucleon absorption (3) and (4-6) describe the NA38 pA and AB data consistently for a choice of the parameters $\sigma_{\psi N}$ in S and the overall prefactor $\Re_{NN} \equiv B_{\mu\mu}\sigma_\psi^{NN}/\sigma_{\rm cont}^{NN}$? The answer is no! To demonstrate this disagreement, I fix the parameters using pA data and then extrapolate to AB. Comparing the A dependence of (3) to NA3 data for pPt and pp, one finds that $\sigma_{\psi N} = 4.8$ mb, a value close to expectations. Comparison to the NA38 pCu and pU data then implies $\Re_{NN} = 2.4$. Alternatively, a fit to NA38 data ignoring the high statistics NA3 results implies $\sigma_{\psi N} = 7$ mb and $\Re_{NN} = 2.8$. In Fig. 2, I show these pA fits along with the corresponding extrapolations to S+U. Observe that there is a 10% systematic uncertainty in comparing pA and AB ratios due to pion contamination of the proton beam.[4] Nucleon absorption does not describe the S+U data within

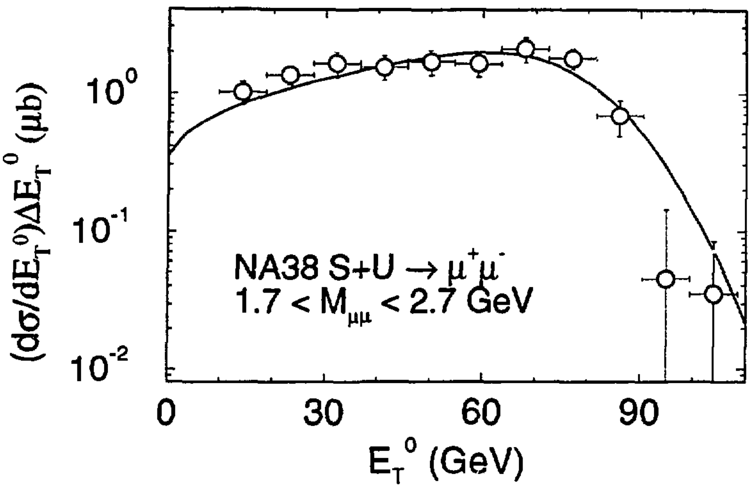

Figure 1: NA38 data for the continuum compared to (5,6) for $\sigma_{\rm cont}^{NN} = 1.6$ mb. Note that both data and calculations are scaled by the experimental bin width $\Delta E_T^0 = 9$ GeV.

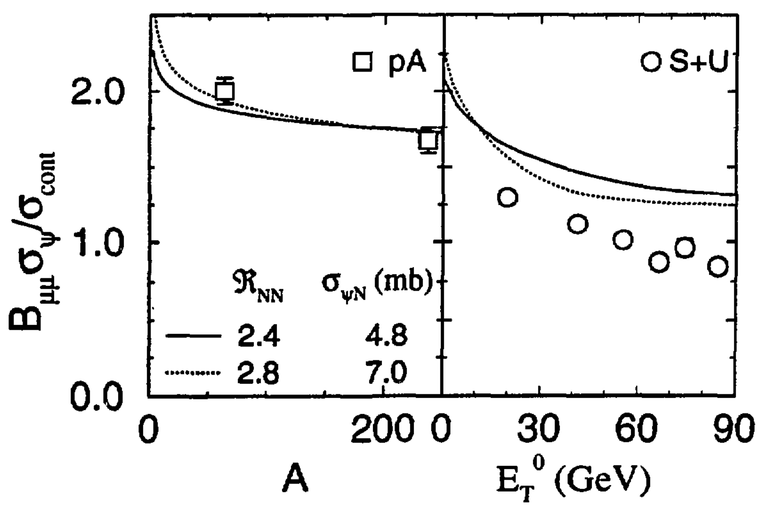

Figure 2: NA38 data for the ratio (1) compared to (3-6) for $\Re_{NN}$ taken from a *pA* fit. These $\Re_{NN}$ values agree with QCD estimates.

this uncertainty; O+U data are in similar disagreement. For completeness, one can also try to fix $\Re_{NN}$ using the O+U and S+U data. The results in Fig. 3 show similar disagreement.

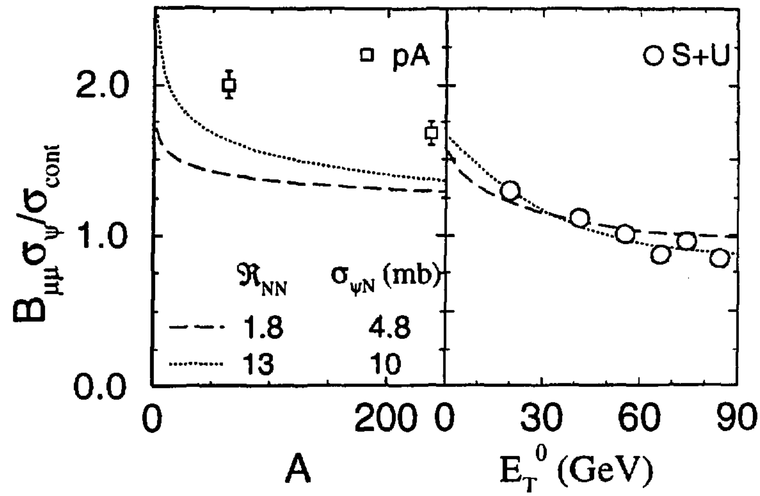

Figure 3: Same as above for $\Re_{NN}$ taken from a AB fit. Here, the $\Re_{NN}$ are at variance with QCD estimates.

Satz, Thews, Vogt and I argue[12] that the pA fit in Fig. 2 is the most physically relevant, *i.e.* that nucleon absorption *underestimates* the suppression in AB. Production cross sections $B_{\mu\mu}\sigma_\psi^{NN} = 4.9$ nb and $\sigma_{\rm cont}^{NN} = 1.8$ nb calculated following Refs. 19 and 17 respectively are in agreement with the $\Re_{NN} \sim 2.7$ extracted from pA data. Furthermore, Fig. 1 shows the measured continuum cross section in comparison with calculations using (2) and (3) for $\sigma_{\rm cont} = 1.8$ nb. The magnitude of the calculated cross section is in excellent agreement with data. Note that the highest measured E_T^0 bin in Fig. 2 corresponds to the top $\sim 5\%$ of the cross section in Fig. 1. Most collisions contributing to this bin have impact parameters $b < 3$, corresponding to a mean path length through the nucleus $3(R_S + R_U)/4 \sim 8$ fm. The authors of Ref. 10 describe S+U data using a simplified nucleon absorption model, but only by assuming an unphysical path length of ~ 12 fm.

Of course, the traditional estimates (3) and (4-6) are very naive. Projectile stopping modifies the spacetime evolution of the collision in the path integrations in (2-5). Formation effects in J/ψ production reduce the absorption cross section relative to the hadronic value $\sigma_{\psi N}$.

Stopping does not change the traditional estimates (3) and (4) if formation effects are neglected. The NN interactions that occur during a 200 GeV pU collision slow down the projectile, shifting its rapidity by $\Delta y \approx 2.5$ units. At the same time the $N_A \sim 5$ participant target nucleons are accelerated to about $\delta y \sim \Delta y/N_A$. A J/ψ of lab rapidity y_ψ therefore encounters target participants with density $\gamma\rho_0$ over a longitudinal distance R/γ, where $\gamma \equiv \cosh(y_\psi - \delta y)$. Nevertheless, the survival probability (2) is $S \equiv \exp\{-\int_0^{R/\gamma} \gamma\rho_0\sigma_{\psi N} dz\} = e^{-\sigma_{\psi N}\rho_0 R}$, which is the traditional result.

More important is the effect of the J/ψ's formation on nuclear absorption. When first produced in a hard interaction, the $c\bar{c}$ pair is small compared to the size of the J/ψ bound state, with a spatial extension of about $M_{\psi}^{-1} \simeq 0.06$ fm. The time needed for the pair to separate to its binding radius is roughly $\tau_{\psi} \sim 1.2$ fm (this estimate accounts for the fact that 40% of J/ψ come from $\chi_c \rightarrow J/\psi + \gamma$). Brodsky and Mueller[20] observed that the dissociation cross section for a color singlet $c\bar{c}$ pair is reduced relative to the hadronic cross section $\sigma_{\psi N}$, because the smaller pre-hadronic pair is harder to hit. To illustrate the associated reduction of absorption, one supposes[11] that the cross section of the growing $c\bar{c}$ increases geometrically,

$$\sigma(\tau) = \sigma_{\psi N} \left(\tau/\tau_{\psi}\right)^2,$$

for $\tau < \tau_{\psi}$; afterwards $\sigma(\tau) = \sigma_{\psi N}$.

The introduction of the J/ψ formation time reduces the amount of suppression relative to the traditional estimates (3) and (4), since $\sigma(\tau) \leq \sigma_{\psi N}$. Taking $\tau = z/\gamma\beta = z \sinh y_{\psi}$, I use (2) and (8) to find

$$S = \exp\{-\sigma_{\psi N} \rho_0 R \;\; (R/d_{\psi})^2 /3\} \leq \exp\{-\sigma_{\psi N} \rho_0 R\},$$

where the r.h.s. is the traditional result. The absorption is therefore reduced over the portion of the path $d_{\psi} \equiv \tau_{\psi} \sinh y_{\psi}$ covered while the $c\bar{c}$ is small. In the presence of stopping, the formation length $d_{\psi}(\delta y) \propto \sinh(y_{\psi} - \delta y)$ is reduced by the rapidity shift δy of the participants. One then finds

$$\sigma_{\psi N} \rho_0 R \;\; \{R/d_{\psi}\}^2/3 \leq \sigma_{\psi N} \rho_0 R \;\; \{R/d_{\psi}(\delta y)\}^2/3 \leq \sigma_{\psi N} \rho_0 R,$$

showing that the suppression is greatest in the conventional eikonal description and least in the case of a finite J/ψ formation time and no stopping.

There are two rather general consequences[12] of (10): First, in a typical pA experiment $R/\gamma\beta \gg \tau_{\psi}$, so that the nascent J/ψ is tiny as it crosses the nucleus. In the 800 GeV interactions studied by Fermilab's E772 a physical J/ψ at $\langle x_F \rangle \simeq 0.3$ appears 100 fm from the center of the target.[7] Therefore, nucleon absorption has very little to do with the measured "suppression" in pA. Second, since J/ψ formation effects always reduce absorption, the traditional approximation to (2) provides an ***upper bound*** on the possible suppression. Even this upper bound cannot account for the AB data.

If nuclear absorption alone cannot account for the systematics of J/ψ suppression, what can? There are many possibilities. Various *partonic* and *dense matter* effects certainly must contribute to J/ψ nuclear effects at some level. Partonic effects such as initial state scattering,[21–23] EMC/shadowing effects[13,14] and intrinsic charm[9] are important in understanding a range of hard processes in nuclei. Initial state scattering modifies J/ψ and Drell Yan transverse momentum distributions, but does not effect integrated quantities such as (1) (except possibly at high x_F, see Ref. 23). This effect explains the p_T dependence of J/ψ production.[16] EMC and the related shadowing effects are discussed by R. Gavai in these proceedings.

Recent work by Gupta and Satz show that shadowing may explain high x_F NA3 and E772 pA data, but cannot explain NA38 AB data.[13] Intrinsic charm may also be relevant at high x_F.[9] It is the current consensus of model builders that these parton effects also do not describe the AB data.

Dense matter effects such as comover scattering[20,8,9] and possibly plasma screening[3] are needed to describe the AB data. Comovers are produced particles that travel along with the J/ψ. Hadronic comovers - pions and resonances - can dissociate the J/ψ by reactions such as $\psi\pi \rightarrow D\overline{D}$. Earlier in the evolution of the AB system when the density is higher, partonic scattering processes like $g + (c\overline{c})_{\rm bound} \rightarrow c + \overline{c} + g$ can also play a role.

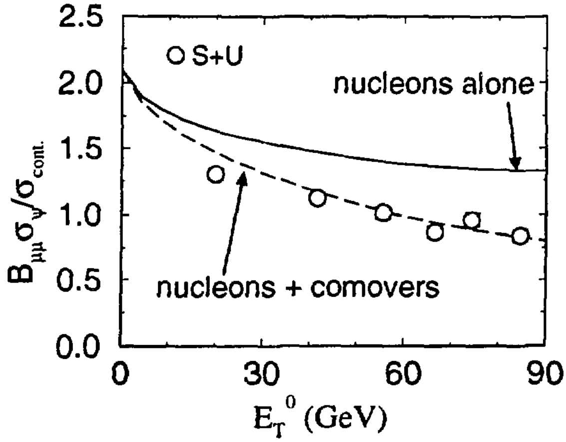

Figure 4: NA38 data for the continuum compared to (4-6) with comovers included.

To illustrate the role of these comovers, one can multiply the integrand in (4) by an additional comover survival probability.[12] I write $S \approx \exp\{-\int d\tau\, v_{\rm rel}\sigma_{\rm co} n\}$, where $\tau = z/v_{\rm rel}$ is the time in the J/ψ's rest frame and $v_{\rm rel} \sim 0.6$ is the average relative velocity between the J/ψ and the comovers. The cross section for dissociation by comovers is assumed to be $\sigma_{\rm co} \sim 2\sigma_{\psi N}/3$. Furthermore, the comover density varies as $n = n(\tau_0)\tau_0/\tau$ from the comover formation time, $\tau_0 = 2$ fm, until interactions effectively cease at $\tau_F \simeq R_A/v_{\rm rel}$. In Fig. 4 $n(\tau_0)$ is varied to fit the NA38 S+U data. A density $n(\tau_0) \sim 0.8$ fm^{-3} $\sim 5\rho_0$ gives reasonable agreement with both S+U and O+U data. These results agree with $n \sim 1$ fm^{-3}, found in earlier J/ψ analyses.[8,9] Densities of this magnitude are quite consistent with the assumption that comovers are hadrons.

I stress that the estimate of nucleon absorption in Fig. 4 is an upper bound, so the actual comover density may be higher. As an alternative extreme, one can assume following Gupta and Satz[13] that all of the suppression measured in pA is due to shadowing rather than absorption. My estimate of AB including their shadowing estimate together with comover scattering yields $n(\tau_0) \sim 1.6$ fm^{-3}. Reality is likely between these extremes.

In summary, I have surveyed the evidence of high densities in nuclear collisions at the SPS from J/ψ suppression. The traditional explanation of J/ψ suppression – nucleon absorption – cannot consistently account for the available J/ψ data from pA and AB collisions. Additional suppression is necessary, and a likely source is interactions with hadronic comovers at densities of perhaps five to ten times nuclear matter density.

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