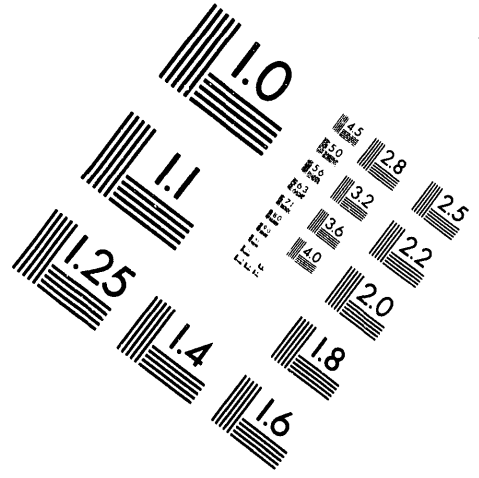
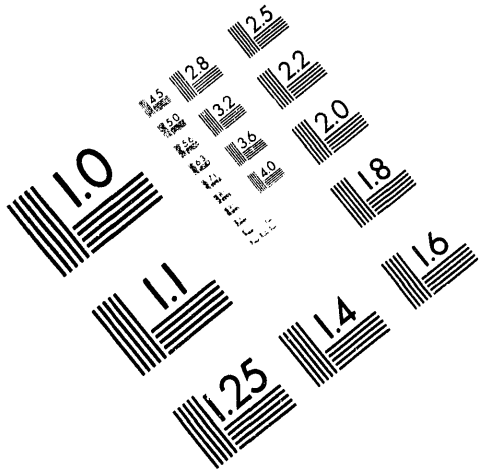




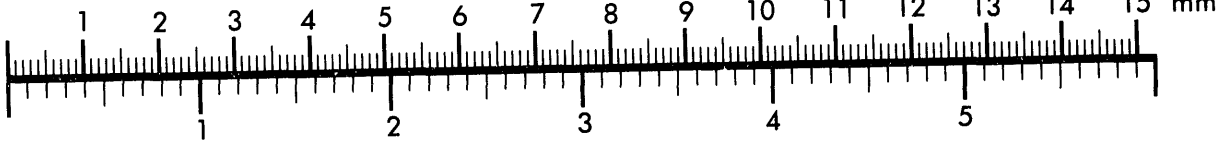
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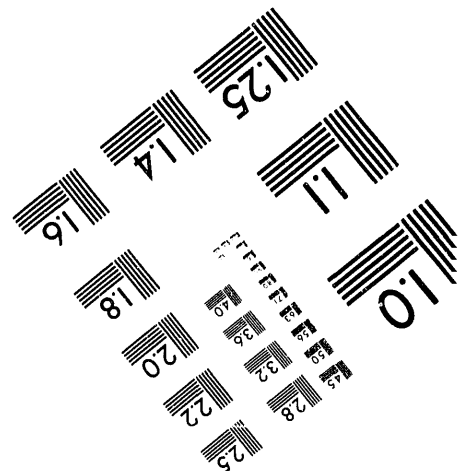
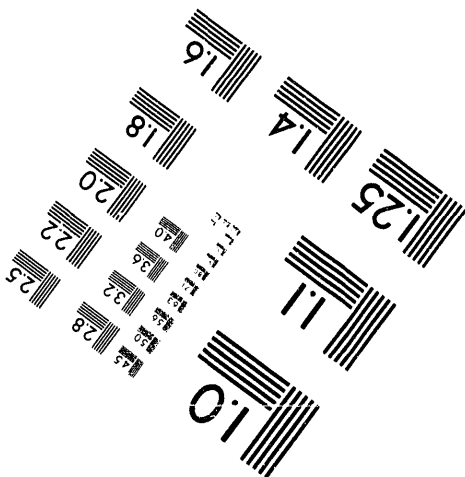
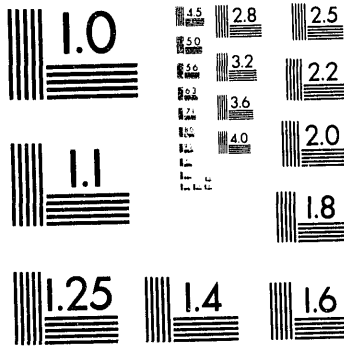
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Theoretical Status of J/ψ Suppression

Sean Gavin

Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

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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THEORETICAL STATUS OF J/ψ SUPPRESSION

SEAN GAVIN

Physics Department, Brookhaven National Laboratory
Upton, New York 11973, USA

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 $B_{\mu\mu\sigma_\psi}/\sigma_{\text{cont}}$ 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 $B_{\mu\mu\sigma_\psi}/\sigma_{\text{cont}}$ 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 absorption¹⁰⁻¹² 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 $D\bar{D}$ pairs.^{17,18}

To gauge the centrality of the event that produced the J/ψ , NA38 also operates an 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

$$\frac{B_{\mu\mu}\sigma_{\psi}}{\sigma_{\text{cont}}} \equiv \frac{B_{\mu\mu} (d\sigma/dE_T^0)_{\psi}^{AB}}{(d\sigma/dE_T^0)_{\text{cont}}^{AB}}, \quad (1)$$

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 section³ varies with the target mass as $A^{1.01 \pm 0.04}$.

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 $\psi N \rightarrow D\bar{D} + X$ 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

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

where \bar{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

$$\sigma_{\psi}^{pA} = \sigma_{\psi}^{NN} \int d^2b dz \rho_A S \quad \text{and} \quad \sigma_{\text{cont}}^{pA} = \sigma_{\text{cont}}^{NN} A. \quad (3)$$

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

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

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

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

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

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

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 $\mathfrak{R}_{NN} \equiv B_{\mu\mu} \sigma_{\psi}^{NN} / \sigma_{\text{cont}}^{NN}$? 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 $p\text{Pt}$ and pp , one finds that $\sigma_{\psi N} = 4.8$ mb, a value close to expectations. Comparison to the NA38 $p\text{Cu}$ and $p\text{U}$ data then implies $\mathfrak{R}_{NN} = 2.4$. Alternatively, a fit to NA38 data ignoring the high statistics NA3 results implies $\sigma_{\psi N} = 7$ mb and $\mathfrak{R}_{NN} = 2.8$. 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

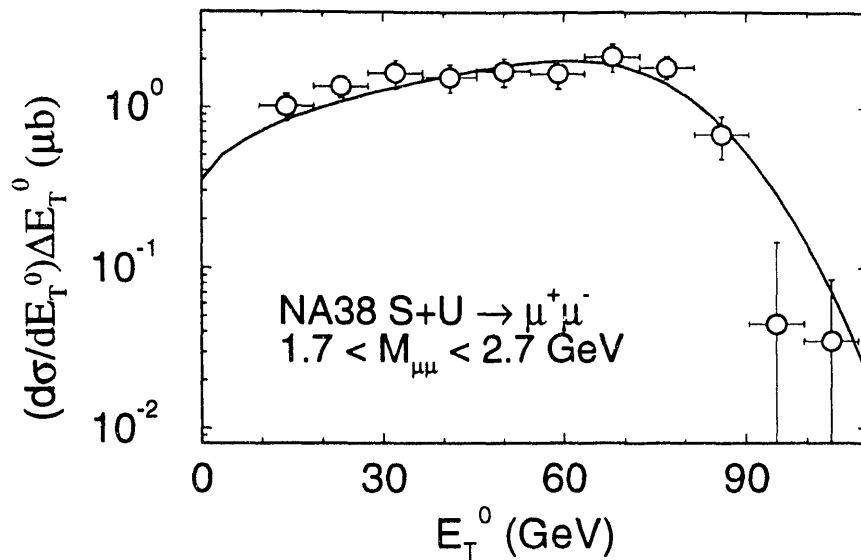


Figure 1: NA38 data for the continuum compared to (5,6) for $\sigma_{\text{cont}}^{NN} = 1.6$ mb. Note that both data and calculations are scaled by the experimental bin width $\Delta E_T^0 = 9$ GeV.

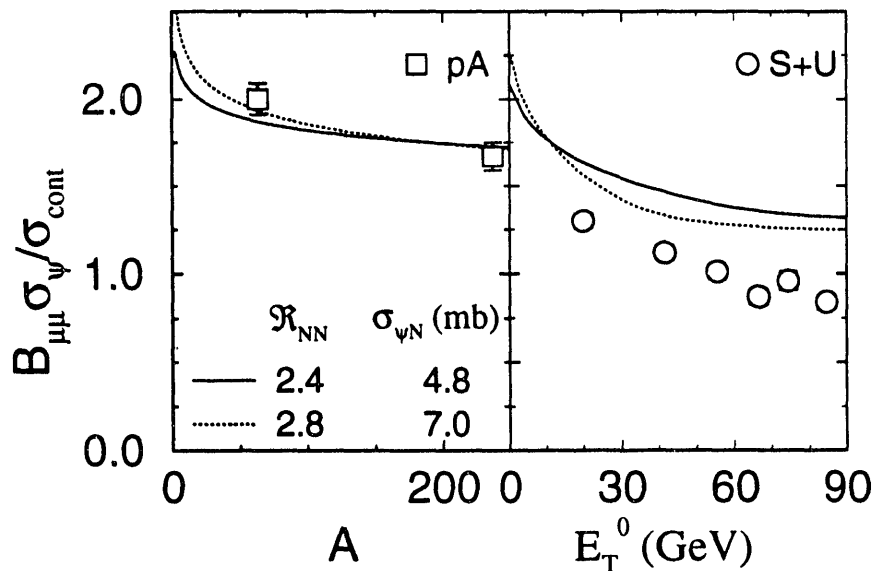


Figure 2: NA38 data for the ratio (1) compared to (3-6) for \mathcal{R}_{NN} taken from a pA fit. These \mathcal{R}_{NN} values agree with QCD estimates.

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

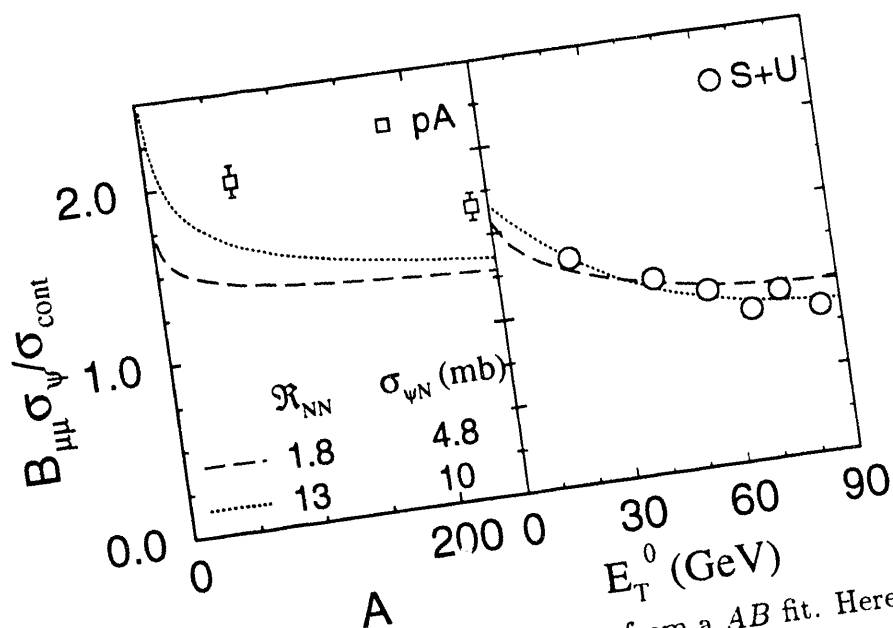


Figure 3: Same as above for \mathcal{R}_{NN} taken from a AB fit. Here, the \mathcal{R}_{NN} are at variance with QCD estimates.

Satz, Thews, Vogt and I argue¹² 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 $\sigma_{cont}^{NN} = 1.8$ nb calculated following Refs. 19 and 17 respectively are in agreement with the $\mathcal{R}_{NN} \sim 2.7$ extracted from pA data. Furthermore, Fig. 1 shows the measured continuum cross section in comparison with calculations using (2) and (3) for $\sigma_{cont} = 1.8$ 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 Mueller²⁰ 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 supposes¹¹ that the cross section of the growing $c\bar{c}$ increases geometrically,

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

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 consequences¹² 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 charm⁹ 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 screening³ 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 $\psi\pi \rightarrow D\bar{D}$. Earlier in the evolution of the AB system when the density is higher, partonic scattering processes like $g + (c\bar{c})_{\text{bound}} \rightarrow c + \bar{c} + g$ can also play a role.

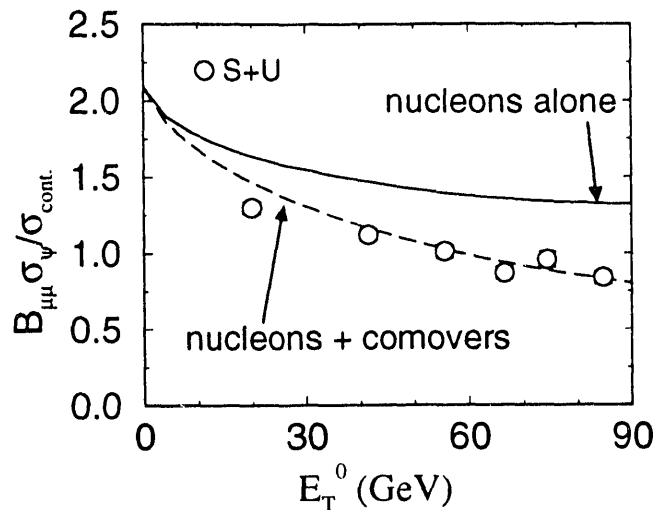


Figure 4: NA38 data for the continuum compared to (4-6) with comovers included.

To illustrate the role of these comovers, one can multiply the integrand in (4) by an additional comover survival probability.¹² I write $S \approx \exp \left\{ - \int d\tau v_{\text{rel}} \sigma_{\text{co}} n \right\}$, where $\tau = z/v_{\text{rel}}$ is the time in the J/ψ 's rest frame and $v_{\text{rel}} \sim 0.6$ is the average relative velocity between the J/ψ and the comovers. The cross section for dissociation by comovers is assumed to be $\sigma_{\text{co}} \sim 2\sigma_{\psi N}/3$. 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 $\tau_F \simeq R_A/v_{\text{rel}}$. In Fig. 4 $n(\tau_0)$ is varied to fit the NA38 S+U data. A density $n(\tau_0) \sim 0.8 \text{ fm}^{-3} \sim 5\rho_0$ gives reasonable agreement with both S+U and O+U data. These results agree with $n \sim 1 \text{ fm}^{-3}$, 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 Satz¹³ 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 $n(\tau_0) \sim 1.6 \text{ fm}^{-3}$. 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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