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INITIAL AND FINAL STATE INTERACTIONS IN J/ψ PRODUCTION*

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The systematics of J/ψ suppression in 200 AGeV $O+U$ and $S+U$ reported by NA 38 are interpreted as consequences of initial-state parton scattering and final-state inelastic scattering with comoving secondary particles.

The substantial suppression of J/ψ production reported at Quark Matter '87 for 200 AGeV $O+U$ gave the first strong indication that high-density matter is produced in ultrarelativistic heavy ion collisions [1]. The analyses of these results and those of the recent Sulphur run are nearly complete, and preliminary results are discussed by Grossiord in these proceedings. In this talk we attribute the overall suppression effect to inelastic final-state scattering with comoving secondary particles [2-5]. We introduce initial-state parton scattering [6-9] to describe the dependence of J/ψ production on the transverse momentum p_t in accord with recent hadron-nucleus data [10-12]. This and other interpretations are discussed in Blaizot's plenary talk.

Grossiord has presented preliminary systematic data on the variation of J/ψ production with the total hadron transverse energy E_T (i.e. centrality) and the projectile mass, in addition to p_t. To confront this data we combine models of final-state absorption and initial-state parton scattering with the LUND-based string-fragmentation model ATTILA [13]. This approach is developed in detail in Ref. [6]. Here we describe the models for initial- and final-state scattering and then compare the results to the Oxygen and Sulphur data.

The strong influence of initial-state parton scattering on the p_t dependence of hard processes such as J/ψ formation in nuclear targets is suggested by recent Drell-Yan dimuon data. NA 10 [12] found a broadening of the p_t distribution in $\pi^- + {}^{184}W \rightarrow \mu^+\mu^-$ relative to $\pi^- + {}^{2}H$ corresponding to an increase of the p_t dispersion of $\langle {p_t}^2\rangle_{\pi W\rightarrow\mu^+\mu^-} - \langle {p_t}^2\rangle_{\pi H\rightarrow\mu^+\mu^-} = 0.15 \pm 0.06\text{GeV}^2$. Such an increase can only arise from initial-state interactions, since the final-state in the Drell-Yan production of high-mass pairs does not interact strongly. This effect is likely [14] due to the quasielastic scattering of the sea quark and antiquark before their annihilation. Such scattering adds to the $\langle {p_t}^2\rangle$ of the resulting dimuons but does not reduce the p_t-integrated dimuon yield, because it directs the beam momentum transversely without changing the net parton flux. The absence of an absorptive component of initial-state interactions is supported by the $A^{1.00\pm0.02}$ dependence of the p_t-integrated cross section.

As the pion crosses the nucleus, the quark (or antiquark) suffers a number of elastic collisions before its annihilation that is $\propto (\overline{n}_A - 1)/2$, where $\overline{n}_A$ is the average number of

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inelastic π-nucleon collisions. This random walk increases the p_t dispersion of the dimuon from the intrinsic Drell-Yan value $\approx \langle p_t \rangle_{\pi p}$ to $\langle p_t \rangle_{\pi A} \approx \langle p_t \rangle_{\pi p} + \lambda_q{}^2\{\overline{n}_A - 1\}$. The NA 10 data implies that the effective $p_\perp$ transfer for quark-nucleon collisions is $\lambda_q \approx 0.24$ GeV, since $\overline{n}_A$ is roughly 3.7 in $\pi + W$.

In J/ψ formation we expect a similar initial-state scattering of gluons to occur prior to $c\overline{c}$ formation, and such scattering can in fact account for much of the p_t dependence seen by NA 38 [6-9]. NA 3 [10] studied $p + A \rightarrow J/\psi + X$ at 200 GeV for Pt and ^2H targets, and we show their measured p_t distributions in Fig. 1a together with the distribution for central $O + U$ from NA 38. We see that the normalized distribution $N_\psi{}^{-1} dN_\psi/dp_t$ for Pt is broader than that for H, and that the $O + U$ distribution is broader still. NA 3 found that $\langle p_t{}^2 \rangle_{pPt} = 1.57 \pm 0.03\,\mathrm{GeV}^2$ and $\langle p_t{}^2 \rangle_{pp} = 1.23 \pm 0.05\,\mathrm{GeV}^2$, so that $\lambda_g{}^2 \approx (0.36\,\mathrm{GeV})^2$ for gluon-nucleon collisions, which is roughly $\approx 9\lambda_q{}^2/4$ as we expect from QCD arguments [6,8]. We fit the $p + A$ distributions in Fig. 1a by taking $N_\psi{}^{-1} dN_\psi/d^2p_t$ to be roughly

$$F(p_t) = \mathcal{A}\, e^{-\alpha\sqrt{p_t{}^2 + m_\psi{}^2}}, \tag{1}$$

where use $\langle p_t{}^2 \rangle = \int p_t{}^2 F(p_t) d^2p_t$ to relate the slope parameter α to the measured dispersion.

In a nucleus-nucleus collision, the number of initial-state interactions depends on impact parameter. The p_t dispersion is increased by the scattering of target partons in the projectile as well as by that of projectile partons in the target, so that the total dispersion is

$$\langle p_t \rangle_{AB} \approx \langle p_t \rangle_{pp} + \lambda_g{}^2\{\overline{n}_A + \overline{n}_B - 2\}. \tag{2}$$

In a central $O + U$ collision the usual Glauber-geometry argument gives $\overline{n}_O + \overline{n}_U \approx 8$. We show in Fig. 1a that the p_t dependence of the NA 38 data is accounted for essentially by (1) and (2), with a 20% contribution from the final-state interactions, which we discuss momentarily.

To compare our model for initial state scattering to the NA 38 data for peripheral collisions, we relate $\overline{n}_{tot} = \overline{n}_A + \overline{n}_B$ to E_T using ATTILA/LUND. In Fig. 1b we compare the measured $\langle p_t \rangle$ as a function of E_T reported by Grossiord to (1) and (2).

We calculate the E_T from the transverse energy of the neutral particles together with a 30% contamination of charged particles in the pseudorapidity range $2.0 \leq \eta \leq 4.2$, in order to simulate the acceptance of NA 38's electromagnetic calorimeter. We find, however, that an additional rescaling of the calculated E_T's by ≈ 1.5 is necessary in $O + U$ to identify the ATTILA $d\sigma/dE_T$ with the preliminary NA 38 distribution [6]. This severe discrepancy is inconsistent with the satisfactory agreement of ATTILA and similar models with the WA 80 and NA 34 E_T distributions. In view of the possible inconsistency in the present experimental E_T scale, one can only compare to the data at a qualitative level.

Final-state interactions can dissociate the $c\overline{c}$ pair through a variety of mechanisms in a heavy ion collision, where the density of secondaries may exceed $1\,\mathrm{fm}^{-3}$. We assume that the $c\overline{c}$ interacts with the comoving secondaries only after the proper time $\tau_\psi \sim 2$ fm at which well defined hadrons form. J/ψ's can then be dissociated by exothermic reactions such as $\rho\psi \rightarrow D\overline{D}$ [3]. With this conservative picture in mind, we write the J/ψ yield as a product of a formation rate $\mathcal{N}F(p_t)$ and a survival probability $S(p_t)$:

$$dN_\psi/d^2p_t = \mathcal{N}F(p_t)S(p_t), \tag{3}$$

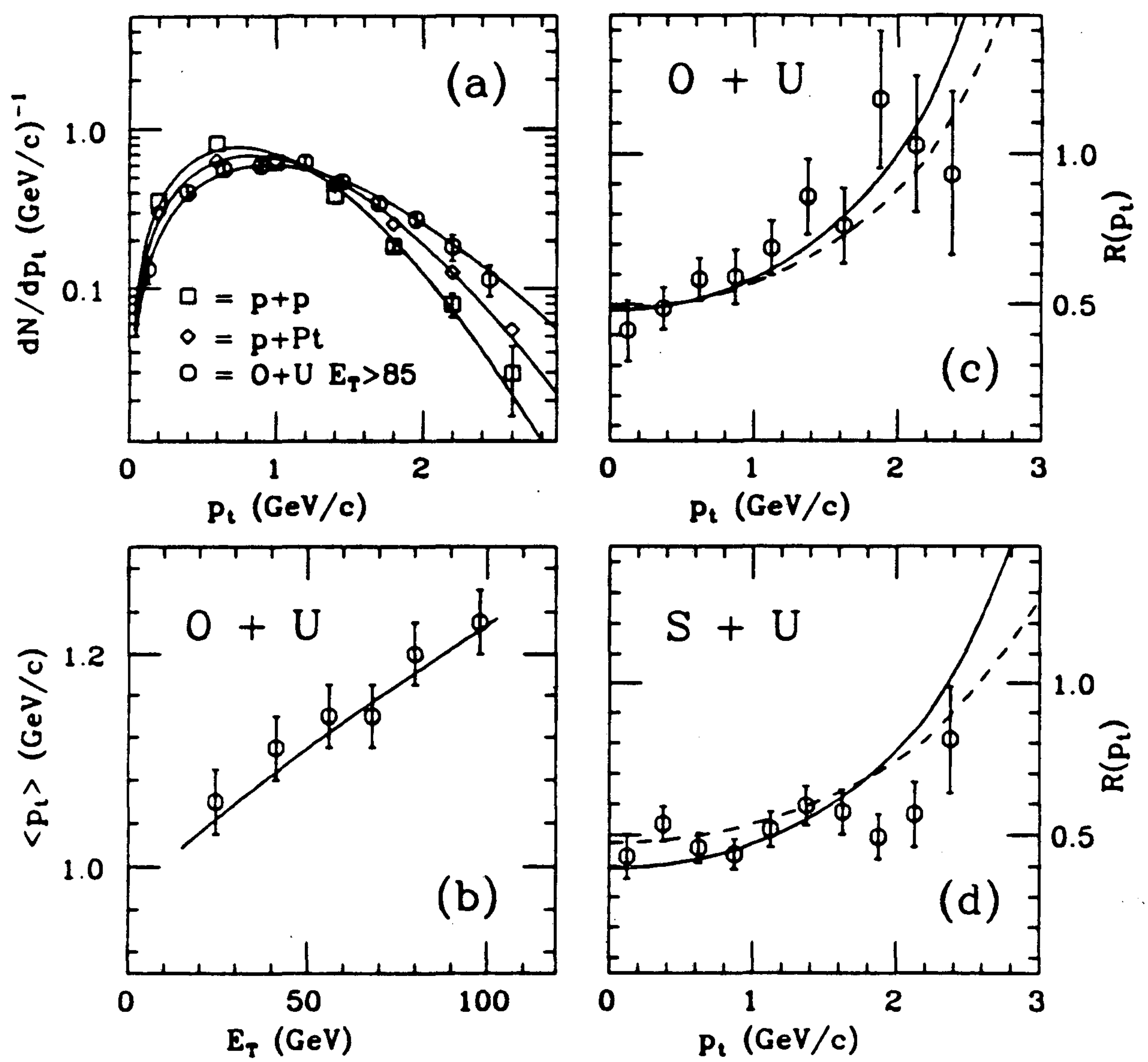

FIGURE 1.

(a) Transverse momentum distributions of $p + A \to J/\psi + X$ at 200 GeV for p (squares) and ^{195}Pt (diamonds) from [10] are compared to those measured in $O + U$ (circles) for $E_T > 85$ GeV. We use (1) and the measured values of $\langle p_t^2 \rangle$ [10] to obtain the $p + A$ curves, and (3) to calculate the $O + U$ curve. (b) Preliminary data on the correlation of $\langle p_t^2 \rangle$ with E_T for 200 AGeV $O + U$ from Grossiord's talk in these proceedings are compared to our calculation using the analogous LUND model E_T scale. (c) Preliminary Oxygen data on the ratio of relative J/ψ-to-continuum yields (5) with $E_T^> > 85$ and $E_T^< < 34$ GeV are compared to our calculations (solid curve) for the analogous ATTILA values $E_T = 60$ and 15 GeV. The dashed curve is obtained for E_T's $\approx 15\%$ larger than the ATTILA values, as explained in the text. Note that the calculated R exceeds unity at $p_t \approx 2.4$ GeV. (d) Sulphur data is compared to our calculations as in (c). The data are for $E_T^> > 125$ and $E_T^< < 51$ GeV, while ATTILA gives $E_T = 105$ and 26 GeV.

where we take the formation probability $F(p_t)$ to have the pA form (1).

We write the survival probability as $S(p_t) \sim e^{-N}$, where N is the number of final-state collisions. If we assume that dissociation reactions occur with a mean cross section $\overline{\sigma}$, then $N \approx \int \overline{\sigma} v_{rel} n(t) dt$, where $v_{rel} \sim 0.6$ is the average relative ρ-ψ velocity and we integrate from the formation time t_ψ to the time t_f at which the J/ψ escapes the high-density matter. We find

$$S(p_t) \approx \exp\left\{-\frac{\overline{\sigma}}{\pi R^2} \log\left(\frac{t_f}{t_\psi}\right) \frac{dN_H}{dy}\right\}, \tag{4}$$

where dN_H/dy is the initial rapidity density of hadrons, and $R \approx 1.2\, A^{1/3}$ is the transverse size of the projectile nucleus [3]. The survival probability varies by less than 20% in the range $0 < p_t < m_\psi$ where data is currently available, due to the Lorentz dilation of the formation time [2-5]. In this range $t_f \propto R$ is essentially the freezeout time of the hadron gas. For concreteness, we take $t_f \approx 5$ fm in $O + U$.

The magnitude of J/ψ suppression is determined by $\overline{\sigma}$. To get a handle on the value of this parameter, we study the E_T dependence of the p_t-integrated J/ψ-to-continuum ratio. Equation (3) implies that this ratio is proportional to $\int d^2p_t\, F(p_t)S(p_t) \approx S(p_t = 0)$, which is exponential in E_T because $dN_H/dy \approx aE_T$. We use ATTILA to determine a, and find that $\overline{\sigma} \approx 5$ mb allows a reasonable fit to the measured $O+U$ relative yield [6]. The value of $\overline{\sigma}$ extracted depends on the various time scales assumed, e.g., for $t_f \approx 4$ rather than 5 fm we find $\overline{\sigma} \approx 7$ mb. Padula and Gyulassy show in these proceedings that $t_f \approx 4$ fm is consistent with the NA 35 $O+Au$ pion interferometry data if resonance decays are included, although a wide range of t_f's are possible depending on the underlying dynamical assumptions.

NA 38 studies the J/ψ yield $dN_\psi/d^2p_\perp$ relative to the $p_\perp$-integrated continuum dimuon yield N_c in the central rapidity region, and reports the transverse momentum dependence of the ratio

$$R(p_\perp) \equiv \frac{(N_c^{-1} dN_\psi/d^2p_\perp)_{E_T^>}}{(N_c^{-1} dN_\psi/d^2p_\perp)_{E_T^<}} \tag{5}$$

for several high transverse energy bins $E_T^>$, compared to the lowest bin $E_T^<$. In Figs. 1c,d we compare Oxygen and Sulphur data for $R(p_t)$ to our estimates. To obtain the solid curves we use ATTILA to calculate $\overline{n}_{tot}$, dN_H/dy and E_T as a function of impact parameter, and construct the ratio $[F(p_t)S(p_t)]_{E_T^>}/[F(p_t)S(p_t)]_{E_T^<}$ for LUND model energies analogous to the centroids of the highest and lowest experimental bins.† We find surprisingly good overall agreement in view of the the schematic nature of our models and the uncertainty in the E_T rescaling procedure. For example, part of the difference between the experimental and LUND model scales can result from enhanced particle production due to rescattering of the secondaries. Such rescattering can increase E_T and dN_H/dy beyond the ATTILA values. To illustrate how rescattering can effect our results, we take the E_T scale to be 15% higher than expected from ATTILA, but keep $\overline{n}_{tot}$ in the high E_T to the maximum allowed by

†We also use the NA 10 data to predict the analogous ratio of normalized distributions for the NA 38 continuum in Ref. [6].

the Glauber geometry. The result shown as the dashed curve in Figs. 1c and d is also consistent with the data.

In summary, we have found that quasielastic initial-state parton scattering accounts for the shape of the NA 38 p_t distributions, and that final-state absorption by comoving secondaries accounts for the overall suppression. The combination of models of these interactions describes the $O+U$ and $S+U$ systematics, and the consistency of this conservative scenario with data supports the contention that matter at densities larger than six times that in normal nuclear matter has been observed at CERN.

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