GLUON MULTIPLE SCATTERING AND THE TRANSVERSE MOMENTUM DEPENDENCE OF J/ψ PRODUCTION IN NUCLEUS-NUCLEUS COLLISIONS +*)

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A J/ψ meson is mainly formed by gluon fusion for 200 GeV pp collisions. In reactions with nuclei the gluons (g) scatter off other nucleons (N) before fusing to a J/ψ, which then shows an additional transverse momentum p_T. Fitting the value of the parameter $\sigma_{gN}\langle p_T^2\rangle_{gN}$ to describe the gluon multiple scattering effect in proton-nucleus data, we can reproduce the p_T distribution of the J/ψ production in 200 GeV/A nucleus-nucleus collisions. The origin of the p_T distribution is traced to soft gluon radiation.

The J/ψ (or simply ψ) suppression observed [1] in nucleus-nucleus collisions s compared to nucleon-nucleon (NN) collisions is usually interpreted as an ffect of the final state. After being produced in one of the NN collisions the ψ ıeson collides with other nucleons and produced hadrons on ints way out of the ıteraction zone and "disappears", i.e., is converted into a state which does not ecay into a $\mu^+\mu^-$ with $m^2_{\mu^+\mu^-} = m^2_\psi$. Indeed, this effect has been proposed as signal about the properties of a quark-gluon plasma produced in a nucleus-ucleus collision [2]. If a quark-gluon plasma is formed, the flux of the ψ's is educed significantly. Up to now the observed ratio of the ψ production relative ɔ continuum muon pairs as a function of the associated transverse hadronic nergy E_T has not yet found a satisfactory, i.e., a parameter free explanation 3—12]. We would like to draw the attention to the additional available data [1] or the ψ production as a function of its transverse momentum p_T. The ratio

$$R^{\exp}(p_T;\, E_T^H,\, E_T^L) = \frac{N_\psi(p_T,\, E_T^H)}{N_\psi(p_T,\, E_T^L)} \tag{1}$$

ompares the number $N_\psi(p_T, E_T^H)$ of the ψ events (i.e. muon pairs in the mass ange $2.7\ \mathrm{GeV/c^2} \le m_{\mu\mu} \le 3.5\ \mathrm{GeV/c^2}$) with a given p_T and a high associated ıadronic energy E_T^H to the number $N_\psi(p_T, E_T^L)$ with the same p_T but a low energy

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E_T^L. The variable E_T is a way to select the impact parameter of a nucleus-nucleus collision. Central collisions are related to high values of E_T. For $E_T^H \gg E_T^L$ the data [1] for R^{exp} from eq. (1) show a monotonic rise in p_T by about a factor 2 from $p_T = 0$ to $p_T = 2$ GeV/c. Several authors [3, 4, 6, 9—12] have explained this behaviour as a geometrical effect of the *final* state. A ψ with a larger p_T can leave the interaction zone more quickly and is therefore less absorbed. The theories based on plasma formation are usually formulated in terms of the formation time of the ψ and the lifetime of the plasma. With the adjustment of a few parameters the data can be reproduced.

In this paper we propose an alternative explanation in that we attribute the p_T dependence of the ratio eq. (1) to *initial* state interactions: gluon multiple scattering *before* the ψ production, Fig. 1. This effect must be present because a widening of the p_T distribution is already observed in proton-nucleus (pA) collisions as compared with pp collisions, both for the ψ production [13] and the Drell-Yan process [14]. The latter has been investigated theoretically by Chiappetta et al. [15], whose reasoning we follow in this paper. At the same time as a preprint of our work was ready, we received the preprints of two other groups, Gavin et al. [17] and Blaizot et al. [18], who independently came to the same conclusions. All three papers will appear in Phys. Lett. B.

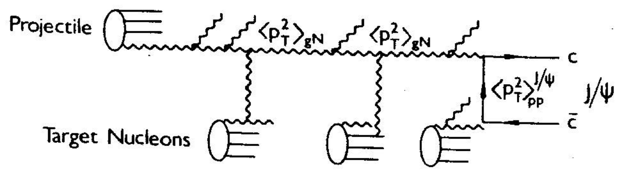

Figure 1: Schematic representation of the gluon multiple scattering before the $c\bar{c}$ production. A gluon from the projectile proton collides with various target nucleons exchanging transverse momentum at each vertex and then leading to $c\bar{c}$ by gluon "fusion".

At 200 GeV laboratory energy the ψ production in pp collisions is dominated by the gluon fusion ($gg \to c\bar{c}$), while the quark annihilation ($q\bar{q} \to c\bar{c}$) contributes only 10 % to the cross section [13]. In a pA collision a gluon from the projectile proton may scatter off one or several target nucleons before fusing with some target gluon to produce the ψ. The mean squared transverse momentum $\langle p_T^2 \rangle_\psi(\boldsymbol{x})$ of the observed ψ is a function of the history of the projectile gluon and therefore depends on the point $\boldsymbol{x} = (\boldsymbol{b}, z)$ of fusion

$$\langle p_T^2 \rangle_\psi(\boldsymbol{b}, z) = \langle p_T^2 \rangle_{pp}^\psi + \langle p_T^2 \rangle_{gN} \cdot \sigma_{gN} \int_{-\infty}^{z} dz' \varrho_A(\boldsymbol{b}, z'). \qquad (2)$$

The projectile gluon moves at the impact parameter $\boldsymbol{b}$ along the z direction. The first term in eq. (2) is the contribution from the $c\bar{c}$ production vertex in an

isolated pp collision, while the second term arises from the gluon multiple scattering before the fusion, $z' \le z$, cf. Fig. 1. The rescattering term depends on the gluon-nucleon (gN) cross section σ_{gN}, on the mean squared transverse momentum $\langle p_T^2 \rangle_{gN}$ acquired in one gN collision and on the nucleon number density $\varrho_A(\boldsymbol{x})$ normalized to the total nucleon number A. The effect of multiple scattering is controlled by one parameter $\sigma_{gN} \cdot \langle p_T^2 \rangle_{gN}$, which we will obtain from the experiment. With the help of $\langle p_T^2 \rangle_\psi(\boldsymbol{x})$ from eq. (2) and assuming a Gaussian p_T dependence [13] the differential cross section for $pA \to \psi X$ can be written as

$$\frac{d\sigma^{pA \to \psi}}{dp_T^2} = \sigma^{pN \to \psi} \int d^3x \varrho_A(\boldsymbol{x}) \frac{\exp(-p_T^2/\langle p_T^2 \rangle_\psi(\boldsymbol{x}))}{\langle p_T^2 \rangle_\psi(\boldsymbol{x})} \cdot \exp\left(-\sigma_{\psi N}^{abs} \int_z^{+\infty} dz' \varrho_A(b, z')\right). \qquad (3)$$

The ψ can be formed at any point $\boldsymbol{x}$ of the nucleus, but depending on $\boldsymbol{x}$ it is formed with a different $\langle p_T^2 \rangle_\psi(\boldsymbol{x})$. Also the absorption in the final state described by the last factor in the integral depends on the point $\boldsymbol{x}$ of the production, $\sigma_{\psi N}^{abs}$ being the absorption cross section of a ψ on a nucleon [5]. The effect of gluon rescattering is completely described as soon as $\langle p_T^2 \rangle_\psi(\boldsymbol{x})$ is known. We use the experimental result [13]

$$\langle p_T^2 \rangle_{pPt}^\psi - \langle p_T^2 \rangle_{pp}^\psi = 0.34 \pm 0.06\,(\mathrm{GeV/c})^2 \qquad (4)$$

for the p_T distribution of a ψ produced in pPt and pp collisions to fix the crucial parameter

$$\sigma_{gN} \langle p_T^2 \rangle_{gN} = (0.39 \pm 0.08)\,\mathrm{fm}^2\,(\mathrm{GeV/c})^2. \qquad (5)$$

Then the shape of the p_T distribution is completely determined while the absolute normalization has been adjusted. Fig. 2 shows the comparison with the

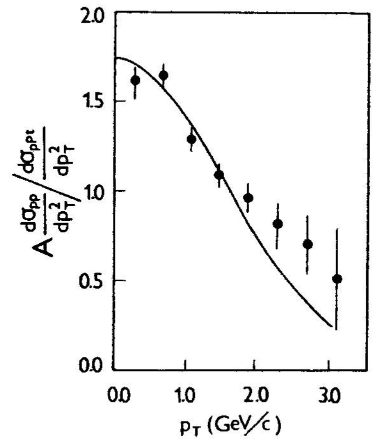

Figure 2: The ratio of $pp \to \psi$ to $pPt \to \psi$ production cross section as a function of transverse momentum. The data are from Badier et al., [13] the solid line represents our calculation which has been normalized to the data at $p_T = 1.5$ GeV/c.

experiment, a satisfactory agreement is obtained for $p_T \leq 2\,\mathrm{GeV/c}$. At larger values of p_T the growing discrepancy may be due to the Gaussian approximation.

Now, we turn to nucleus-nucleus collisions. There both, projectile and target gluons, can scatter before they fuse to form a $c\bar{c}$ pair. The mean squared additional momentum of the ψ acquired via the gluon multiple scattering depends on the total length L, the sum of the projectile and the target gluon trajectories. This length is a function of the impact parameter or equivalently of the transverse energy E_T. The ratio eq. (1) $R(p_T, E_T^H, E_T^L)$ of the events with a given p_T but different transverse energies E_T can be written in terms of the different lengths $L(E_T)$ of gluon trajectories. As described in ref. [5] we use for the experimental data [1] under consideration $(O + U)$

$$L(E_T) = \frac{3}{4} R_O + \begin{cases} 4 \ \ \mathrm{fm}; \ E_T = E_T^L \\ 6.5 \ \mathrm{fm}; \ E_T = E_T^H. \end{cases} \tag{6}$$

For sulphur as projectile we replace the radius R_O of oxygen by the one for sulphur. Except for an overall normalization no parameter enters our calculation. The shapes of the experimental data are reasonably well reproduced, cf. Fig. 3. Therefore we conclude that the *shape* of the p_T distribution of ψ's produced in nucleus-nucleus collisions is well (i.e. parameter free) described by the initial state interactions, but that the final state interactions are responsible for the absolute magnitude and are not yet under control. The mechanism of the initial state interactions also predicts that the ratio $R(p_T)$ in Fig. 3 should grow above one, while the final state theories always predict a saturation, $R(p_T) = 1$ for all $p_T > p_T^c$. Unfortunately, the data are not yet conclusive. The data of ref.

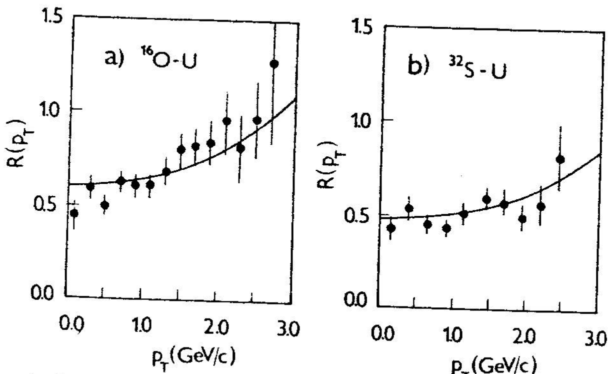

Figure 3: The ratio $R(p_t)$ of the number of events with large values of E_T to the number of events with small E_T for muon pairs in the mass range $2.7 \leq M_{\mu^+\mu^-} \leq 3.5\,\mathrm{GeV/c^2}$ as a function of the transverse momentum for oxygen-uranium and sulphur-uranium collisions at 200 GeV/A. The data are from Abreu et al. [1], the solid line is our calculation, with an overall factor adjusted at $p_T = 0$.

[1] for p_T-distributions in pU collisions have too poor statistics to draw any conclusions.

Only one parameter, $\sigma_{gN}\langle p_t^2\rangle_{gN}$, enters our calculation. It is determined from experiment and permits to describe the p_t dependence of the ψ production in pA and nucleus-nucleus collisions. We note that a similar analysis of the Drell-Yan process in nuclei can be done where the quantity corresponding to eq. (7) has been measured for the $\pi A \to \mu^+\mu^-(DY)$ reaction [15]

$$\langle p_T^2\rangle_{\pi W}^{DY} - \langle p_T^2\rangle_{\pi D}^{DY} = (0.17 \pm 0.03 \pm 0.02)\ (\mathrm{GeV/c})^2. \tag{7}$$

From this result we deduce that

$$\sigma_{qN}\langle p_T^2\rangle_{qN} = \frac{1}{2}\sigma_{gN}\langle p_T^2\rangle_{gN}. \tag{8}$$

It is not clear, however, at which kinematical variables the two sides have to be taken. The data of ref. [1] on the p_T-dependence of the continuum have an insufficient statistical accuracy to obtain a value for $\sigma_{qN}\langle p_T^2\rangle_{qN}$.

Finally we analyse the values $\langle p_T^2\rangle_{gN}$ and $\langle p_T^2\rangle_{qN}$ from a QCD point of view. We assume that the mechanism to produce transverse momentum in gN collisions $(gN \to gX)$ is the same as in the $c\bar{c}$ creation $(gg \to c\bar{c})$, except for possibly different mass scales $\hat{s} = x_g \cdot \bar{x}_N s$ in the multiple scattering process compared to $Q^2 \simeq m_\psi^2$ for the $c\bar{c}$ creation. For $\hat{s} \approx Q^2$ and since two gluons are involved in the $c\bar{c}$ creation and only one in the multiple scattering, we have

$$\langle p_T^2\rangle_{gN} = \frac{1}{2}\langle p_T^2\rangle_{pp}.$$

If the kinematic conditions are such that eq. (13) holds, we may use the experimental value [13] $\langle p_T^2\rangle_{pp}^{\psi} = 1.23\ (\mathrm{GeV/c})^2$ to calculate $\langle p_T^2\rangle_{gN} = 0.62\ (\mathrm{GeV/c})^2$ and from eq. (5) $\sigma_{gN} = 6\,\mathrm{mb}$. Can $\langle p_T^2\rangle_{gN}$ be understood from QCD? The contribution of the radiated soft gluons to the p_T distribution can be estimated by a resummation technique in the leading double logarithmic approximation (Altarelli et al. [16]), and we find for the momentum distribution $\frac{dn_j}{dp_T^2}$ of the parton j (gluon or quark) in analogy to ref. [15]

$$\frac{dn_j}{dp_T^2}(p_T, Q^2) = \int d^2b\, e^{ip_T \cdot b} e^{\frac{1}{2}S_j(b, Q^2)}$$

$$S_j(\boldsymbol{b}, Q^2) = c_j \int_0^{q_m} \frac{dq_T^2}{q_T^2}[J_0(bq_T) - 1]\,\frac{\alpha_s(q_T^2)}{\pi}\left(\ln\frac{Q^2}{q_T^2} - \frac{3}{2}\right). \tag{10}$$

The quantity $S_j(b, Q^2)$ is the Sudakov formfactor, the factor $\frac{1}{2}$ which is missing in ref. [15] arises from the fact that one deals with one parton only. The function $S_j(b, Q^2)$ depends on the type j of the parton via the colour factor c_j, which equals 3 for a gluon and 4/3 for a quark. The integral gets its dominant contributions from small values of q_T and therefore $S_j(b^2, Q^2) a c_j b^2 \cdot f(Q^2)$ is a good approxiamtion. Then the colour factor c_j determines directly the ratio of mean squared momenta for the gluon and the quark (for the same value of Q^2)

$$\langle p_T^2 \rangle_q(Q^2) = \frac{4}{9} \langle p_T^2 \rangle_g(Q^2). \tag{11}$$

Is this the origin of the factor of two in eq. (8)? We have also evaluated the Q^2 dependence of $\langle p_T^2 \rangle$ from eq. (10)

$$\langle p_T^2 \rangle_g = \begin{matrix} 0.5 \\ 1.1 \end{matrix} \begin{cases} \text{for } Q^2 = 9 \\ \text{for } Q^2 = 25 \end{cases} \tag{12}$$

(all units are $(\mathrm{GeV}/c)^2$). The case $Q^2 = 9$ is appropriate for the $c\bar{c}$ production and the calculated value $\langle p_T^2 \rangle_{pp}^{\psi} = 2 \langle p_T^2 \rangle_g = 1\,(\mathrm{GeV}/c)^2$ agrees well with the experiment.

In conclusion we have successfully described the nuclear effects on the p_T distribution of the ψ production by initial state interactions. We treated them on the *partonic* level, i.e. as gluon multiple scattering. Is it also possible to work on the *hadronic* level, i.e. to consider the $\langle p_t^2 \rangle$ as a consequence of the multiple scattering of the incident hadron as a whole (for pA collisions)? We think that the comparison of the nuclear ψ production ($\pi A \to \psi$) via the *gluon* fusion and the Drell-Yan process ($\pi A \to \mu\mu$) via the *quark* fusion excludes the hadron rescattering mechanism. According to the experiments [13, 14] the initial state effects for the two processes differ by a factor of two but would be equal if the initial state interaction of the incident *hadron* were the relevant process. In our analysis gluon multiple scattering is the dominant mechanism for the p_T distribution of the ψ in nuclear collisions while quark/antiquark multiple scattering is the relevant source for the transverse momentum of the Drell-Yan pairs.

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ГЛЮОННОЕ МНОГОКРАТНОЕ РАССЕЯНИЕ И ЗАВИСИМОСТЬ ПОПЕРЕЧНОГО МОМЕНТА ПРИ J/ψ ПРОДУКЦИИ ПРИ СОУДАРЕНИЯХ ТИПА ЯДРО-ЯДРО

J/ψ-мезон в основном формируется синтезом глюонов в pp-соударениях при 200 GeV. В реакциях с ядром глюоны рассеиваются на нуклонах, прежде чем образовать J/ψ, который впоследствии обладает дополнительным поперечным моментом p_T. Подгоняя значения параметра $\sigma_{gN} \langle p_T^2 \rangle_{gN}$ с целью описать эффект многократного рассеивания глюонов на основе данных из протоноядерных реакций, мы можем воспроизвести рождение J/ψ в соударениях типа ядро-ядро при 200 GeV/A. Природа p_T распределения связана с мягким глюонным излучением.