A NEW MECHANISM FOR 
J/ψ SUPPRESSION IN NUCLEAR COLLISIONS

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Abstract

We present new results based on an improved version of the Glauber
model, used to describe the nuclear absorption of J/ψ in reactions be-
tween nuclei at high energy. The excitation of the colour degrees of
freedom of nucleons, due to collisions mediated by one-gluon exchange,
is taken into account. It is found that the proposed mechanism leads to
larger nuclear absorption of J/ψ than previously considered.

The origin of the anomalous behaviour of the J/ψ cross section measured
in Pb+Pb collisions [1] is still not understood and competing interpretations
have been proposed [2]. In order to resolve this important and controversial
issue, more detailed calculations are demanded. Providing further insight in
this difficult problem, preliminary results, obtained with a new formulation
of the Glauber approach to the early stage of a nuclear collision, are hereby
presented.

Preparing the ground for the discussion, it is useful to recall the Glauber
model expression for the cross section in a A+B collision at impact param-
eter $\vec{b}$. Denoting a generic colour singlet $c\bar{c}$ state by $\psi$, one has

$$
\frac{d^2\sigma_{AB}^{\psi}}{d^2\vec{b}}(\vec{b}) = \sigma_{\psi}^{NN} \int d^2\vec{s} \ dz_A \ dz_B \ \rho_A(z_A,\vec{s}) \ \rho_B(z_B,\vec{b} - \vec{s}) \ S_{abs}^{\psi}(z_A, z_B, \vec{b}, \vec{s}), \tag{1}
$$

where $\rho_A$ and $\rho_B$ are the densities of the colliding nuclei and

$$
S_{abs}^{\psi}(z_A, z_B, \vec{b}, \vec{s}) = \exp \left[ -\sigma_{\psi N}^{abs} \left( \int_{-\infty}^{z_A} d\vec{z}_A' \ \rho_A(\vec{z}_A', \vec{s}) + \int_{z_B}^{+\infty} d\vec{z}_B' \ \rho_B(\vec{z}_B', \vec{b} - \vec{s}) \right) \right] \tag{2}
$$

is the nuclear suppression factor, which contains the effective absorption cross
section $\sigma_{\psi N}^{abs}$ for $\psi$-nucleon scattering.

Provided that $\sigma_{\psi N}^{abs} = 7.3$ mb, the above expressions can account for p+A
and S+Pb data, but not for the Pb+Pb measurements. On the other hand,
the usual version of the Glauber model must be improved, since in eqs. (1) and (2) one assumes that the nucleons which absorb the produced $\psi$ are in their ground state. This cannot be correct. In fact, before encountering the produced meson, they scatter several times while the nuclei stream through each other. In doing so they leave the ground state. A first attempt to address this problem was recently made, by including in the calculation the effect of the cloud of prompt gluons around nucleons [3]. On the other hand, nucleon themselves were still treated as non-interacting. Since the centre of mass energy of each NN collision is $\simeq 17$ GeV at the SPS, it is reasonable to ascribe the main contribution to the inelastic cross sections to one-gluon exchange processes, as done, for example, in the Dual Parton Model [4]. This has an important consequence: two colour-singlet nucleons jump into octet states after the elementary collision and therefore become coloured. In same way one also allows the possibility that some ‘nucleons’ are in a decuplet state. From now on the quotes will be dropped when referring to a coloured nucleon.

Having realized that nucleons become coloured, soon after enough rescattering has taken place, it is necessary to establish whether this fact has any effect at all on $\psi$ absorption. In other words one must quantify the differences in the inelastic cross sections for $\psi N$ scattering due to the various colour states of the nucleon. This can be achieved within the Low-Nussinov model [5], first evaluating the elastic cross section for a meson scattering off a nucleon, and then making use of the optical theorem, which relates the forward elastic amplitude to the total cross section. The model consists in the exchange of two gluons characterised by a phenomenological mass $\mu_G \simeq 140$ MeV, which effectively mimics confinement. Neglecting the elastic contribution compared to the inelastic one, one can show that

$$\sigma_{\psi N}^{abs} = \int d^2 \rho |\Phi_{\psi}(\rho)|^2 \sigma_a(\rho),$$

where $\Phi_{\psi}(\rho)$ is the transverse part of the $\psi$ meson wave function, while

$$\sigma_a(\rho) = \frac{16}{3} \alpha_s^2 \int d^2 k \frac{1}{(k^2 + \mu_G^2)^2} \left[ 1 - a F_N(3k^2) \right] \left(1 - e^{i\vec{k} \cdot \vec{\rho}}\right),$$

is the colour dipole-nucleon cross section. The function $F_N$ is the two-quark form factor of the nucleon, usually identified with the charge form factor. The coefficient $a$ in front of the form factor specifies the colour state of the nucleon. For the singlet state one has $a = 1$ and the expression reduces to the usual one, exhibiting the partial cancellation of amplitudes, implying $\sigma(\rho) \to 0$ for $\rho \to 0$ (Colour transparency). A detailed calculation shows that $a = 1/4$ for
Figure 1: Left - Dipole cross section for different colour states. Right - Evolution of the colour probabilities $P_S$, $P_O$, $P_D$, along $z$ and with $\vec{b} = 0$. Also shown is the profile of a Pb nucleus.

an octet nucleon while $a = -1/2$ for the decuplet state. The dipole cross section can be computed analytically in terms of modified Bessel functions. One can fix the value of the strong coupling in order to reproduce $\pi N$ cross section of $\simeq 23$ mb, therefore taking $\alpha_s \simeq 0.65$. Successively, the $\psi N$ cross sections can be obtained using eqs. (3) and (4) without additional parameter fixing. The results of the calculations are illustrated in the left side of Figure 1, which shows the dipole cross section for the three colour states of the nucleon. It largely increases when the dipole scatters off a coloured object. This new result is important and could not have been guessed prior to calculation. One must now evaluate the corresponding absorption cross sections. To do so it is useful to first rewrite eq. (4) in the form

$$\sigma_a(\rho) = \sigma(\rho) \left[ 1 + (1 - a) \Delta(\rho) \right],$$

where the function $\Delta(\rho)$ was found to be approximately constant and amounts to $\simeq 0.46$. This shows that the colour cross sections have a simple $\rho$-dependence and scale with respect to the singlet one. Then, using eq. (5), one obtains the absorption cross sections for $\psi$ as

$$\sigma_{\psi N_j}^{abs} = \sigma_{\psi N}^{abs} \times \begin{cases} 1 & \text{Singlet} \\ 1.35 & \text{Octet} \\ 1.7 & \text{Decuplet} \end{cases}.$$  

A large increase with respect to the singlet value is found, suggesting that the newly proposed absorption mechanism is indeed important. Using a Gaussian
parametrisation for the $\psi$ wave function, such that the root mean squared radius is $\sim 0.2$ fm, one obtains $\sigma^{\text{abs}}_{\psi N} \simeq 6$ mb. On the other hand, at this preliminary stage of the calculation, the effect of the feeding into $J/\psi$ from $\psi'$ and $\chi_c$ states is neglected. To compare with the conventional Glauber model, it is therefore preferable to use the effective value used to reproduce the p+A data, therefore setting $\sigma^{\text{abs}}_{\psi N} = 7.3$ mb and scaling the colour cross section accordingly by means of eq. (11).

To correct eqs. (1) and (2), one must now understand how the colour state of a nucleon evolves while passing through a nucleus. This is a non-trivial problem which can be formulated by means of a master equation. Its content is to express the evolution of the colour probabilities $P_S, P_O$ and $P_D$, due to subsequent scatterings. The framework is again that of the Glauber model of multiple collisions. What one finds is the solution [6]

$$P_S(z, \vec{b}) = \frac{1}{27} + \frac{20}{27} F(z, \vec{b}) + \frac{6}{27} G(z, \vec{b}), \quad (7)$$

$$P_O(z, \vec{b}) = \frac{16}{27} - \frac{40}{27} F(z, \vec{b}) + \frac{24}{27} G(z, \vec{b}), \quad (8)$$

$$P_D(z, \vec{b}) = \frac{10}{27} + \frac{20}{27} F(z, \vec{b}) - \frac{30}{27} G(z, \vec{b}), \quad (9)$$

where

$$F(z, \vec{b}) = \exp \left( -X(z, \vec{b}) \right), \quad G(z, \vec{b}) = \exp \left( -\frac{2}{3}X(z, \vec{b}) \right), \quad (10)$$

and

$$X(z, \vec{b}) = \frac{9}{8} \sigma_{NN}^\text{in} \int_{-\infty}^{z} \rho(z', \vec{b}) \, dz', \; \text{with} \; \sigma_{NN}^\text{in} = 30 \text{ mb}. \quad (11)$$

One notices several properties of the found probabilities. First of all, the limit $z \to -\infty$ implies $X \to 0$ and $F, G \to 1$. This means that $P_S \to 1$ and $P_O, P_D \to 0$. In other words the nucleon, before entering the nucleus, is in singlet state as it should be. Moreover, $P_S + P_O + P_D = 1$ for any $z$, therefore probability is always conserved. Finally, if $z \to +\infty$ and if the nucleus is large enough, one has $X \gg 1$ and $F, G \ll 1$. This implies that if enough scatterings take place, the colour probabilities reach the statistical limit, given by the first coefficients of eqs. (7), (8) and (9). The $z$-dependence of the colour probabilities is illustrated in the right side of Figure 1 together with the longitudinal profile of a Pb nucleus at $\vec{b} = 0$. Soon after the nucleon has penetrated the nuclear profile, a process that involves $\sim 4$ fm, the statistical limit is reached. About $2/3$ of the nucleons are in octet state while $1/3$ are in decuplet. The amount of singlet is negligible.

It is now possible to describe how to perform the calculation of the $\psi$ cross section in A+B collisions. One must modify eqs. (1) and (2) to account for
the previously discussed colour absorption cross sections and probabilities. It is necessary to replace eq. (2) with
\[ S_{abs} = \exp \left[-(f_A + f_B)\right] \]
where
\[ f_A(z_A, z_B, \vec{b}, \vec{s}) = \int_{-\infty}^{z_A} dz'_A \Sigma_B(\tilde{z}_B, \vec{s}) \rho_A(z'_A, \vec{s}) \]
\[ f_B(z_A, z_B, \vec{b}, \vec{s}) = \int_{z_B}^{+\infty} dz'_B \Sigma_A(\tilde{z}_A, \vec{s}) \rho_B(z'_B, \vec{b} - \vec{s}) \]

The effective cross sections \( \Sigma \) take into account the colour cross sections and probabilities, as previously discussed. They are
\[ \Sigma_A(\tilde{z}_A, \vec{s}) = \sum_{j=S,O,D} \sigma_{\psi N_j}^{in} P_j^A(\tilde{z}_A, \vec{s}) \]
\[ \Sigma_B(\tilde{z}_B, \vec{b} - \vec{s}) = \sum_{j=S,O,D} \sigma_{\psi N_j}^{in} P_j^B(\tilde{z}_B, \vec{b} - \vec{s}) \]

In the above expressions the values \( \tilde{z} \) correspond to the \( \psi \) absorption points as in the illustration shown in the left side of Figure 2. With a simple geometrical construction one obtains
\[ \tilde{z}_A = z_A - (z'_B - z_B) \frac{1 - v_\psi}{1 + v_\psi} \quad \text{and} \quad \tilde{z}_B = z_B - (z'_A - z_A) \frac{1 + v_\psi}{1 - v_\psi} \]

The velocity \( v_\psi \) of the meson is related to the measured value of \( x_F = p_\psi/p_{max} \approx 0.15 \) and to the centre of mass energy \( \sqrt{s_{NN}} \) of the NN collisions. One has
\[ v_\psi = \sqrt{x_F^2 s_{NN}/[4m_\psi^2 + x_F^2 s_{NN}]} \approx 0.4 \]
The $\psi$ cross section expressed by eq. (1) can now be evaluated. Its ratio with the Drell-Yan cross section is obtained in a conventional manner and is converted into an $E_T$-dependent function by fixing the scale to the number of participants, in order to describe the minimum bias data as measured by the NA50 experiment. No spread in the $E_T(b)$ correlation is taken into account for simplicity. The calculated ratio is compared with the standard Glauber approach and to the data as shown in the right side of Figure 2. The result exhibits a stronger suppression when compared to the usual Glauber calculation. Although several improvements are under investigation, the effect is clear and cannot be neglected in future work. Among the aforementioned improvements is the inclusion of a retardation effect for the so far sudden switch of colour in NN collisions. This becomes relevant at large impact parameters, where there are only few collisions, implying that the present result overestimates the suppression at small transverse energy. Another improvement which works in the same direction consists in accounting for important formation time effects \[7\]. All this is presently under careful study.

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