Charmonium Suppression – Interplay of Hadronic and Partonic Degrees of Freedom *

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Last year the E866-group of the Fermilab measured the x_F dependence of J/Ψ and Ψ' suppression in pA collisions. We discuss two of the effects found in that experiment with regard to color coherence effects: the different suppression of the J/Ψ and the Ψ' at $x_F < 0$ and the significant suppression of both at large x_F. The small x_F regions is dominated by fully formed charmonium states and thus enables us to discuss the formation time and the cross section of the different charmonium states. In the large x_F region the interaction of the charmonium states with nuclear matter has to be described by partonic degrees of freedom, because in that kinematic domain the formation time is much larger than the nuclear radii. The understanding of this region will be crucial for the interpretation of the data of the future heavy ion colliders RHIC and LHC.

1. Introduction

From considerations on formation times the interaction of charmonium states with a nucleus in a pA collision can be roughly divided in three different kinematical regions. The formation time is given by [1]

$$t_f(J/\Psi) = \frac{1}{E_{\Psi'} - E_{J/\Psi}} \approx \frac{2p}{M_{\Psi'}^2 - M_{J/\Psi}^2} \approx 0.3 \text{ fm/c} \cdot \gamma \tag{1}$$

Here, $E_{\Psi',J/\Psi}$ ($M_{\Psi',J/\Psi}$) are the energies (masses) of the Ψ' and the J/Ψ and γ is the Lorentz-factor. The formation time of a Ψ' should be larger than that of a J/Ψ by the ratio of the radii of these states, which is ≈ 2. In a recent letter [2] the attempt to extract the formation time from the experimental data on $e^+e^- \rightarrow Q\bar{Q}$ has been made. The authors found $t_f(J/\Psi) = 0.44$ fm/c $\cdot \gamma$, $t_f(\Psi') = 0.91$ fm/c $\cdot \gamma$ which is slightly larger than the values used here. Using eq. (1) in the rest frame of the nucleus leads to the following three kinematical regions:

- hadronic: $t_f < 1.8$ fm/c
  The formation time is smaller than the average inter-nucleon distance in the nucleus. Only fully formed charmonium states interact with the nucleons. In pA collisions at $E_{lab} = 800$ GeV this means $x_F < -0.3$.

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meson	J/Ψ	Ψ'	χ_{10}	χ_{11}
(1) σ [mb]	2.5	10	3.8	7.6
(2) σ [mb]	3.1	12.6	4.6	9.3

Table 1
The non-perturbative charmonium nucleon cross section (1) with the transverse size b calculated with the wave function from [6] and (2) from [7].

- mixed: 1.8 fm/c $< t_f < 2 \cdot R_A$
  The formation time is larger than the average distance of the nucleons in the nuclei but smaller than the diameter of the nucleus. The charmonium states already can interact within their formation time but some of them are still formed in the nucleus. In pA (E_{lab} = 800 GeV) this means $-0.3 < x_f < 0$ (the upper limit depends of course on A, $x_f < 0$ is for Be).

- partonic: $2 \cdot R_A < t_f$
  All charmonium states are formed beyond the nucleus. Hence the interaction has to be treated on the parton level.

In this work we discuss the hadronic and the mixed region. In section 2 we describe the model and present the results. A brief summary is given in section 3.

2. Model and Results

In [3] we showed that the cross section of a fully formed J/Ψ as predicted by pQCD [4] is much smaller than the cross section extracted from photoproduction processes at E_{lab} = 20 GeV [5] (here we have $\gamma = 6$ and thus are in the hadronic region). We concluded that the cross section of charmonium states at Fermilab energies is dominated by a non-perturbative contribution. At the same time the pQCD contribution to the cross section increases rapidly with energy. It will be relevant at RHIC and may even dominate at LHC.

To calculate the non-perturbative contribution to the charmonium nucleon cross section (shown in Tab. 1) we used the parametrization $\sigma(b) = C \cdot b^2$. Here, b is the transverse diameter of the charmonium state (transverse to the beam direction) and C is a constant. This model is capable to describe the total cross sections of $\pi - N$, $K - N$, $\phi - N$ and pp collisions. We adjusted the constant $C = \sigma(\pi)/b^2(\pi)$, i.e. $\sigma(\pi) = 25$ mb and $b^2(\pi) = 0.96$ fm^2 to the cross section and the size of the pion. (Note that the size of the pion is estimated from form factor measurements and thus is based on the idea of a non-relativistic continous charge density. Thus it may appear dangerous to use it as a spatial distribution of current quarks.)

The transverse sizes of the charmonium states has been calculated with non-relativistic wave functions taken from [6,7]. The results of this calculations differ by $\approx 25\%$. This difference illustrate the dependence of the prediction on the charmonium model. The subscripts of χ_{lm} are the quantum numbers of the spherical harmonics, the angular momentum dependent part of the wave functions. The χ mesons have two different cross sections because the transverse size of P-states ($l = 1$) depends on the third component of the angular momentum m: $\sigma(\chi_{11})/\sigma(\chi_{10}) = 2$. This angular momentum dependent absorption leads to a polarization of the χ-meson in pA and AB collisions.

We assume in this work that the production of $c\bar{c}$-pairs is a hard process, i.e. $\sigma(pA \to c\bar{c}) = A \cdot \sigma(pp \to c\bar{c})$. In the kinematic region discussed here, this assumption is consistent

with the data (for a recent review see e.g. [8]) but may be inappropriate at large x_F [9]. Additionally we assume that the suppression of charmonium states is only due to their final state interactions. In particular, we neglect the nuclear modifications of the parton distribution functions.

In the following we calculate the survival probability S of a state X in pA-collisions defined as $S_A^X = \sigma(pA \to X)/(A \cdot \sigma(pN \to X))$. Thus $S = 1$ for the production of $c\bar{c}$-pairs (the total charm cross section), with the assumptions made above. Our assumptions allow to calculate the survival probability within the semiclassical approximation of the Gribov-Glauber model as in [10]:

$$S_A^X = \frac{1}{A} \int \mathrm{d}^2 B \, \mathrm{d}z \, \rho(B, z) \cdot \exp\left(-\int_z^\infty \sigma_X \rho(B, z') \mathrm{d}z'\right) , \qquad (2)$$

where B is the impact parameter, z the beam direction, ρ the density of the nucleus and σ_X the cross section for a XN collision.

Now, we can calculate S in the kinematical region that we called hadronic in the introduction. However, we also want to discuss the mixed region and therefore we have to describe the XN cross section within the formation time of the state X. We assume that the state X is produced as a small color singlet $c\bar{c}$ pair that expands during its formation time. Interesting physics related to the propagation of color octet $Q\bar{Q}$ pairs is beyond our scope since it requires methods beyond the semiclassical approximation. For the region of negative x_F the propagation of color octets should be suppressed because its energy is insufficient to separate color from the quark-gluon environment. The cross section then reads [11]:

$$
\begin{aligned}
\sigma(z, z')_X &= \sigma(z) + \frac{z' - z}{t_f}(\sigma_X - \sigma(z)) \text{ for } z' - z < t_f \\
\sigma(z, z')_X &= \sigma_X \qquad\qquad\qquad\qquad \text{otherwise.}
\end{aligned}
\qquad (3)
$$

Here, $\sigma(z, z')_X$ is the cross section of the state X produced at the position z after it moved to z'; $\sigma(z) = 1$ mb is the cross section at the production point z and σ_X is the cross section of the state X after the formation time elapsed. That means $\sigma(z, z')_X \propto t$ and thus $b \propto \sqrt{t}$ as it should be for the expansion of wave packages in nonrelativistic quantum mechanics [1]. This behaviour is called quantum diffusion.

In Fig. 1 $R(W/Be) := S(pW)/S(pBe)$ is plotted versus x_F for the J/Ψ and the Ψ'. Note that a large fraction of the J/Ψ's comes from the decay of Ψ' and χ, therefore:

$$S = 0.6 \cdot (0.92 \cdot S^{J/\Psi} + 0.08 \cdot S^{\Psi'}) + 0.4 \cdot S^\chi , \qquad (4)$$

where $S^{J/\Psi}$ is the genuine survival propability of the J/Ψ, while S is the survival probability that takes into account the J/Ψ's from the decay of the higher resonances. This calculation was done with the cross sections denoted (2) in Tab. 1 and the data from Ref. [12]. At $x_F < 0$, we find reasonable agreement between data and calculation. At $x_F = 0$ we have $l_c = 20.6 \cdot 0.3$ fm $> 2 \cdot R_{Be}$ and thus eq. (3) is not longer valid.

3. Summary

- The pQCD contribution into $\sigma(J/\Psi - N)$ is too small at SPS-energies to explain $\sigma(\gamma A \to J/\Psi)$, and increases rapidly with energy – this could be important for RHIC and LHC.
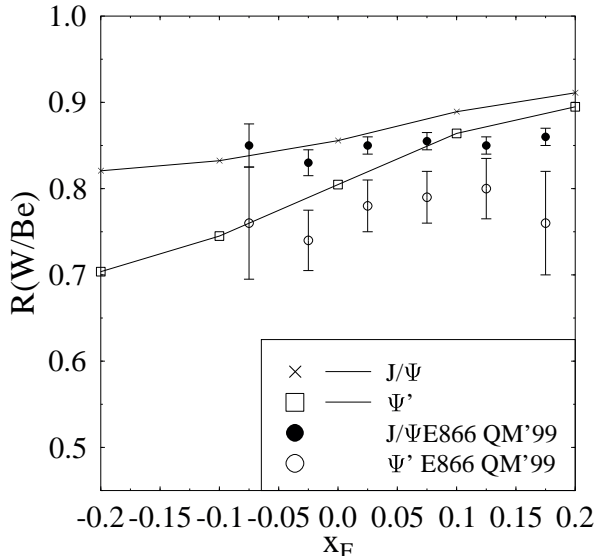
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Figure 1.
The ratios $R(W/Be) := S(pW)/S(pBe)$ of the J/Ψ and the Ψ' are plotted versus x_F at $E_{lab} = 800$ GeV. The used model (see text) is only valid for $x_F < 0$. In this region the calculation is in good agreement with the data.

- Motivated by the pQCD cross section, the nonperturbative model for $\sigma(\bar{q}q) = c \cdot b^2$ predicts four different types of charmonium nucleon cross sections. This reflects the fundamental property of QCD, where interactions depend strongly on the scale.

- QCD predicts different cross sections for the χ_{lm}-mesons, because high energy interactions are dominated by the transverse size: $\sigma(\chi_{11} - N) \approx 2 \cdot \sigma(\chi_{10} - N)$.

- The production of small $\bar{c}c$ pairs and their expansion are relevant for the $\Psi':J/\Psi$-ratio, which is weakly dependend on A at larger Lorentz-factors.

- The assumption that the production of $c\bar{c}$-pairs is hard and not soft could be tested by measuring the A-dependence of the total charm cross section. This could also provide insight in nuclear shadowing and parton energy loss at large x_F.

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