Charmonium production in relativistic proton-nucleus collisions: What will we learn from the negative x_F region?

D. Koudela[1] and C. Volpe[1,2]
[1] *Institut für Theoretische Physik der Universität, Philosophenweg 19, D-69120 Heidelberg, Germany*
[2] *Groupe de Physique Théorique, Institut de Physique Nucléaire, F-91406 Orsay Cedex, France*
(Received 22 January 2003; published 27 May 2004)

We study the nuclear medium effects on the $c\bar{c}$ time evolution and charmonium production in a relativistic proton-nucleus collision. Little is known of the nuclear effects in the fragmentation region where the charmonium formation length is shorter than the nuclear size. We use a quantum-mechanical model which includes an imaginary potential to describe the $c\bar{c}$-nucleon collisions. This introduces a transition amplitude among the charmonium states and results in an interference pattern in the survival probability, and is particularly pronounced for ψ'. We present the comparison with data from NA50 and E866/NuSea and make predictions for the J/ψ, ψ', and χ_c suppression factors as a function of the nuclear mass, and for the negative x_F region, where data will be available soon.

DOI: 10.1103/PhysRevC.69.054904 PACS number(s): 25.75.Dw, 12.38.Mh

I. INTRODUCTION

An exciting era in the study of strong interactions has begun with high energy heavy ion collision experiments which have opened the exploration of new states of matter, such as the color glass condensate, or the so-called quark-gluon plasma, also important for understanding the early universe. Evidence for the quark-gluon plasma may come from combining information from different signals, such as strangeness, dilepton, photon, or charmonium production.

Matsui and Satz [1] first suggested that the suppression of charmonia could signal a phase transition. This pioneering idea has triggered a series of experiments [2,3], whose interpretation has been controversial. It has become clear that, to use charmonium as a signal, all possible mechanisms affecting charmonium production need to be understood [4,5].

In this context, *pp* and *pA* collisions have been intensively studied [2–8]. In fact, these processes are used as a reference for *AB* collisions where a critical energy density may be attained, producing the plasma. This should affect various observables and, in particular, may lead to extra (anomalous) charmonium suppression. There have been indications recently that the plasma has been produced, but it is too early to draw conclusions [9]. These studies will be pursued at RHIC and at LHC.

It takes a certain time for a $c\bar{c}$ produced in a collision to become a color singlet state, then it expands to the size of a ψ meson (ψ stands from now on for any charmonium meson, i.e., J/ψ, ψ', and χ_c) [4,10,11].

Fast (slow) $c\bar{c}$ pairs can traverse the nucleus before a ψ meson is fully formed (as fully formed ψ meson) [12,13]. Experimentally, one can pinpoint these kinematic regions by measuring charmonium production at positive and negative Feynman x_F values and/or through inverse kinematics measurements [4]. The negative x_F region has been studied in [13–15]. Interesting features may appear in this region in going from *pA* to *AB* experiments [16].

The nuclear medium effects on the $c\bar{c}$ pair evolution is one of the aspects that needs to be better understood. In particular, little is known of these effects when the formation time of the charmonium is smaller than the time taken to traverse the nucleus. *pA* and *AB* collision measurements will be performed soon by the HERA-B and PHENIX Collaborations. Similar experiments with photoproduced charmonia will be done by the E160 Collaboration [17], for which predictions are given in Ref. [18].

Here, we focus on the fragmentation region of the nucleus (negative x_F or slow $c\bar{c}$) and study the effects of the nuclear medium on the $c\bar{c}$ time evolution and on charmonium production in relativistic *pA* collisions [19]. Because of the kinematics region we are interested in, we assume that the $c\bar{c}$ quickly becomes a color singlet state (premeson) and on its way through the nucleus, this premeson expands to a ψ meson, while experiencing collisions with the nucleons. We use a quantum-mechanical model where, contrary to previous works [4,12,13,20], the $c\bar{c}$ pair is bound by a realistic potential [21] and the premeson (and then meson) wave function is expanded on the basis given by the charmonium eigenstates. An imaginary potential depending on the dipole charmonium-nucleon cross section [12,22] is included to describe the collisions with the nucleons. This introduces a transition amplitude among the charmonium states. (We assume the premeson wave function has a fixed angular momentum quantum number and different radial components.)

We show that the interaction of the premeson, and later on the meson, with the nuclear medium produces an interference pattern on the charmonium survival probability. We show how this affects the charmonium suppression factor both when the path in the nucleus is varied, by changing the nuclear mass, and as a function of x_F. These effects are particularly important for ψ'. We compare our results with data from the NA50 [7] and E866/NuSea [8] Collaborations. We present predictions for the production of J/ψ, ψ', and χ_c in a range of small negative x_F values, for different nuclei [19], for which measurements will be performed soon [17].

II. THE MODEL

Our $c\bar{c}$ pair, produced in a *pA* collision, is described in its center of mass (c.m.) frame by the internal Hamiltonian

$$H_0 = \frac{p^2}{m_c} + V(r), \tag{1}$$

where m_c is the charm quark mass. The realistic potential $V(r)$ binding c and $\bar{c}$ reproduces the charmonium family properties [21]. (The spin-dependent terms are neglected.) Only transitions between charmonium states with different n quantum numbers are considered.

By solving the static Schrödinger equation with H_0, one gets the eigenenergies $E_{n,\ell}$ and the corresponding wave functions $|n,\ell\rangle$ (to simplify notations, we drop the dependence on magnetic quantum number). The $1S$ and $2S$ states correspond in our model to J/ψ and ψ', respectively, and $1P$ to χ_c. The different total spin states of χ_c are not split in energy (our χ_c is produced through a two-gluon mechanism). We replace the $D\bar{D}$ continuum (above the $D\bar{D}$ threshold at $E_{c\bar{c}} \approx 3.7$ GeV) by resonances in the $c\bar{c}$ system having the bound state energies from H_0 and the observed widths.

The time dependent wave function for $c\bar{c}$ in its rest frame is expanded on the basis of eigenstates of H_0:

$$|c\bar{c},\ell\rangle(\tau) = \sum_{n=0}^{\infty} c_{n,\ell}(\tau) e^{-iE_{n,\ell}\tau} |n,\ell\rangle \tag{2}$$

$(\hbar, c=1)$. In practice, for a given ℓ value one truncates the sum to a number $\bar{n}$ of eigenstates.

To model the interaction of $c\bar{c}$ with the nuclear medium we add an imaginary part to Eq. (1):

$$iW = i\frac{\gamma v}{2}\sigma(\vec{r}_T, \sqrt{s_{\psi N}})\rho(\vec{b},z), \tag{3}$$

where v is the speed of the nucleus with respect to the $c\bar{c}$ frame, σ is the dipole cross section associated with the interaction of the $c\bar{c}$ and a nucleon N, r_T is the c and $\bar{c}$ transverse distance, $\sqrt{s_{\psi N}}$ the energy in the c.m. of the ψN system, and ρ is the nuclear density evaluated at the position $(\vec{b},z)$ of the $c\bar{c}$ c.m., z being the beam direction. For σ we use $\sigma(r_T, \sqrt{s}) = \sigma_0(s)(1 - e^{-r_T^2/r_0^2(s)})$, determined by fitting deep inelastic scattering data and which reproduces the charmonium photoproduction data [22]. Concerning the nuclear density ρ, we present results obtained with a Woods-Saxon profile, with parameters chosen to reproduce the nuclear radii.

The time evolution of the $c\bar{c}$ wave function (2) in the nucleus is determined by solving the time dependent Schrödinger equation for $H = H_0 - iW$ Eqs. (1)–(3). This leads to the coupled-channel equations

$$\dot{c}_{n,\ell}(t) = -a\sum_{k=1}^{\bar{n}} c_{k,\ell}(t) e^{i(E_{n,\ell}-E_{k,\ell})t/\gamma} \langle n,\ell|\sigma|k,\ell\rangle \tag{4}$$

for the amplitudes $c_{n,l}(t)$, with $a = v\rho(\vec{b},z)/2$. The time $t = \gamma\tau$ is now in the laboratory frame. We have neglected in this first calculation the higher Fock states that emerge from the Lorentz boost [22]. We see from Eq. (4) that the imaginary potential (3) introduces a transition amplitude among the charmonium eigenstates.

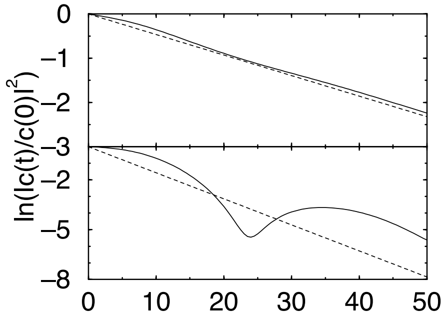

FIG. 1. Survival probability of J/ψ (upper) and ψ' (lower) as a function of time (laboratory frame), normalized to the initial probability, with (solid) or without (dashed line) the transition amplitudes among the charmonia.

A difficult choice is that of the initial conditions $c_{n,\ell}(0)$ for Eq. (4), related to the hadroproduction of charmonia, which are still not well known [4,5,10,11]. We use

$$\langle \vec{r}_T, z|c\bar{c},\ell\rangle(0) = a_\ell f_\ell(r_T) e^{-(1/2)\beta^2(r_T^2+z^2)}, \tag{5}$$

where a_ℓ is a normalization constant. We describe the conversion of a gluon into a $c\bar{c}$ through a Gaussian multiplied by $f_\ell(r_T) = r_T^2$ (or $\vec{r}_T$) to account for the two (one) supplementary gluons necessary to produce J/ψ, ψ' (or χ_c). The initial wave function depends on one parameter only, β, determined by fixing $|c_{2,0}/c_{1,0}|^2$ to the experimental ratio of ψ' over J/ψ, in pp collisions at 450 GeV, i.e., $B_{\psi'\to\mu\mu}\sigma^{pp\to\psi'}/B_{J/\psi\to\mu\mu}\sigma^{pp\to J/\psi} = (1.60 \pm 0.04)\%$ [23], where $B_{\psi\to\mu\mu}$ is the branching ratio to dimuon production and $\sigma^{pp\to\psi}$ the pp reaction cross section. This leads to $|c_{2,0}/c_{1,0}|^2(0) = 0.22 \pm 0.03$ and $\beta = 1.33 \pm 0.5$ GeV (the same β is used for the χ_c states).

The number $\bar{n}$ of states in Eq. (2) has to be large enough that the results do not depend on the truncation. We have checked that the inclusion of extra states (up to four channels for the S states and up to two for the P states) always slightly affects the last state included, whereas the results for the states of interest here remain practically unchanged.

III. RESULTS AND DISCUSSION

We present the results obtained in infinite nuclear matter first, i.e., where ρ is taken as constant in Eq. (4). In Fig. 1 we show the time evolution of the J/ψ and ψ' probabilities obtained by solving Eq. (4) with Eq. (5), both neglecting and including the transition amplitudes between different eigenstates (nondiagonal terms). While in the former case the probabilities decrease exponentially, in the latter they present an oscillation. The interference pattern is more pronounced in the case of ψ', whereas for J/ψ the oscillations stay very close to the exponential. This effect directly influences the suppression factors in pA collisions as we will see. The dominant oscillation frequency in Eq. (4) is $\omega = (E_{2,\ell} - E_{1,\ell})/\gamma$. The deviation from the uncoupled solution becomes stronger the higher the γ factor.

Let us now consider a $c\bar{c}$ pair produced in a pA collision which evolves according to Eq. (4). Integrating over all pos-

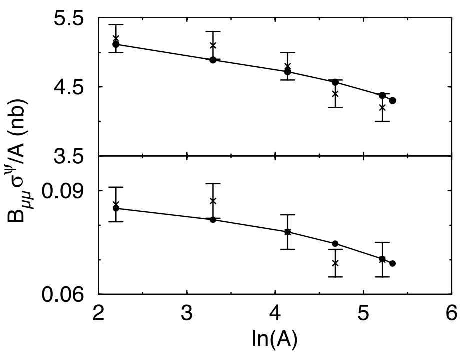

FIG. 2. ψ production cross section times the branching ratio to dimuon production, for the "J/ψ" (top) and ψ' (bottom) at E_p =450 GeV, as a function of the nuclear mass. Data are from the NA50 Collaboration [7]. (The curves are only to guide the eye.)

sible paths $|c_\psi(\infty)/c_\psi(0)|^2$, and giving the ψ survival probability in the nucleus, one gets the $pA\to\psi$ reaction cross section

$$\sigma^{pA\to\psi} = \int d\vec{b}dz\rho(\vec{b},z)\sigma^{pN\to\psi}\left|\frac{c_\psi(t(\vec{b},z))}{c_\psi(0)}\right|^2. \qquad (6)$$

$t(\vec{b},z)$ is the time necessary for a $c\bar{c}$ produced at a point $(\vec{b},z)$ to traverse the nucleus. If one assumes a constant nuclear density, i.e., $\rho=\rho_0\Theta(R-r)$, this time is given by a simple geometrical formula $t(b,z)=(\sqrt{R^2-b^2}-z)/v$, where v is the velocity of the $c\bar{c}$ and R the nuclear radius. Here we use a Woods-Saxon profile for $\rho(\vec{b},z)$. In this case, we determine the survival probability (4) by substituting the time $t(\vec{b},z)$ with the distance covered by the $c\bar{c}$ in the nucleus and directly integrate the survival probability $c_\psi(\vec{b},z)$ in Eq. (6). If $\sigma^{pA\to\psi}=A\sigma^{pN\to\psi}$, the suppression factor, defined as

$$S_A^\psi \equiv \frac{\sigma^{pA\to\psi}}{A\sigma^{pN\to\psi}}, \qquad (7)$$

becomes $S_A^\psi=1$.

Before comparing with the experimental values, the directly produced J/ψ's as well as J/ψ's produced by ψ' and χ_c decays have to be considered. The total J/ψ number is then $S_{pA}^{``J/\psi"}=0.62S_{pA}^{J/\psi}+0.30S_{pA}^{\chi_c}+0.08S_{pA}^{\psi'}$ [6].

Let us first discuss charmonium production as a function of the nuclear mass. The $c\bar{c}$ pair travels along different lengths, spending different time intervals in the nuclei. Experiments with different A explore the time dependence of the $c_{n,\ell}$ amplitudes (Fig. 1). We present results on "J/ψ" and ψ' (Fig. 2) in comparison with data from the NA50 Collaboration [7]. The data are given as branching ratios multiplied by the cross section and divided by the nuclear mass, which only differs from the suppression factor by a constant. (We normalize the data by this constant, determined from the average of the ratio experimental/calculated values.) Our results are in good agreement with the experiment both for "J/ψ" and ψ'. In Fig. 3 we give predictions for the χ_c suppression factor as a function of the nuclear mass. The largest suppression is observed when γ is the lowest, corresponding to a longer time spent in the nucleus.

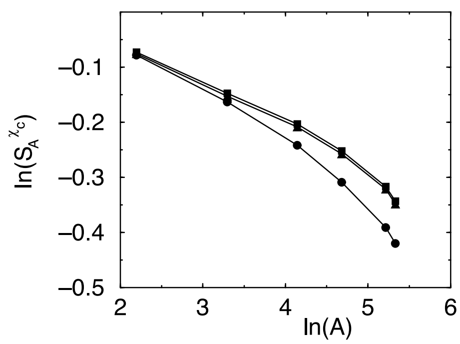

FIG. 3. Predictions for the χ_c suppression factor as a function of the nuclear mass, at γ=5 (circles), 16 (squares), and 21 (triangles).

Let us now look at the x_F dependence. The suppression is often parametrized as $S_A^\psi(x_F,\sqrt{s_{pp}})=A^{\alpha_\psi(x_F,\sqrt{s_{pp}},A)-1}$ [4]. In Fig. 4 the α values for "J/ψ" and ψ' are compared to data from the E866/NuSea Collaboration [8]. In the small positive and negative x_F region, our calculations are in good agreement with the experiment for "J/ψ", whereas the ψ' data are overpredicted. In fact, in the small positive x_F region, the $c\bar{c}$ can traverse the nucleus before developing into a ψ meson. In this kinematic regime, other effects, such as gluon shadowing [24], can play a role.

Finally, we present predictions for the α values (Fig. 5) for "J/ψ", ψ', and χ_c in the negative x_F region, where experimental data from the HERA-B and the PHENIX Collaborations [17] will be available soon. Results for both "J/ψ" and χ_c have a rather flat behavior, whereas ψ' is very sensitive to the x_F values. A stronger variation with the nuclear mass is present for ψ'. This is because the coupling between the charmonium eigenstates affects ψ' much more than J/ψ (and χ_c) (Fig. 1).

Figure 5 also shows that the α parametrization of the suppression (often used with α taken independent of A) is especially not good in the negative x_F region, since there is a strong dependence of the α values on the nuclei.

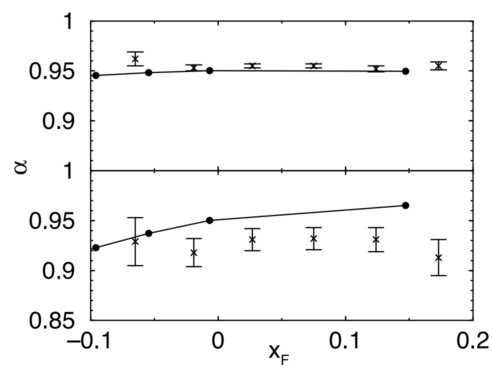

FIG. 4. Calculated and experimental α values for "J/ψ" (top) and ψ' (bottom) as a function of Feynman x_F at E_p=800 GeV. The α values are from W/Be measurements. Data are from the E866/NuSea Collaboration [8].

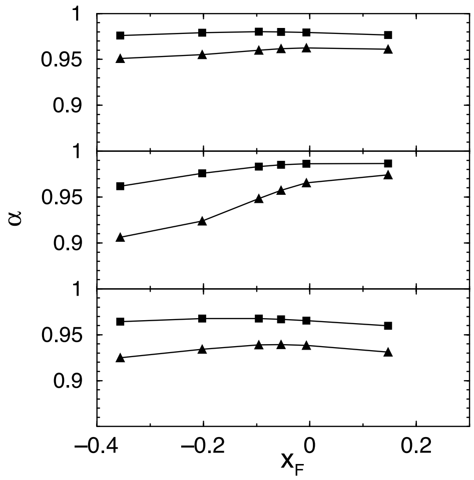

FIG. 5. Predictions for the α dependence of "J/ψ" (top), ψ' (middle), and χ_c (bottom), as a function of x_F, obtained at E_p =800 GeV, for tungsten (triangles) and beryllium (squares).

IV. CONCLUSIONS

In summary, we have studied the production of charmonium $(J/\psi,\psi',\chi_c)$ in relativistic proton-nucleus collisions. We focused on the nuclear effects of the $c\bar{c}$ time evolution and on the charmonium production when the time for a $c\bar{c}$ to develop into a ψ meson is short compared to the time necessary to traverse the nucleus. This kinematic region may be explored experimentally by looking at slow enough $c\bar{c}$ and therefore charmonium produced in the negative x_F region. The quantum-mechanical model used here includes a realistic potential binding for the $c\bar{c}$ pair and an imaginary potential, which describes the collision of the $c\bar{c}$ with the nucleons, and depends on the dipole charmonium-nucleon cross section. The imaginary potential introduces transition amplitudes among charmonium eigenstates. This in turn, produces an interference pattern on the charmonium survival probability, and is particularly pronounced for ψ', and consequently affects the charmonium suppression factors. The results are compared to experimental data from the NA50 and E866/NuSea Collaborations. Predictions on the J/ψ, ψ', and χ_c suppression factors in the fragmentation region of the nucleus are presented for different nuclei. Experiments will be performed soon by the HERA-B and the PHENIX Collaborations. The exploration of the negative x_F region will bring new information on the charmonium-nucleon cross section and on the initial conditions which are currently not well known, especially for χ_c. A better understanding of the mechanisms for charmonium production in proton-nucleus collisions in this yet unexplored region will help us in the interpretation of relativistic nucleus-nucleus collision measurements.

ACKNOWLEDGMENTS

Thanks to Jörg Hüfner for having turned our attention to this problem, and for his suggestions and comments. Thanks to Boris Kopeliovich and Stephane Peigné for discussions and remarks, and to Yuri Yvanov for his help. One of us (C.V.) acknowledges the Institut für Theoretische Physik (Heidelberg), for their warm hospitality.

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[2] J. Badier *et al.*, Na3 Collaboration, Z. Phys. C **20**, 101 (1983).
[3] C. Baglin *et al.*, NA38 Collaboration, Phys. Lett. B **220**, 471 (1989); **255**, 459 (1991); **345**, 617 (1995).
[4] C. Gerschel and J. Hüfner, Annu. Rev. Nucl. Part. Sci. **49**, 255 (1999).
[5] R. Vogt, Phys. Rep. **310**, 197 (1999).
[6] L. Antoniazzi *et al.*, E705 Collaboration, Phys. Rev. Lett. **70**, 383 (1993).
[7] P. Cortese *et al.* NA50 Collaboration, Nucl. Phys. **A715**, 679 (2003).
[8] M. J. Leitch *et al.*, E866/NuSea Collaboration, Phys. Rev. Lett. **84**, 3256 (2000).
[9] M. C. Abreu *et al.*, NA50 Collaboration, Phys. Lett. B **477**, 28 (2000); J. P. Blaizot, P. M. Dinh, and J. Y. Ollitrault, Phys. Rev. Lett. **85**, 4012 (2000); A. Capella, E. G. Ferreiro, and A. B. Kaidalov, *ibid.* **85**, 2080 (2000).
[10] M. Kramer, Prog. Part. Nucl. Phys. **47**, 141 (2001).
[11] P. Hoyer, N. Marchal, and S. Peigné, Proceedings of the CERN 2001–2002 Workshop "Hard Probes in Heavy Ion Collisions at the LHC," hep-ph/0209365.
[12] B. Z. Kopeliovich and B. G. Zakharov, Phys. Rev. D **44**, 3466 (1991).
[13] D. Kharzeev and H. Satz, Phys. Lett. B **356**, 365 (1995).
[14] L. Gerland *et al.*, Nucl. Phys. **A663**, 1019 (2000).
[15] R. Vogt, Nucl. Phys. **A700**, 539 (2002).
[16] B. Z. Kopeliovitch, A. Polleri, and J. Hüfner, Phys. Rev. Lett. **87**, 112302 (2001).
[17] See http://www-hera-b.desy.de/general/info; J.-C. Peng and K. Griffioen (private communications).
[18] L. Frankfurt *et al.*, hep-ph/0301028.
[19] D. Koudela, Diplomarbeit, Heidelberg, 2002; http://www.ub.uni-heidelberg.de/archiv/3043
[20] F. Arleo, P.-B Gossiaux, T. Gousset, and J. Aichelin, Phys. Rev. C **61**, 054906 (2000); Y. B. He, J. Hüfner, and B. Z. Kopeliovich, Phys. Lett. B **477**, 93 (2000); J. Hüfner and B. Kopeliovich, Phys. Rev. Lett. **76**, 192 (1996); J. Cugnon and P. B. Gossiaux, Z. Phys. C **58**, 77 (1993).
[21] W. Buchmüller and S. H. Tye, Phys. Rev. D **24**, 132 (1981).
[22] J. Hüfner, Y. P. Ivanov, B. Z. Kopeliovich, and A. V. Tarasov, Phys. Rev. D **62**, 094022 (2000).
[23] M. C. Abreu *et al.*, Phys. Lett. B **466**, 408 (1999).
[24] B. Z. Kopeliovich and A. V. Tarasov, Nucl. Phys. **A710**, 180 (2002).