Color screening and the suppression of the charmonium state yield in nuclear reactions

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We discuss the negative Feynman-x regime of the new data for the production of the ψ' meson in pA collisions at 450 GeV at CERN-SPS (of the NA50 Collaboration). We extract from the CERN data $\sigma(\psi' N) \approx 8$ mb under the assumption that the ψ' is produced as a result of the space-time evolution of a pointlike $c\bar{c}$ pair which expands with time to the full size of the charmonium state. In the analysis we assume the existence of a relationship between the distribution of color in a hadron and the cross section of its interaction with a nucleon. However, our result is rather sensitive to the pattern of the expansion of the wave packet and significantly larger values of $\sigma(\psi' N)$ are not ruled out by the data. We show that recent CERN data confirm the suggestion of Gerland *et al.* [Phys. Rev. Lett. **81**, 762 (1998); Nucl. Phys. **A663**, 1019 (2000)] that color fluctuations of the strengths in charmonium-nucleon interaction are the major source of suppression of the J/ψ yield as observed at CERN in both pA and AA collisions.

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I. INTRODUCTION

The aim of the present paper is to show that the theoretical description of the production and annihilation yield of particles with hidden charm, which accounts for color fluctuations in charmonium-nucleon interactions, agrees with new data of the NA50 Collaboration [1] who observed quite different J/ψ- and ψ'-nucleon cross sections. Analogous results have been found at negative Feynman x (x_F) in proton-nucleus collisions at 800 GeV at Fermilab by the E866 Collaboration [3]: Both experiments found that the charmonium-nucleon cross section is smaller in the target fragmentation region than at midrapidity. This is in good agreement with models that assume that the ψ' is produced due to a space-time evolution of colorless, pointlike $c\bar{c}$ pairs, which expands with time to its full size and that there exists a relationship between the distribution of color in a hadron and the cross section of its interaction with a nucleon. The agreement of this scenario with the negative x_F Fermilab data [3] was first demonstrated in Ref. [2].

The major new effect is that QCD predicts different interaction cross sections for the interaction of different charmonium states (J/ψ, ψ', and χ) with usual hadrons due to their different spatial size if the cross section is proportional to the distribution of color in the projectile. This relationship is proved in pQCD (perturbative QCD) [4] as equivalent of the QCD evolution equations and it is a plausible suggestion in the nonperturbative QCD regime, which assumes smooth matching with pQCD predictions. If this is so, the ψ'-nucleon cross section is expected to be on the order of the interaction cross section of nucleons with mesons built of light quarks, e.g., the ϕ or the K.

It is a well-known fact that spatially larger hadrons have larger interaction cross sections. For example, the inelastic J/ψ-nucleon cross section was found to be around 3.5 mb at SLAC [5] while the inelastic π-nucleon cross section at these energies is ≈ 20 mb. From charmonium models, e.g., in Refs. [6,7] it is known that the different charmonium states (J/ψ, χ, and ψ') have different spatial sizes. The average relative distances $\sqrt{\langle r^2\rangle}$ with $\langle r^2\rangle = \int \Psi^2(r) r^2 d^3r$ of the $Q\bar{Q}$ pairs are $\sqrt{\langle r^2\rangle}_{J/\psi} = 0.38$ fm, $\sqrt{\langle r^2\rangle}_{\chi} = 0.57$ fm, and $\sqrt{\langle r^2\rangle}_{\psi'} = 0.76$ fm for the wave functions $\Psi(r)$ of Ref. [6].

The relation between the spatial size of a color dipole and the interaction cross section was found in pQCD [4] for a spatially small dipole as another form of the QCD evolution equations. It will be shown in Sec. II E that the charmonium-nucleon cross section predicted from pQCD is significantly smaller than the measured ones. We concluded in Ref. [2] that these cross sections are dominated by nonperturbative contributions. A plausible parametrization within the constituent quark model for this soft contribution is reviewed in Sec. II D.

In Ref. [2] it was shown that the production of J/ψ's in pA collisions can be understood if one takes into account the production and the subsequent decays of higher mass charmonium state resonances (χ, ψ') into J/ψ's. Those higher resonances have larger cross sections for the scattering off nucleons due to their larger spatial size. This leads to a significant increase of the effective absorption of J/ψ's as compared to the propagation of pure J/ψ states. In Ref. [8] it was shown also that the production of J/ψ's in AA collisions is additionally suppressed by the final state interaction of charmonium states with newly produced hadrons such as π's, ρ's, and so on. These interactions of charmonium states with light hadrons are predominantly soft in the SPS regime, because they take place at lower energies than the collisions with the initial nucleons.

The positive Feynman-x regime, i.e., the fragmentation region of the nucleus in pA collisions, is not a subject of this paper. At higher energies the formation time of the charmonium states will be longer due to Lorentz dilatation. Then a hadronic description is no longer useful. In a kinematic regime where charmonium states are formed only after the $c\bar{c}$ pair left the nucleus a partonic description is preferable. A

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model for the positive Feynman-x regime was discussed elsewhere [9].

II. MODEL DESCRIPTION

A. Semiclassical Glauber approximation

The suppression factor S for the charmonium production in minimum bias pA collisions can be evaluated within the semiclassical approximation (cf. Ref. [10]) as

$$S_A = \frac{\sigma(pA \to X)}{A\sigma(pN \to X)} = \frac{1}{A}\int d^2B dz \rho(B,z) \times \exp\left(-\int_z^\infty \sigma(XN)\rho(B,z')dz'\right). \quad (1)$$

$\rho(B,z)$ is the local nuclear ground state density (we used the standard parametrization from Ref. [11]). $\sigma(XN)$ is the interaction cross section of the charmonium state X with a nucleon. We want to draw attention to the fact that this cross section changes with time due to the space-time evolution of color fluctuations. Therefore, it is necessary to keep σ under the integral. In principle one should deal with the expansion effects on the amplitude level. However, numerically the difference is small on the scale of the uncertainties of the modeling of the effect.

We make the standard assumption that the production of $c\bar{c}$ pairs is a hard process and that the QCD factorization theorem is applicable, similar to the Drell-Yan process. In practice this means for Drell-Yan pair production that $S=1$, because $\sigma(pA \to l^+l^-) = A \cdot \sigma(pp \to l^+l^-)$ for Drelly–Yan lepton pairs. Deviations from $S=1$ for the Drell-Yan process can result from nuclear effects on the parton distribution only, which are neglected, because in the kinematics of SPS they are a small correction. However, in contrast to the dilepton pair produced in the Drell-Yan process, the charmonium states have strong final state interactions. They can be split into open charmed hadrons by colliding with other hadrons. Therefore, $0 < S < 1$ for the charmonium states.

The $S=1$ assumption on the level of the charm quark production leads to a restriction on the range of applicability of the discussed model as the gluon distribution is modified at small x due to the shadowing and antishadowing effects. At the very least the requirement is that for very high energies

$$E_{J/\psi} \leqslant \frac{m_{J/\psi}^2}{2x_0 x_P m_N}, \quad (2)$$

where $x_0 \sim 0.03$ is in the region where gluon shadowing sets in. x_P is the Bjorken x of the projectile. For $y_{\text{c.m.}}=0$ the restriction corresponds to $x_0 = m_{J/\psi}/2\sqrt{s}$, because $x_P = x_T$ with x_T the Bjorken x of the target. In addition, as soon as x_A of the nuclear gluon becomes small enough the $c\bar{c}$ pair is produced at a distance $\sim 1/(2x_A m_N)$ from the interaction point and one has to take into account the evolution of the pair before it reaches the interaction point. Hence the picture of the formation of $c\bar{c}$ states in the proton fragmentation region is qualitatively different from that in the nuclear fragmentation region.

The suppression factor S of J/ψ's produced in the nuclear medium is calculated as

$$S = 0.6(0.92S^{J/\psi} + 0.08S^{\Psi'}) + 0.4S^{\chi}. \quad (3)$$

S^X are the respective suppression factors of the different pure charmonium states X in nuclear matter. Equation (3) accounts for the decay of higher resonances after they left the target nucleus into J/ψ's. The fractions of J/ψ's that are produced in the decays of higher resonances in Eq. (3) are taken from Ref. [12]. However, in Ref. [12] it is assumed that the different charmonium states interact with nucleons with the same cross section, which is in disagreement with the data from Refs. [1,3].

In line with the above discussion we want to stress that Eqs. (1) and (3) are applicable at CERN energies for central and negative rapidities, but have to be modified if applied already at $y_{\text{c.m.}} \sim 0$ at RHIC or higher energies, because at higher energies charmonium states can be produced outside of the nucleus and the $c\bar{c}$ pairs propagate through the whole nucleus without forming a hadron.

Data are often presented in the form

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}. \quad (4)$$

The relation between S and α is

$$S = A^{\alpha - 1}. \quad (5)$$

B. Color fluctuations in charmonium rescattering

The first evaluations of $\sigma_{tot}(J/\psi - N)$ have been obtained by applying the vector dominance model (VDM) to J/ψ photoproduction data. This leads to $\sigma_{J/\psi N} \sim 1$ mb for $E_{inc} \sim 20$ GeV. However, the application of the VDM leads to a paradox [13] — one obtains $\sigma_{\text{tot}}(\psi' - N) \approx 0.7\sigma_{\text{tot}}(J/\psi - N)$, although, on the other hand, $r_{\psi'} \approx 2r_{J/\psi}$ in charmonium models such as in Refs. [7,6]. This clearly indicates that the charmonium states produced in photoproduction are in a smaller than average configuration. Therefore, the VDM significantly underestimates $\sigma_{tot}(J/\psi - N)$ and $\sigma_{tot}(\psi' - N)$ [13].

Note that the generalized VDM, which assumes that the dominant process is photoproduction of spatially small $c\bar{c}$ pairs and accounts for the space-time evolution of this pair, predicts significantly larger $\sigma_{tot}(\psi' - N)$ [14].

Indeed, the A dependence of the J/ψ production studied at SLAC at $E_{inc} \sim 20$ GeV exhibits a significant absorption effect [5] corresponding to $\sigma_{abs}(J/\psi - N) = 3.5 \pm 0.8$ mb. It was demonstrated in Ref. [15] that, in the kinematic region at SLAC, the effects due to the space-time evolution of the J/ψ are still small for the formation of J/ψ's and lead only to a small increase of the value of $\sigma_{abs}(J/\psi - N)$. So, in contrast to the findings at higher energies, at intermediate energies this process measures the *genuine* $J/\psi - N$ interaction cross section at energies of $\sim 15-20$ GeV [15]. However, the dynamical effect of the production of charmonium states in squeezed configurations is still there. We account for this effect as due to the propagation of the J/ψ and ψ' system. Experimental evidence for this expansion was found, e.g., in the photoproduction of charmonium states. This will be discussed in Sec. II C.

In the semiclassical Glauber approximation, we take into account these color fluctuations in an effective way as described in Ref. [15]. We assume that a charmonium state X is produced at z as small $c\bar{c}$ configuration, then it evolves — during the formation time t_f ,respectively, while it passes the formation length l_c — to its full size. Please note that there is up to now no theoretical or experimental proof for the assumption that charmonium states are produced in pointlike configurations as predicted in pQCD; a way to test this experimentally was suggested recently in Ref. [16]. Therefore, if the formation length of the charmonium states, l_f, becomes larger than the average internucleon distance ($l_f > r_{NN} \approx 1.8$ fm), one has to take into account the evolution of the cross sections with the distance from the production point $z' - z$ [15]:

$$\sigma(z,z')_X = \sigma(z) + \frac{z'-z}{l_f}[\sigma_X - \sigma(z)] \quad \text{for} \quad z'-z < t_f$$

$$\sigma(z,z')_X = \sigma_X \quad \text{otherwise}. \tag{6}$$

The formation length of the J/ψ is given by the energy denominator $l_f \approx 2p/(m^2_{\psi'} - m^2_{J/\psi})$, where p is the momentum of the J/ψ in the rest frame of the target. With $p = 30$ GeV, the momentum of a J/ψ produced at midrapidity at SPS energies ($E_{\text{lab}} = 200A$ GeV), this yields $l_f \approx 3$ fm, i.e., a proper formation time of $\tau_f = 0.3$ fm.

As formation time of the ψ' in its rest system we use the radius given by nonrelativistic charmonium models, e.g., see Refs. [7,6]. This radius is $r = 0.45$ fm for the ψ'. Please note that this radius differs from the variable r in charmonium models, which rather denotes the diameter of positronium-like states. Within the formation time the cross section increases linearly with the distance from the production point [15,2].

We chose a larger value for the cross section of the $\psi' N$ interaction than for the J/ψ because the radius of ψ' is a factor 2 larger and its radius is larger than the formation time of the J/ψ. A larger value of t_f for the ψ' is supported also by the extraction of the formation time of the J/ψ from e^+e^- data [17].

Recently another attempt to describe the space-time evolution within the formation time was published in Ref. [18]. The authors develop a quantum mechanical model to describe the expansion of the small wave packages. Their initial condition is motivated by the nonrelativistic QCD (NRQCD) approach from Ref. [19]. The charmonium states are described as superposition of six charmonium states (four S waves and two P waves). Diagonal and nondiagonal transitions due to collisions with nucleons are taken into account. In contrast to the generalized VDM (GVDM) in the model of Ref. [18] partons interact with the nuclear target within the formation time. Because this model also leads to a stronger suppression at smaller Feynman x, the $c\bar{c}$ pairs within the formation time have a smaller absorption cross section than the fully formed charmonium states. This is because the formation time decreases with the decrease of the Lorentz factor of the $c\bar{c}$ pairs relative to the nuclear target.

However, we restrict ourselves to the simpler model of Refs. [15,2] because of simplicity and better control over the impact. For a quantum mechanical description such as in Ref. [18] a complete set of states is needed. The contribution of higher S and P states might be small, but the contribution of the continuum, given by open charm states, is unclear (remember that the ψ' is close to the $D\bar{D}$ threshold, and a mixing with $D\bar{D}$ may be relevant for the properties of large size configurations in the ψ', cf. Ref. [20]).

The NRQCD approach for the production of charmonium states is only valid if a large scale exists in the process, e.g., a high transverse momentum. For p_t integrated data, where small transverse momenta dominate, this description does not work. This is because [19] colored states are produced that become color neutral by radiation of gluons. Without a large scale in the process only soft gluons can be emitted, which cannot transport quantum numbers (see, e.g., Ref. [21]). Another problem in Ref. [18] is that a quantum mechanical model is unable to describe the emission of gluons. Therefore in this model the effect of the gluon emission on the $c\bar{c}$ distribution is put in the initial distribution at the production point, though the emission of soft gluons takes a relatively long time.

In our ansatz these deviations from quantum mechanics predicted by quantum field theories are taken into account in an effective way. In the expansion of $c\bar{c}$ pairs suggested in Refs. [15,2] the cross sections of wave packages produced as small size objects increase with time, because the area of the color distribution increases. It is here not important if this increase is due to the motion of the partons or due to radiation of gluons. This scenario can be described like the diffusion of a $Q\bar{Q}$ pair in statistical mechanics, because the total cross section of such a pair does not change due to gluon radiation if one sums over all channels, i.e., over the number of emitted gluons [22].

Reference [23] claimed that the FNAL data on the J/ψ photoproduction contradict the expansion of $c\bar{c}$ pair discussed in Ref. [15]. But Ref. [15] discussed the space-time evolution of $c\bar{c}$ in the inclusive photoproduction of charmonium states ($\gamma + A \to \Psi + X$) for the energies where the coherence length is $l_c \sim 2E_\gamma / M^2_\psi \ll R_A$. In the energy range of FNAL data the coherence length is comparable or exceeds nuclear radius R_A. At high energies the J/ψ is not produced locally as it is the case at the SLAC energies considered in Ref. [15] and hence the analysis of Ref. [15] is not literally applicable — one needs to take into account both the formation of the $c\bar{c}$ before the nucleus and the increase of the cross section of $c\bar{c} - N$ interaction with energy. Besides this Ref. [23] discussed the quasielastic photoproduction of charmonium states $[\gamma + A \to \Psi + p + (A-1)]$. The selection of one specific channel means that there is no summation over all radiated gluons as for the inclusive process. Therefore the model of Ref. [15] should be modified to account for the suppression of gluon radiation. The expansion of the $c\bar{c}$ pair in the kinematics of FNAL photoproduction data is described better by the generalized gluon distribution, i.e., by the well understood QCD evolution, see Refs. [24,25]. In this paper we discuss the total charmonium-nucleon cross sections at moderately large energies. Therefore the expansion model of Ref. [15] should be applicable.

TABLE I. The average square of the transverse distances of the charmonium states and the total quarkonium-nucleon cross sections σ for two different charmonium models. For the χ two values arise, due to the dependence of the wave functions on the third component of the angular momentum m (lm=10, 11). The σ_{hard} values are calculated with Eqs. (9) and (11). $b \leqslant 0.35$ is an upper limit for the integral in Eq. (11). For the row σ(hard, all b) we used a parametrization like Eq. (9) above b=0.9 fm, because in this region Bjorken x becomes larger than 1 and the gluon distribution of Eq. (9) cannot be defined in this region.

$c\bar{c}/b\bar{b}$ state	J/ψ	ψ'	χ_{c10}	χ_{c11}
$\langle b^2\rangle$(fm^2)	0.094	0.385	0.147	0.293
σ(Cornell)(mb)	2.2	9.1	3.5	6.9
σ(ln)(mb)	2.7	13	4.4	8.7
σ(hard, $b<0.35$ fm)	0.42	0.13	0.41	0.28
σ(hard,all b)	2.2	8.2	3.7	7.4

C. Vector dominance model

Somewhat different values for the cross section of the J/ψ- and ψ'-nucleon interaction arise in charmonium models when the cross section is assumed to be determined by the radius of the color distribution within a hadron (Table I) and also in the analysis of photoproduction data within the GVDM [26]. The χ-nucleon interaction cannot be investigated with this model, because it has different quantum numbers than the photon. Therefore, parametrizations such as in Sec. II D are needed to make an educated guess for the χ-nucleon cross section.

The VDM takes into account only the direct diffractive production of the J/ψ and the ψ', while the GVDM accounts also for the nondiagonal transitions ($\psi'+N \to J/\psi+N$ and $J/\psi+N \to \psi'+N$). The latter are needed, because in photoproduction the particles are produced as pointlike configurations and develop then to their average size. In a hadronic model such as the GVDM this is taken into account in form of the interference due to the nondiagonal matrix elements.

In the GVDM the photoproduction amplitudes $f_{\gamma\psi}$ and $f_{\gamma\psi'}$ for the J/ψ and the ψ' are given by [14]

$$f_{\gamma\psi} = \frac{e}{f_\psi} f_{\psi\psi} + \frac{e}{f_{\psi'}} f_{\psi'\psi},$$

$$f_{\gamma\psi'} = \frac{e}{f_\psi} f_{\psi\psi'} + \frac{e}{f_{\psi'}} f_{\psi'\psi'}. \qquad (7)$$

f_ψ and $f_{\psi'}$ are the $J/\psi-\gamma$ and the $\psi'-\gamma$ coupling and $f_{VV'}$ are the amplitudes for the processes $V+N \to V'+N$, where V and V' are the J/ψ and the ψ', respectively. In the VDM the nondiagonal amplitudes with $V \neq V'$ are neglected. The importance of the nondiagonal transitions is evident, because the left-hand side of Eq. (7) is small. If it is neglected as a first approximation [14], then $f_{\psi'\psi} = -(f_\psi/f_{\psi'}) f_{\psi\psi} \approx 1.7 f_{\psi\psi}$, and due to the CPT theorem $f_{\psi'\psi} = f_{\psi\psi'}$. The right-hand side of Eq. (7) is illustrated in Fig. 1.

To get a real description of this expansion, it would be necessary to have a complete set of hadron states, i.e., infinitely many bound S-wave charmonium states plus the continuous spectrum (only S waves have the same quantum numbers as the photon). For illustrating the physics, we restrict ourselves to the contribution of two states only.

In Ref. [26] the GVDM yields 8–10 mb for the ψ'-nucleon interaction cross section at SPS energies. The sign of the photoproduction amplitudes $f_{\gamma\psi}$ of the J/ψ and $f_{\gamma\psi'}$ of the ψ' is positive relative to f_ψ, $f_{\psi'}$ within the conventions of nonrelativistic charmonium models. The sign of the wave functions in the origin is usually chosen to be positive. It is easy to see that a change of this convention would not change Eq. (7). The J/ψ-nucleon interaction cross section at SPS energies $\approx$3.5–4 mb is used as input into the analysis of Ref. [26]. The accuracy of such GVDM in predicting the $\psi' N$ cross sections is not clear. The above calculation demonstrates that implementing color transparency leads to significantly larger cross sections of the $\psi' N$ interaction.

D. Charmonium-nucleon cross section within the charmonium models

One possibility to evaluate the predominantly nonperturbative QCD contribution is to use an interpolation formula for the dependence of the cross section on the transverse size b of a quark-gluon configuration within the constituent quark model,

$$\sigma_{abs} = cb^2, \qquad (8)$$

where b is the distance between the two constituent quarks, transverse to the collision direction. Such a form for the interpolation formula is also supported by pQCD, where the relation

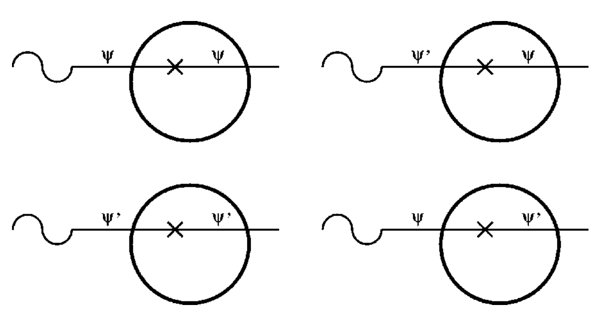

FIG. 1. Schematic illustration of the right-hand side of Eq. (7).

$$\sigma(b) = \frac{\pi^2}{3} b^2 \alpha_s(Q^2) x G(x, Q^2), \tag{9}$$

$Q^2 = 9/b^2$, was found [4] for small b^2 only. Beyond small b^2 Eq. (8) has no justification — it is merely an educated guess.

The constant c can be adjusted within the constituent quark model: $b_\pi^2 = 8/3 r_\pi^2$ and r_π^2 is the square of the pion radius. This radius is known from the vector meson dominance model to be $r_\pi = \sqrt{6}/m_\rho \approx 0.65$ fm [27], $m_\rho \approx 770$ MeV is the mass of the ρ meson. This result is confirmed by measurements of the electromagnetic form factor [28] of the pion. Thus within this model

$$c = \sigma_{\pi N}/b_\pi^2 = 25 \text{ mb}/1.06 \text{ fm}^2 = 23.5 \text{ mb/fm}^2. \tag{10}$$

We use in the following $\sigma_{\pi N} = 25$ mb. This is in good agreement with the data [29] for both energies discussed here, $E_{lab}(\text{CERN}) = 450$ GeV and $E_{lab}(\text{HERA B}) = 920$ GeV, because the energy dependence of this cross section is not so strong in this kinematical region. b_π^2 is increasing with energy as the cross section. Within soliton-type models for the pion, the relation between b and the radius of the pion will be different. Therefore Eq. (8) is model dependent.

The $X-N$ cross section is calculated via

$$\sigma = \int \sigma(b) |\Psi(r)|^2 d^3 r, \tag{11}$$

where $\Psi(r)$ is the charmonium wave function. In our calculations we use the wave functions from two nonrelativistic charmonium models: (1) A Cornell confining potential,

$$V_{Cornell}(r) = -\frac{0.52}{r} + \frac{r}{(2.34 \text{ GeV}^{-1})^2}, \tag{12}$$

see Ref. [6] and references therein, and (2) a logarithmic potential

$$V_{\ln}(r) = -0.6635 \text{ GeV} + (0.733 \text{ GeV}) \ln(r \times 1 \text{ GeV}) \tag{13}$$

from Ref. [7]. We chose two different charmonium models to exhibit the theoretical uncertainties of this approach. The resulting cross sections are given in Table I.

This also resolves the puzzle why in photon-nucleus collisions a smaller (3–4 mb) cross section for the J/ψ was found than in proton-nucleus collisions (6–7.5 mb): In pA collision 40% of the genuine J/ψ's are from decays of χ mesons, which are strongly suppressed in γA collisions, because the χ has angular momentum $L=1$, while J/ψ and ψ' have the same quantum numbers as the photon.

E. Hard cross section

We also calculate $\sigma(X-N)$ assuming that pQCD is applicable. In this calculation we ignore the differences between bare quarks of the QCD Lagrangian and the constituent quarks, because these are nonperturbative QCD effects. The numerical calculations shown in Table I yield at CERN energies $\sigma(X-N)$ values which are significantly smaller than in Ref. [5]. The σ_{hard} values [30] in Table I are also calculated with Eq. (11), but here we integrate only over the region 0 fm $< b <$ 0.35 fm, because α_s increases with b. b is the *transverse distance* between the heavy quarks transverse to the momentum of the heavy quarkonium. For the row σ(hard,all b) we used a parametrization like Eq. (9) above $b = 0.9$ fm, because in this region Bjorken x becomes larger than 1: the gluon distribution of Eq. (9) cannot be defined in this region. For the calculation of the hard cross section, the $\sigma(b)$ in Eq. (11) is given by Eq. (9). We employ the CTEQ5L parametrizations of the gluon distribution functions in the proton [31].

The Bjorken x needed for the calculation of $\sigma_{hard}(X-N)$ is calculated by $x = Q^2/(2 m_N \nu)$, where $Q^2 = 9/b^2$, m_N is the nucleon mass, and ν is the energy of the heavy quarkonium state X in the rest frame of the nucleon. The calculation in Table I is done for a state X produced at midrapidity for SPS energies, but in the target fragmentation region for RHIC and LHC. One can see that the hard contributions to the cross sections are just a correction at SPS energies, but at RHIC energies both contributions become compatible, while at LHC the hard contributions dominate (we neglect here that the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equation might be violated [32]).

The extrapolation of Eq. (9) yields similar values as a parametrization like Eq. (8). This is because the factor $\alpha_s x G(x, Q^2)$ depends only weakly on x and Q^2, even in the region where $Q^2 \ll 1$ GeV^2. This is no proof that parametrizations like Eq. (8) can be applied to charmonium states, but at least it shows that there is no discontinuity between the pQCD result and the parametrizations for the soft regime.

III. EXPERIMENTAL RESULTS

A. Comparison with CERN data

On the left-hand side (lhs) of Fig. 2 we show a comparison between calculations with different cross sections and different expansion times and the NA50 data [1] for pA collisions and the NA51 data [33] for pp and pD collisions for the cross section of $\psi' N$ interaction vs the mass of the target. The y axis shows $B_{\mu\mu}\sigma_{\psi'}/A$ where $B_{\mu\mu}$ is the branching ratio for the decay of the ψ' into dimuon pairs and $\sigma_{\psi'}$ is the production cross section. The "5.1-mb instant formation" curve in Fig. 2 (lhs) is the fit of the NA50 Collaboration to their data. Instant formation means that they assumed that the ψ' is produced with the full cross section and not as a pointlike particle as in the description of this paper. (Note the NA50 Collaboration fitted $B_{\mu\mu}\sigma_{\psi'}/\sigma_{\text{DY}}$, where DY means Drell-Yan, therefore we multiplied their fit with the Drell-Yan cross section in pp collisions measured by NA51).

The "8-mb, $t_f = 0.45$ fm" curve is the eyeball fit of the model described in this paper. For the comparison with the data we need the production cross section of the ψ' in pp collisions as input. We used here the average of the pp and pD data of the NA51 Collaboration. The value of 8 mb agrees well with the model parametrizations discussed in Secs. II A and II B. However, we compare also with the calculation with the parameters of Ref. [2], i.e., $\sigma(\psi' N)$

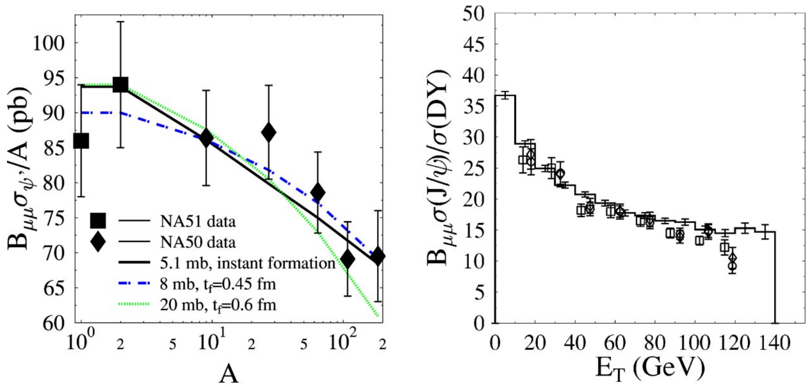

FIG. 2. (Color online) On the lhs are plotted the $B_{\mu\mu}\sigma_{\psi'}/A$ values extracted from calculations with different absorption cross sections and different formation times, the NA51 data for *pp* and *p*D, and the NA50 data for *p*Be, *p*Cu, *p*Ag, and *p*W vs the mass *A* of the target, and the rhs shows $B_{\mu\mu}\sigma(J/\psi)/\sigma(\mathrm{DY})$ with the absorption cross sections from Ref. [2] and the NA50 data for PbPb collisions vs the transverse energy E_t.

=20 mb and t_f=0.6 fm. For this comparison we used the production cross section of the ψ' in *p*D collisions divided by 2 as input. This is also close to the value of the NA50 fit. One can see on the left-hand side of Fig. 2 that the calculation with these parameters is also in good agreement with the data. A value for $\sigma(\psi' N)$ of the size of 20 mb is favored by the nucleus-nucleus data as shown in Ref. [8].

On the right-hand side of Fig. 2 is plotted $B_{\mu\mu}\sigma(J/\psi)/\sigma(\mathrm{DY})$ and the NA50 data [34] for PbPb collisions vs the transverse energy E_t, a measure for the centrality of the collision. The result of the calculation within the ultrarelativistic quantum molecular dynamics model [35] is also shown in form of the histogram in Fig. 2 [right-hand side (rhs)]. In the calculation (for more details see Ref. [8]) for the charmonium-nucleon absorption cross sections the values from Ref. [2] were used. In this calculation the charmonium states can interact also with secondary produced particles. Based on the additive quark model the cross section for charmonium baryon interactions was assumed to be the same as the charmonium-nucleon cross sections and for charmonium meson interactions two-thirds of the charmonium-nucleon cross sections.

The calculation for the J/ψ agrees well with the data. The calculation for the ψ' underestimates the data. However it is not understood if this is due to the high value of $\sigma(\psi' N)$ =20 mb, or if nondiagonal transitions such as in Sec. II C should be taken into account in *AA* collisions, too.

The value of 8 mb for the ψ'-nucleon cross section from the fit to the *pA* is smaller than the theoretical estimate 20 mb of Ref. [2]. This is because in Ref. [2] a formation time of 0.6 fm was chosen for the ψ', while we used here 0.45 fm, the radius of the ψ' given by the charmonium models. The fact that the formation time is not known very well is another uncertainty. Further uncertainty comes from using the diffusion model of expansion at distances comparable to the scale of the soft interaction. Within the error bars the ψ'-nucleon cross section extracted from these *pA* data and the prediction of the GVDM, discussed in Sec. II C, are qualitatively similar. However, further data are needed to learn more about this cross section.

B. Predictions for HERA B

Figure 3 shows our predictions of $S(J/\psi)$ (lhs) and $S(\psi')$ (rhs) for HERA B vs Feynman *x* for *pA* collisions at E_{lab} =920 GeV. Two different nuclear targets, carbon (A=12) and tungsten (A=184), are shown for the two different sets of cross sections resulting from the different charmonium models.

We used here the cross sections of the constituent quark model shown in Table I in Sec. II D, because this model is the only one which predicts also χ-nucleon cross sections. We calculated the suppression factor *S* for the ψ' additionally with a cross section of 20 mb and a formation time of 0.6 fm to estimate theoretical uncertainties. These are the values discussed in Ref. [2].

Note that we plotted in Fig. 3 the result of our model up to a Feynman *x* of 0.2 to show the behavior of the model. However, it is known from E866 [3] and NA3 [36] data that there are additional suppression mechanisms at positive Feynman *x*, e.g., parton energy loss and nuclear shadowing.

IV. CONCLUSIONS

The new data of the NA50 Collaboration [1] and the data of the E866 Collaboration [3] prove that the ψ'-nucleon

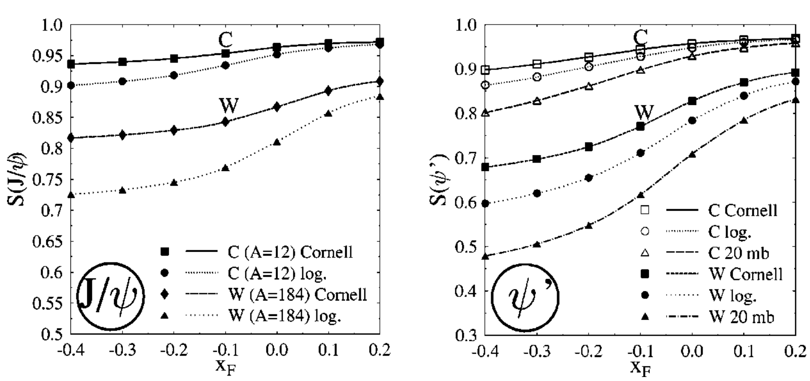

FIG. 3. $S(J/\psi)$ (lhs) and $S(\psi')$ (rhs) are shown vs x_F for carbon and tungsten at HERA B energies (E_{lab}=920 GeV).

cross section is much larger than the J/ψ-nucleon cross section. This is in agreement with the photoproduction data for these charmonium states as discussed in the framework of the GVDM in Sec. II C. This confirms the QCD prediction that the strength of hadron-hadron interactions depends on the volume occupied by color.

Within the assumption that charmonium states are produced as pointlike white states, we demonstrated that the data [1] can be fitted with a ψ'-nucleon cross section of $\sigma(\psi' N) \approx 8$ mb. We discuss different models for this cross section and show that they prefer a ψ'-nucleon cross section of $\sigma(\psi' N, \text{model}) = 9-13$ mb. However, due to the large experimental errors we conclude that the data and the QCD-motivated models agree, further data with higher accuracy and covering a larger rapidity range in the fragmentation region of the nucleus are needed.

This cross section will be measured soon in proton-nucleus collisions at HERA B at an energy of $E_{lab} = 920$ GeV. The advantage of this experiment is that it covers a larger range of Feynman x_F, especially in the negative x_F region. In this region effects due to the formation time of the hadron will be less important. These data will give new information about the relations between the size of mesons and the strength of hadron-hadron interactions as well as the possibility to test the existing models for this relation.

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