The cross section between a $c\bar{c}$ pair and a nucleon is small and sensitive to the $c-\bar{c}$ separation if the pair is in a color-singlet state, but very large and insensitive to the separation if it is in a color-octet state. We use this property in an absorption model involving both color components to deduce the color structure of $c\bar{c}$ pairs produced in $p(B)A \rightarrow \psi X$ reactions. Our analysis shows that if the NA3, NA38 and E772 data are not inconsistent with the theoretical picture that color-octet and color-singlet precursors are produced in roughly equal proportions if the produced color-singlet precursors are pointlike and transparent. However, if the color-singlet precursors are not transparent but have a cross section of a few mb, these data do show a definite preference for a larger fraction of color-singlet precursors. In either case, the color-octet fraction increases with $x_F$, approaching unity as $x_F$ becomes large.

I. INTRODUCTION

There has been much recent interest in the mechanisms of heavy quarkonium production. Bodwin, Braaten, and Lepage have developed a factorization formalism based on nonrelativistic quantum chromodynamics (NRQCD) for very massive quarks, a formalism that allows a systematic calculation of inclusive $J/\psi$ production cross sections. The formalism accounts for the production of both color-singlet ($C1$) and color-octet ($C8$) $c\bar{c}$ precursor states that will evolve into $C1$ quarkonium states. It has been used to study many heavy quarkonium production processes.

In NRQCD, production amplitudes are expanded in powers of both the strong coupling constant $\alpha_s$ and the velocity $v$ of the heavy quark. For hadroproduction of quarkonia at fixed-target energies of several hundred GeV, the lowest (called hereafter the “leading”) order in $J/\psi$ production turns out to be $\alpha_s^3 v^5$ for $C1$ precursors, and $\alpha_s^2 v^7$ for $C8$ precursors. Theoretical analyses have shown that in these leading orders, the total $J/\psi$ production comes from $C8$ and $C1$ precursor states in roughly equal proportions.

However, for hadroproduction of $J/\psi$, $\psi'$ and $\chi$ with low $p_t$ at fixed-target energies, the calculated lowest-order results of this double expansion seem to disagree with the observed polarization and production rates of $J/\psi$ and $\chi_{1,2}$. Although one can adjust input parameters to fit the observed production rates, the discrepancy with the polarization data remains. This seems to indicate a need for higher-order quarkonium production mechanisms at these energies.

One of the important parameters that characterize the nature of these quarkonium production processes is the color-octet fraction at production. We would like to point out in this paper that this information can be extracted from the observed nuclear suppression of $pA$ or $BA \rightarrow \psi X$ cross sections. The possibility arises because the produced $C8$ precursors are expected to be absorbed much more strongly than $C1$ precursors.

This possibility is realized by generalizing the absorption model, in Sec. II, to handle these two color components. The color dependence of $c\bar{c}$-$N$ cross sections are then reviewed in Sec. III to provide a theoretical background against which the analysis of the available experimental data for low $p_t$ $J/\psi$ production at fixed-target energies will be made, in Sec. IV, using our two-component absorption model.

Our analysis shows that the data are not inconsistent with the theoretical picture that $C8$ and $C1$ precursors are produced in roughly equal proportions if the $C1$ precursors are produced in pointlike transparent or noninteractive states. However, when freed from these prevalent theoretical prejudices, the available data do show a definite preference for a larger fraction of $C1$ precursors if they are produced, and are propagating, in states that are significantly absorbed by the nuclear medium. In either case, the $C8$ fraction increases with the Feynman $x_F$, approaching unity as $x_F$ becomes large.

Additional implications of our models are briefly discussed, and the need for more experimental absorption data is noted, in the concluding Sec. V.

II. A GENERALIZED ABSORPTION MODEL WITH TWO COLOR COMPONENTS

In NRQCD, dynamical processes in NRQCD are controlled by various time scales: (1) the quark-antiquark production time $1/M$ where $M$ is the $c$ quark mass, (2) the time for orbital motion in quarkonium $1/Mv \approx r \approx \sqrt{1/\Lambda_{QCD}^2}$, where $r$ are the characteristic spatial extension of the quarks in the $c\bar{c}$ pair and $\Lambda_{QCD}$ is the QCD confinement scale, and (3) $1/Mv^2 = 1/\Lambda_{QCD}^2$ for ei-
ther the characteristic time for the c ¯c pair to be blown up from a point to quarkonium size, or equivalently the QCD confinement time. The C8 precursor will eventually hadronize into C1 J/ψ mesons by color neutralization through the absorption or emission of soft gluons by the end of the strong-interaction time.

The traditional understanding is that this color-neutralization process takes place over a much longer nonperturbative QCD time scale of about 1/A_{QCD} ≈ 0.5 fm/c in the c ¯c rest frame. In this frame, the longitudinal spacing between target nucleons in a pA reaction is d/γ(x_F), where d = 2 fm is the internucleon spacing in a nucleus at rest and γ(x_F) is the relativistic energy/mass ratio of the moving target nucleons,

\[ \gamma(x_F) = \sqrt{s_{NN}} \left\{ \sqrt{m_{J/\psi}^2 + x_F^2 s_{NN}^2/4} + p_{t,J/\psi} \right\} / (2 m_{J/\psi} m_N), \]

where p_{t,J/ψ} is the transverse momentum of the produced J/ψ, and \(< p_{t,J/\psi} >= 1.26 \text{ GeV}^2 \). Thus, the dynamics of J/ψ propagation after production in nuclei is further controlled by the passage time d/γβ = d/(γ^2 - 1)^{1/2} the next target nucleon takes to meet the produced c ¯c pair. Since the value of γ(x_F) can be large in high-energy pA collisions (about 15 at x_F = 0 when the NN c.m. energy is \( \sqrt{s_{NN}} = 30 \text{ GeV} \)), one finds d/γβ(x_F) << 0.5 fm/c for x_F > 0 at fixed-target energies of several hundred GeV. Therefore, for pA collisions in fixed-target experiments, many of the collisions between target nucleons and the produced (c ¯c)s pair with x_F > 0 are expected to take place before its color is neutralized. This is particularly true at higher energies where the Lorentz contraction is stronger.

The collisions of this C8 c ¯c pair with target nucleons at high energies have been studied earlier by Kharzeev and Satz [32]. They have argued that these collisions do not lead to absorption (the eventual breakup of the c ¯c system). They assume instead that the pair will stay together as it traverses the medium, suffering only quasi-elastic scatterings caused by stretchings of the (c ¯c)s string that shift the same integrated production cross section to lower x_F. To account for the nuclear suppression shown in the data, they appeal to the idea of gluon shadowing, i.e. the assumption of a nuclear modification of the gluon density of target nucleons that depends only on the fractional momentum x_2 carried by the target partons [33,34].

We would like to describe here a very different picture of J/ψ suppression in nuclei based on a generalization of the standard absorption picture of [24,35]. A precursor can remain in the same precursor state after colliding with a target nucleon, but its transformation into other precursors through the exchange of a Pomeron or a hard gluon cannot in general be avoided. The only exception is for C1 precursors in the pointlike, or color transparency, limit, a situation we shall discuss further below. The c ¯c precursor could still stay close together, but its future fate in the absence of further collisions is already determined in this precursor representation of states. When the precursor remains in its original precursor state after scattering, we have elastic scattering. All other scattering processes contribute to the reaction cross section σ_r.

We begin by considering the hard scattering between a parton of the projectile nucleon and a parton of a target nucleon inside a nucleus with A nucleons, a hard scattering that produces both C1 and C8 precursor (c ¯c) pairs which will evolve into various quarkonium and open-charm meson states. The probability element for precursor production by the collision at a target nucleon at \( r_A = (b_A, z_A) \) is

\[ \rho(b_A, z_A)db_A dz_A, \]

where the density distribution is normalized by

\[ \int \rho(r_A)dr_A = 1. \]

A produced precursor will collide with target nucleons along its path with a (c ¯c)-N reaction cross section of σ_r. The probability of the precursor colliding with a target nucleon is therefore

\[ T_{A>}(b_A, z_A)σ_r, \]

where

\[ T_{A>}(b_A, z_A) = \int_{z_A}^{\infty} \rho(b_A, z'_A)dz'_A, \]

and \( T_{A>}(b_A, -∞) = T_A(b_A) \), the usual thickness function. Thus, the probability for the precursor to collide with n target nucleons and miss the other \((A - 1) - n \) target nucleon is

\[ \binom{A - 1}{n} [T_{A>}(b_A, z_A)σ_r]^n[1 - T_{A>}(b_A, z_A)σ_r]^{(A - 1) - n}. \]

After the precursor has collided with the target nucleons, the precursor will be in different degrees of woundedness. We denote by S_n the probability of finding the J/ψ precursor (which will eventually evolve into a J/ψ) at the end of the strong-interaction time) after colliding with n target nucleons. The meson production cross section in a pA collision with a nuclear target of mass number A can then be related to the production cross section in nucleon-nucleon collision by

\[ \frac{dσ^{pA}_{J/ψ}/dx_F}{A dσ^{NN}_{J/ψ}/dx_F} = \int \rho(b_A, z_A)db_A dz_A \sum_{n=0}^{A-1} S_n \binom{A - 1}{n} \times[T_{A>}(b_A, z_A)σ_r]^n[1 - T_{A>}(b_A, z_A)σ_r]^{(A - 1) - n}. \]
By integrating over $z_A$ and extending the above considerations to include both C1 ($i = 1$) and C8 ($i = 8$) components, we obtain the $x_p$-dependent nucleon to nucleon yield ratio per nucleon for the quarkonium under consideration:

$$R(pA/NN, x_p) = \frac{d\sigma^{pA}_{J/\psi}/dx_F}{Ad\sigma^{NN}_{J/\psi}/dx_F} = \sum_{i=1,8} f_i(x_p) \sum_{n=0}^{A-1} S_{i,n} R_{i,n}(A), \quad (5)$$

where $f_i(x_p)$ is the $(c\bar{c})_i$ fraction normalized to $f_1 + f_8 = 1$, and

$$R_{i,n}(pA) = \int \frac{db_A}{\sigma_{ir}} \sum_{m=0}^{n} \left( A - 1 \right) \times \left( \frac{n}{m} \right) \frac{(-1)^m}{A - n + m} \left[ 1 - \left( 1 - T_A(b_A)\sigma_{ir} \right)^{A-n+m} \right]. \quad (6)$$

This is our generalized absorption model.

It is clear that when a $J/\psi$ precursor produced at a nucleon site passes through the rest of the target nucleus without further collision, it will evolve into a final-state $J/\psi$ as if it had been produced in a pN collision in free space: a C1 precursor will evolve into a $J/\psi$, while a C8 precursor $(c\bar{c})_8$ will evolve into a $J/\psi$ with the additional absorption or emission of a soft gluon after a relatively long QCD color neutralization time that is still short compared to electromagnetic interaction times. Because of this, $S_{i,0}$ is unity by definition. Furthermore, $f_i$ are the actual color fractions right after production at the production site of a target nucleon.

A minor complication should now be mentioned. In addition to the direct production considered so far, the experimental detector also counts $J/\psi$ particles that come indirectly from radiative decays of excited quarkonium states, particularly the $\chi_{1,2}$ mesons. These indirect contributions can simply be added to the direct contribution in both the numerator and the denominator differential cross sections that make up the yield ratio $R$ in Eq. (3). Equivalently, as we choose to do from now on, we can re-define our precursor states so that they include both direct and indirect $J/\psi$ mesons that will enter the experimental detector.

The original collision at a production site produces precursors not only for the final $J/\psi$, but also for all other permissible hadronic final states not included in the experimental yield for $J/\psi$ production. Hence these other precursors do not contribute to our model formula when there is no further collision at the target nucleus.

Let us consider next a precursor that suffers one or more collisions in the target nucleus after production. At the end of all these collisions, the original $J/\psi$ precursor will be transformed into precursors for all possible final hadronic states including $J/\psi$, with a total probability of 1. At the same time, other precursors different from the $J/\psi$ precursor, all produced at the original target nucleon site, will be changed into $J/\psi$ precursors with some finite probabilities. The normalized probability $S_{i,n}$ for $n \geq 1$ is just the population of $J/\psi$ precursors present after $n$ collisions with target nucleons, normalized to a $J/\psi$ precursor population of $S_{i,0} = 1$ for precursors that escape any hit. Containing contributions from all precursors produced at the production site, it describes the probability of recovering a $J/\psi$ precursor after $n$ precursor-nucleon collisions.

These recovery probabilities are relatively complicated quantities that contain the effects of available phase space and of coherent coupled-channel dynamics [22]. A simple assumption one can make is that on the average a certain fraction of $\sigma_{ir}$ is recoverable, while the remainder, denoted the effective absorption cross section $\sigma_{i,abs}$ in nuclei, is irrevocably lost. Using this fractional $\sigma_{i,abs}$ in our formulas, we should now set all recovery probabilities $S_{i,n}$ for $n \geq 1$ to zero, because precursors are now, by definition, irrevocably lost after each hit by the effective $\sigma_{i,abs}$. Generalizing to nucleus-nucleus (BA) collisions, we obtain the following equation for the $x_p$-dependent nucleus-nucleus to nucleon-nucleon yield ratio per target nucleon per projectile nucleon for $J/\psi$ production:

$$R(BA/NN, x_p) = \sum_{i=1,8} f_i(x_p) R_i(BA), \quad (7)$$

where $f_i(x_p)$ is the $(c\bar{c})_i$ fraction normalized to $f_1 + f_8 = 1$, and

$$R_i(BA) = \int \frac{d\sigma_A}{A\sigma_{i,abs}} \frac{d\sigma_B}{B\sigma_{i,abs}} \times \left\{ \frac{1 - \left( 1 - T_A(b_A)\sigma_{i,abs} \right)^B}{1 - \left( 1 - T_A(b_A)\sigma_{i,abs} \right)^A} \right\}. \quad (8)$$

This is just the familiar “simple” absorption model, now generalized to handle two color components. The absorption cross sections that appear are effective values in the nuclear medium involving precursors not at the moment of their production, but when they hit the next nucleon in the colliding nuclei.

In generalizing the $pA$ result of Eq. (4) to Eq. (5) for BA collisions, we have made the implicit assumption that the absorption of the precursor of $J/\psi$ due to its collision with produced soft particles is not important in BA collisions. This is because the average relative kinetic energy between the produced particles and the precursors of $J/\psi$ is smaller than the threshold energy (about 640 MeV) for the precursor to breakup. It is further supported by comparing experimental $pA$ and $AB$ data [30].
From the perspective of our generalized absorption picture, the model of Ref. [35] contains only elastic scattering of precursors and no absorption at all. With no absorption present, the authors are forced to introduce another source of absorption based on gluon shadowing.

Gluon shadowing describes a change in the momentum distribution of a parton in a nucleon in the target as compared to that in free space. The momentum distribution of a projectile parton is also changed because of the loss of initial energy due to collisions before the hard scattering at the production site. These shadowing effects are real, and they should be included in a complete theory. However, they appear to be small, as evidenced by the weak dependence of the charm yield per nucleon on the target mass number $A$ in $pA$ collisions given by $A^{0.00\pm0.05\pm0.02}/A$ for $x_F$ from 0.05 to 0.4 [17]. Therefore, we shall not include them in our analysis.

###III. COLOR-DEPENDENCE OF ($c\bar{c}$)-$N$ CROSS SECTIONS

For the absorption cross sections needed in Eq. (6), we rely conceptually on the fact that high-energy hadron-hadron cross sections are dominated by Pomeron exchange [14][15]. In the Two-Gluon Model of the Pomeron (TGMP) studied by Low, Nussinov and others [17–24], the flavor dependence of the total cross sections is a size-dependent effect arising from the color separation in colorless hadrons. The total hadron-nucleon cross section can be expressed as $T_1 - T_2$, where $T_n$ is the contribution in which the two exchanged gluons interact with $n$ particles (here quarks) in the projectile. The cross section vanishes if one of the colliding hadrons shrinks to a point, because in this limit $T_2 = T_1$. In this point limit, the hadron cannot even scatter into intermediate C8 states by single gluon exchange because it is color neutral. Thus pointlike C1 precursors are transparent in the nuclear medium, with zero total cross section when the colliding energies are sufficiently high so that meson-exchange contributions become unimportant. This phenomenon of “color” transparency is the transparency of pointlike colorless hadrons in a nuclear medium of large colorless nucleons. (For a recent review of color transparency, see [24].)

If the C1 precursors are produced in pointlike states, and if the collision energies are so high that the passage time to the next target nucleon is too short for such pointlike precursors to grow much in size, these C1 precursors will be quite transparent as they propagate in the nuclear medium. Under the circumstances, nuclear absorption in $J/\psi$ production can only come from the absorptive C8 precursors. This gives us a window for watching C8 precursors in $J/\psi$ production. It will be interesting to find out the extent to which this theoretical picture is actually supported by the experimental data on nuclear suppression.

The cross section is very different for $(q\bar{q})$-$N$ scattering, however, as pointed out by Dolejsi and Hufner [22]. This is because the one- and two-quark contributions now add together in the form of $T_1 + T_2/8$. The result is then insensitive to the $q\bar{q}$ separation in C8 precursors.

Recently, this TGMP for both singlet and octet $(q\bar{q})$-$N$ scattering has been studied in detail by one of us [24]. The main motivation is to understand why the experimental cross sections for radially excited mesons of much larger sizes are actually close to one another in value. This unexpected feature can be understood in the TGMP if the mesons are propagating in an eigenmode with a common eigen cross section because of strong coupling between them. In addition, a detailed model has been fitted in [24] that contains a number of important refinements: (1) A nonperturbative gluon propagator (the Cornwall propagator) is used [25][26] with the gluon mass obtained by fitting the $\pi N$ and $KN$ total cross sections. (2) Complete meson form factors are used without making the small meson approximation. (3) For (singlet meson)-$N$ scattering, a coupled-channel problem [40] is solved using many scattering channels containing radially excited mesons. By fitting $NN$ cross sections and the ratios of (meson-$N$)/$NN$ cross sections, the extrapolated octet $(c\bar{c})_8 - N$ total cross section, to be denoted $\sigma_8$, turns out to be 48 mb, in agreement with the range of 30–60 mb found by Dolejsi and Hufner [22]. These color-octet cross sections are quite insensitive to meson size and flavor contents.

We shall need in our analysis that part of the reaction cross section denoted in this paper as the effective $\sigma_{sabs}$ in nuclei. A $c\bar{c}$-$N$ collision at high energies can be expected to cause the $c\bar{c}$ pair to be broken up, i.e. removed from the $J/\psi$ channels, with relatively little elastic or quasi-elastic scatterings. In the nuclear medium, however, this reaction cross section must be reduced by its fractional recovery in subsequent collisions. Hence we shall use the estimated theoretical value only for conceptual guidance, and shall try to find out what the data might tell us about this cross section.

To complete our review of Pomeron exchange cross sections, we should point out that the color-singlet $(c\bar{c})_1$-$N$ total cross section in free space, to be denoted $\sigma_1$, can be estimated in a number of ways. The model fitted in [24] gives a result of 5-6 mb at $\sqrt{s} = 20$ GeV, but requires an input of the $J/\psi$ meson rms radius, for which we have only theoretical estimates. A result of at least
2.5 mb at this energy has been calculated by Kharzeev and Satz [11] from hadron gluon structure functions in short-distance QCD. A third estimate can be made by converting the experimental forward $J/\psi$ photoproduction cross section [12] to a total $\psi-N$ cross section with the help of vector-meson dominance (VMD), i.e., the idea that the photon actually contains a small admixture of vector mesons. This gives $\sigma_1 \approx 1.8$ mb at $\sqrt{s} = 20$ GeV. However, the VMD model is known to underestimate the $\rho-N$ cross section by about 15% and the $\phi-N$ cross section by about 50% [13]. This could mean that $\sigma_1$ should be larger, perhaps around 2 to 3.5 mb. Although these three estimates are only in rough agreement with one another, they are all an order of magnitude smaller than $\sigma_8$.

All these estimates are for the “asymptotic” total cross section in one c$\bar{c}$-nucleon scattering, and without the additional $s$ dependence appropriate to the Pomeron dominance of the cross sections at high energies [16]. We are interested only in its absorptive part in nuclei, after the recovery corrections mentioned previously. There is, in addition, a threshold effect which reduces the cross section more and more below its asymptotic value the lower the collision energy [11]. Hence we shall adopt a more opportunistic phenomenological approach in choosing $\sigma_{1,\text{abs}}$ in our model analyses.

### IV. THE COLOR-OCTET FRACTION

We are now in a position to extract the $C_8$ fraction $f_8$ from the experimental cross section or yield for $J/\psi$ production in nuclei by using Eq. (1). We first analyze the experimental $x_F$ integrated yields as functions of the target mass number $A$ at fixed-target energy of 800 GeV of the $pA$ data (E772 Collaboration) [22] and at 200 GeV of the combined $pA$ data (NA3 Collaboration) [31] and $BA$ (nucleus-nucleus) data (NA38 Collaboration) [32]. (The average values of the kinematical variables in the experimental data at 800 GeV are $<x_F> \approx 0.27$ and $<p_t> \approx 0.7$ GeV [32].)

The results for the $C_8$ fraction $f_8$ obtained in our model analysis are shown in Fig. 1a as functions of $\sigma_{8,\text{abs}}$ for the color-transparency choice of $\sigma_{1,\text{abs}} = 0$. The associated $\chi^2$ per degree of freedom of the model fit to data are given in Fig. 1b. We see that the best fit to the E772 data appears at $\sigma_{8,\text{abs}} = 15$ mb, a value that is considerably smaller than the best theoretical asymptotic value of 48 mb. However, the data are consistent with a rather wide range of range $\sigma_{8,\text{abs}}$. The fit is noticeably poorer for the 200 GeV data, which show a preference for much smaller values of $\sigma_{8,\text{abs}}$. This is probably only partially due to the threshold effect mentioned previously.

At 800 GeV, the extracted $C_8$ fraction $f_8$ at best fit is about 0.8, but the fraction decreases with increasing $\sigma_{8,\text{abs}}$, being about 0.55 at $\sigma_{8,\text{abs}} = 30$ mb. The results at 200 GeV are noticeably smaller, being usually below 0.5.

It is interesting to compare our results with the information on the $C_8$ fraction at production deduced from analysis of production data on nucleon targets. A theoretical analysis of the 300 GeV CDF data on the $\pi N \rightarrow (J/\psi)X$ by Tang and Vanttinen [4] has yielded a theoretical $C_8$ fraction from both direct production and indirect production (from their Table 1) of $0.20/(0.20 + 0.14) \approx 0.59$. However, the total theoretical $J/\psi$ production cross section is only 0.38 of the observed value. (Indirect production comes from the radiative decays of excited quarkonium states, primarily $\chi_{1,2,\cdots}$).

![Graph](image_url)
where C8 precursors are strongly absorbed. The C8 fractions that come out of this model are quite substantial, in agreement with independent analyses of hadron production rates in free space.

It is now worth asking if the available nuclear suppression data require color transparency. To answer this question, we look for models with nonzero $\sigma_{1 \text{ abs}}$. Nonzero absorption for C1 precursors means that they have a substantial size when they hit a nucleon after production. At fixed target energies, these C1 precursors usually do not have enough time to grow enough in size if they had been produced pointlike. Thus significant C1 absorption usually means that these precursors are produced with finite sizes.

![Graph](attachment:image.png)

**Fig. 2.** Same as Fig. 1 but for $\sigma_{1 \text{ abs}} = 3.5 \text{ mb}$.  

Fig. 2 gives the results for model fitting using $\sigma_{1 \text{ abs}} = 3.5 \text{ mb}$, close to many of the values estimated for the J/ψ-N cross section in free space, as reviewed in Sec. III. We see that the fits are comparable to those shown in Fig. 1 for the E772 data, and they are better for the 200 GeV data. Similar fits can be obtained for the E772 data at $\sigma_{1 \text{ abs}} = 6.7 \text{ mb}$, the best-fit value if $\sigma_{8 \text{ abs}}$ is fixed at the theoretical value of 48 mb. However, the 200 GeV data cannot be fitted well with this large value of $\sigma_{1 \text{ abs}}$. One common feature of these models with fairly large $\sigma_{1 \text{ abs}}$ is that the C1 precursors are now providing a substantial part of the experimental nuclear suppression. Hence the octet fraction $f_8$ needed is reduced. Fig. 2 shows that for the 200 GeV data, the extracted $f_8$ is usually less than 0.2. This is much smaller than the octet fraction found in the theoretical picture of hadron production given in leading-order NRQCD [3–5].

Our phenomenological analyses seem to show that the available data alone are not sufficiently discriminating to tell us if the C1 precursors are transparent because they are produced pointlike, or if they are easily absorbed because they are produced at almost full size.

![Graph](attachment:image.png)

**Fig. 3.** The color-octet fraction $f_8$ as a function of $x_F$. (a) is for $\sigma_{1 \text{ abs}} = 0 \text{ mb}$, and (b) is for $\sigma_{1 \text{ abs}} = 3.5 \text{ mb}$.  

We next analyze the $x_F$-dependent experimental yields for the pA data using $\sigma_{8 \text{ abs}} = 20 \text{ mb}$ and $\sigma_{1 \text{ abs}} = 0 (3.5) \text{ mb}$. The results for the C8 fraction $f_8$ are given in Fig. 3a (3b). The error bars shown describe only the uncertainties from data fitting for the chosen values of $\sigma_{8 \text{ abs}}$. The effects coming from the uncertainties of the chosen absorption cross sections themselves can be seen by comparing the results of Figs. 3a and 3b, but we should also remember that these figures describe rather different physical models, one with color transparency and one with significant C1 absorption. These figures seem to show that for $x_F > 0.5$, the C8 fraction $f_8$ is rather close to 1, and seems to scale in $x_F$.

To account for the abnormally small yields at large $x_F$, Badier et al. [31] have to postulate the existence of a new mechanism of J/ψ production. We have attributed this phenomenon instead to the presence of a greater fraction of C8 precursors and to their strong absorption as they propagate in nuclear matter. Fig. 3 also shows that below $x_F = 0.5$, the extracted $f_8$ fraction seems to decrease with decreasing collision energy. The decrease is very dramatic when $\sigma_{1 \text{ abs}}$ is large.

A tantalizing possibility is that it is not so much the
production mechanisms themselves that are strongly energy dependent, but rather that the produced precursors at different energies have different times to evolve before hitting the next nucleon. For example, the precursors might have been produced predominantly in C8 states, as suggested by the leading-order NRQCD calculations, but their colors might have been neutralized in a time-dependent way after production. It is therefore interesting to plot the deduced C8 fraction against the passage time $t_p = d/\gamma \beta$ for the two models shown in Fig. 3. The results, given in Fig. 4, show that the low-$x_p$ points might indeed depend smoothly on $d$, but unfortunately the points from the two data sets do not overlap so that we cannot establish a case for this dependence at low-$x_p$.

V. DISCUSSION AND CONCLUDING REMARKS

A scenario rather close to premature color neutralization has been proposed by Kharzeev and Satz [44]. They have suggested that by the time the $(c\bar{c})_8$ pair leaves the nucleon where it was produced, its color has already been neutralized by the pickup of an additional gluon to form a $J/\psi$ precursor that is a $(c\bar{c})_8-g$ hybrid [13]. Nuclear suppression comes from hybrid absorption in hybrid-nucleon collisions. They estimate that the required effective absorption cross section of about 6 mb for the integrated yield is consistent with a hybrid size of $r_h \approx 1/\sqrt{2M_{QCD}} \approx 0.2 - 0.25$ fm. It is not immediately clear that this estimate of $r_h$ is theoretically reliable since it is also an estimate for the size of the quark wave function in the quarkonium. One would naively expect that with increasing quark mass $M$, the hybrid size would decrease more slowly than the quarkonium size, and perhaps not at all, if the effective gluon mass does not change much with the quark mass $M$.

This hybrid picture has been used in [24] to interpret the effective absorption cross section as a function of $x_p$ obtained by us in a preliminary version of our analysis based on the standard one-component analog of Eq. (6). In the TGMP of hybrid-nucleon scattering, the total cross section is approximately $(9/4) \sigma_{1\text{ abs}}$ if the $(c\bar{c})_8$ constituent is treated as a point particle, and if the average $(c\bar{c})_8-g$ separation is the same as that between the quark and the antiquark in the $(c\bar{c})_1$ quarkonium. However, the hybrid-nucleon cross section can be made to vary by changing the hybrid size. The $x_p$ dependence of the deduced effective absorption cross sections can then be translated into an $x_p$ dependence of the hybrid size, with the rms separation between the $(c\bar{c})_8$ and $g$ ranging from about $0.14 \pm 0.02$ fm for $x_p = 0.07$ to $0.5 \pm 0.15$ fm at $x_p = 0.6$ [24]. The picture seems to be that the gluon separation from the $c\bar{c}$ pair in the hybrid is larger the higher the precursor energy.

The description given in Fig. 3 of the $x_p$ dependence of $J/\psi$ absorption in terms of a change in the C8 fraction also differs from the explanation given by [13] based on the energy loss of initial-state partons, the modification of initial target parton momentum in nuclei, and the energy loss of final-state $c\bar{c}$ systems. The experimental open-charm production cross section in $pA$ collisions has been found to behave as $A^{1.00 \pm 0.05 \pm 0.02}$ [27] for $x_p$ from 0.05 to 0.4. Such a behavior implies that the initial-state effects of energy loss and the modification of initial target parton momentum distribution in nuclei are small. Thus, the initial-state effects on $J/\psi$ production should also be small. Furthermore, the final-state precursor-$N$ collisions involved are high-energy processes that are more likely to lead to eventual breakup than to energy loss by quasi-elastic scattering.
Our absorption models have interesting implications in another aspect of the nuclear absorption problem. The experimental nuclear suppression of produced $\psi'$ mesons appears to be quite similar to that for $J/\psi$ mesons. For C1-dominated absorption models, this could be understood only as a coupled-channel effect, with different mesons propagating in nuclei in the same coherent eigenmode and therefore the same “eigen” cross section. The need for coherent propagation is greatly reduced in C8-dominated models, since the cross sections between C8 precursors and nucleons are now size-insensitive, and about the same for C8 precursors of different $c\bar{c}$ separations. Also cross-channel matrix elements are likely to be quite small for Pomeron exchange. However, these C8 precursor channels could still be coupled together via the exchanges of single hard gluons. Hence the C8 precursors for different quarkonium states might still propagate together coherently.

In conclusion, we find that our absorption model with two color components seems to be a useful tool for extracting the color-octet fraction in quarkonium production under a variety of physically interesting circumstances. The available experimental data on $J/\psi$ absorption in nuclei are not inconsistent with the theoretical picture that color-octet precursors are abundantly produced and strongly absorbed in nuclear collisions at fixed target energies, while color-singlet precursors that are also produced might be transparent because they are produced in pointlike states. However, better fits to these data are obtained by using an older picture that color-singlet precursors are significantly absorbed by nuclei and might be responsible for most of the observed nuclear absorption by being dominant in the absorption step of the reaction at least in certain energy and kinematical regions.

Much more effort will be needed to clarify the situation. It might be necessary to have a better understanding and treatment also of neglected effects in quarkonium production. These effects include higher-twist mechanisms of production, higher Fock-space components in projectile or target, and nonperturbative final-state interactions in the production processes (the $K$-factor), such as that between $c$ and $\bar{c}$ in color-octet production and between the $c\bar{c}$ pair and the accompanying gluon in color-singlet production near threshold. In any model, one needs to understand the nature and physical origin of the $x_p$ dependence of the extracted color-octet fraction. The effect of the coherent mixing of precursor states at subsequent collisions with nucleons should also be studied.

Above all, new experimental $J/\psi$ production data for different colliding nuclei at different energies will be very helpful in discriminating between different physical models, especially when extended to negative values of $x_p$.

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