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Color-Octet ψ' Production at Low $p_\perp$

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ABSTRACT

We study contributions from color-octet quarkonium formation mechanisms to $p_\perp$-integrated ψ' production cross sections in pion-nucleon reactions. The observed polarization of the ψ' is not reproduced by the lowest-order leading-twist color-singlet and color-octet mechanisms. This suggests that there are important quarkonium production mechanisms beyond leading twist.

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The production of heavy quarkonium has been widely studied using perturbative QCD. Due to the large masses of the c and b quarks, quarkonium production amplitudes can be factorized as products of perturbative $Q\bar{Q}$ production amplitudes and non-perturbative quarkonium formation amplitudes. In the conventional model of hadroproduction [1], a $Q\bar{Q}$ pair with the appropriate quantum numbers is produced in the collision of two partons, *i.e.* at leading twist, and the formation process is represented by a color-singlet Schrödinger wavefunction.

The CDF collaboration has recently reported several measurements of quarkonium production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [2, 3] which contradict the predictions of the conventional model. Possible theoretical explanations of these experimental results include parton fragmentation into quarkonium, which was first studied in perturbative QCD by Braaten and Yuan [4]. Unlike the conventional parton-parton fusion mechanisms [1], fragmentation is consistent with the approximate $1/p_\perp^4$ shape of the cross sections $d\sigma/dp_\perp(p\bar{p} \to \psi(1S, 2S) + X)$ at large $p_\perp$. However, if the quarkonia are treated as color-singlet $Q\bar{Q}$ systems, the normalization of the cross sections still falls short of the data by as much as a factor of 5 for $J/\psi(1S)$ production and a factor of 30 for $\psi'(2S)$ production.

A number of possible resolutions have been suggested to explain the observed ψ' surplus [5, 6, 7, 8]. In particular, Braaten and Fleming have proposed that non-perturbative transitions between color-octet and color-singlet $c\bar{c}$ states be included in the fragmentation calculation [8]. The inclusion of color-octet matrix elements is attractive both from the theoretical and phenomenological point of view. Theoretically, octet contributions are an essential part of the perturbative picture [9, 10]. Phenomenologically, octet contributions can boost the cross section of heavy quark production, not just at high $p_\perp$, but also at low $p_\perp$, where large discrepancies are also observed [11].

In the mechanism proposed by Braaten and Fleming, a gluon first produces a color-octet $c\bar{c}$ pair in a $^3S_1$ angular momentum state. The color-octet pair then evolves into a ψ' by a non-perturbative double chromoelectric dipole transition described by the matrix element $< 0|\mathcal{O}_8^{\psi'}(^3S_1)|0 >$. This process is illustrated in Fig. 1, where the non-perturbative transition is represented by the blob. The non-perturbative matrix element is related to the weight of the $|c\bar{c}gg>$ Fock state in the ψ' wavefunction. Because the matrix element is not constrained by other existing data, it can be adjusted to fit the CDF data. The value obtained in Ref. [8] is

$$< 0|\mathcal{O}_8^{\psi'}(^3S_1)|0 >= 0.0042 \text{ GeV}^3.$$

Cho and Leibovich [12], on the other hand, have combined color-octet transitions with a formula that smoothly interpolates between parton-parton fusion mechanisms and fragmentation mechanisms of $Q\bar{Q}$ production. They find that

$$< 0|\mathcal{O}_8^{\psi'}(^3S_1)|0 >= 0.0073 \text{ GeV}^3.$$

Color-octet mechanisms were originally introduced as part of a rigorous treatment of P-wave charmonium decays [10]. In the color-singlet model some of these decay widths, as well as the corresponding leading-twist P-wave production cross sections, are infrared divergent. The divergences can be absorbed into the non-perturbative color-octet matrix elements. In S-wave production and decay, such divergences do not appear. Color-octet production mechanisms nevertheless provide an attractive explanation of the wrong normalization of quarkonium production. Note that CDF have also observed a surplus of S-wave bottomonium [3] with respect to the color-singlet parton-parton fusion predictions. The bottomonium surplus appears also at $p_\perp \lesssim m_b$, where parton-parton fusion mechanisms are expected to dominate over fragmentation mechanisms.

The predictions of the color-singlet parton-parton fusion model disagree with fixed-target hadroproduction data as well. In a recent paper on charmonium production in pion-nucleon reactions [11], we pointed out that the model fails to reproduce the relative production rates of the J/ψ, χ_1 and χ_2 states [13] and the polarization of the J/ψ [14] and ψ' [15]. We interpreted these discrepancies as evidence for important higher-twist mechanisms of charmonium production. It is, however, necessary to check whether the data could be reproduced within the leading-twist picture by including the color-octet transitions. At the same time, such an analysis could provide an independent determination of the color-octet matrix elements whose values have previously been extracted from CDF data.

In this letter, we study the $p_\perp$-integrated ψ' production cross section in pion-nucleon collisions. The analysis also applies to the direct component of J/ψ production. Total J/ψ production is a somewhat more complicated process because there are significant contributions from the decays of the χ_J and ψ' states [13].

The polarization of the ψ' gives important information on its production mechanisms. Measurements of polarization actually indicate that there must be other production mechanisms in addition to the leading-twist color-singlet and color-octet mechanisms.

At leading order in α_s and up to next-to-leading order in v^2/c^2, the subprocesses for ψ' production through color-octet intermediate states are

$$gg \to c\bar{c}\left[{}^3P_J{}^{(8)}\right] \to \psi' + X, \tag{1}$$

$$q\bar{q} \to c\bar{c}\left[{}^3S_1{}^{(8)}\right] \to \psi' + X, \tag{2}$$

$$gg \to c\bar{c}\left[{}^1S_0{}^{(8)}\right] \to \psi' + X. \tag{3}$$

These are illustrated in Fig. 2. The process $q\bar{q} \to c\bar{c}\left[{}^3P_J{}^{(8)}\right] \to \psi' + X$ is of higher order in v^2/c^2 since the lowest-order non-perturbative transition (single chromoelectric dipole) is forbidden by charge conjugation. We also find that the subprocess amplitude $A\left(gg \to c\bar{c}\left[{}^3S_1{}^{(8)}\right]\right)$ vanishes in the leading order in α_s. Note that charge conjugation or Yang's theorem [16] do not require this amplitude to vanish because the $c\bar{c}$ pair is not in a color-singlet state.

The notation in eq. (1) includes a total angular momentum quantum number J. However, we assume that the color-octet states with different J do not propagate as resonances of different masses. Therefore, unlike in the case of color-singlet P-wave states [11], we can neglect the JJ_z coupling and work in the L_zS_z basis throughout.

The polarization of the final-state ψ' is measured by the polar-angle distribution, $1 + \alpha\cos^2\theta$, of its decay dileptons in their rest frame. The parameter α in the Gottfried-Jackson frame angular distribution is related to the polarized ψ' production cross sections in the following way:

$$\alpha = \frac{d\sigma(\lambda = 1) - d\sigma(\lambda = 0)}{d\sigma(\lambda = 1) + d\sigma(\lambda = 0)}, \tag{4}$$

where λ is the helicity of the ψ'. Since the transverse momenta of the initial partons and the momenta of the soft gluons emitted in the non-perturbative transition are small and can be neglected, the helicity of the ψ' is equal to the z component of its spin. It is determined by the perturbative dynamics of the subprocesses $q\bar{q}, gg \to c\bar{c}$ and by the heavy quark spin symmetry of the non-perturbative transition. In the process (1), the non-perturbative transition is a chromoelectric dipole transition. In (2), it is a double chromoelectric dipole transition and in (3), a chromomagnetic dipole transition. In the chromoelectric dipole transitions, the helicities of the heavy quark and antiquark are not flipped, whereas in the chromomagnetic dipole transition one of the helicities is flipped. In processes (1) and (2), the helicity λ of the ψ' therefore equals the z component of the spin of the color-octet $c\bar{c}$ state. In process (3), the total spin of the quark-antiquark system changes from $S = 0,\ S_z = 0$ in the color-octet state to $S(\psi') = 1,\ S_z(\psi') = \lambda = \pm 1$ in the final state.

In terms of the matrix elements of non-relativistic QCD, the squares of the amplitudes of processes (1), (2) and (3) are

$$
\begin{aligned}
&\left|A\left(gg \to c\bar{c}\left[{}^3P_J{}^{(8)}\right] \to \psi'(\lambda) + X\right)\right|^2 \\
&= \frac{1}{24m_c} < 0|\mathcal{O}_8^{\psi'}({}^3P_J)|0 > \delta_{aa'}\delta_{\lambda S_z}\delta_{\lambda S'_z}\delta_{L_z L'_z} \\
&\quad \times A\left(gg \to c\bar{c}\left[{}^3P_J{}^{(8)}; a, S_z, L_z\right]\right) A^*\left(gg \to c\bar{c}\left[{}^3P_J{}^{(8)}; a', S'_z, L'_z\right]\right), \qquad (5) \\
&\left|A\left(q\bar{q} \to c\bar{c}\left[{}^3S_1{}^{(8)}\right] \to \psi'(\lambda) + X\right)\right|^2 \\
&= \frac{1}{24m_c} < 0|\mathcal{O}_8^{\psi'}({}^3S_1)|0 > \delta_{aa'}\delta_{\lambda S_z}\delta_{\lambda S'_z} \\
&\quad \times A\left(q\bar{q} \to c\bar{c}\left[{}^3S_1{}^{(8)}; a, S_z\right]\right) A^*\left(q\bar{q} \to c\bar{c}\left[{}^3S_1{}^{(8)}; a', S'_z\right]\right), \qquad (6) \\
&\left|A\left(gg \to c\bar{c}\left[{}^1S_0{}^{(8)}\right] \to \psi'(\lambda) + X\right)\right|^2 \\
&= \frac{1}{24m_c} < 0|\mathcal{O}_8^{\psi'}({}^1S_0)|0 > \delta_{aa'}\frac{1}{2}(1 - \delta_{\lambda 0}) \\
&\quad \times A\left(gg \to c\bar{c}\left[{}^1S_0{}^{(8)}; a\right]\right) A^*\left(gg \to c\bar{c}\left[{}^1S_0{}^{(8)}; a'\right]\right), \qquad (7)
\end{aligned}
$$

where $a, a', S_z, S'_z, L_z, L'_z$ are the color quantum numbers and angular momentum components of the color-octet intermediate states. The perturbative amplitudes are

$$
\begin{aligned}
A\left(gg \to c\bar{c}\left[{}^3P_J{}^{(8)}; a, S_z, L_z\right]\right) &= \sqrt{2}\, T^a_{AB}\epsilon^{*\alpha}(L_z) \\
&\quad \times \frac{\partial}{\partial q^\alpha} \mathrm{Tr}\left[\mathcal{O}^{AB}_{gg \to c\bar{c}}(P,q) P_{1S_z}(P,q)\right]\Big|_{q=0}, \qquad (8)
\end{aligned}
$$

$$A\left(q\bar{q}\to c\bar{c}\left[{}^3S_1{}^{(8)};a,S_z\right]\right) = \sqrt{2}\,T^a_{AB}\,\mathrm{Tr}\left[\mathcal{O}^{AB}_{q\bar{q}\to c\bar{c}}(P,q)P_{1S_z}(P,q)\right]\Big|_{q=0}, \quad (9)$$

$$A\left(gg\to c\bar{c}\left[{}^1S_0{}^{(8)};a\right]\right) = \sqrt{2}\,T^a_{AB}\,\mathrm{Tr}\left[\mathcal{O}^{AB}_{gg\to c\bar{c}}(P,q)P_{00}(P,q)\right]\Big|_{q=0}, \quad (10)$$

where P is the total four-momentum and $2q$ the relative four-momentum of the $c\bar{c}$ pair, $\mathcal{O}^{AB}_{ij\to c\bar{c}}$ is the perturbative amplitude for the production of a $c\bar{c}$ pair with color indices A, B (the heavy quark legs are truncated), ϵ is a spin-1 polarization four-vector, and P_{1S_z}, P_{00} are the covariant spin projection operators of Ref. [12]. Taking the four-momentum of the ψ' equal to P, the ψ' production cross section is

$$\begin{aligned}\sigma(\pi N\to\psi'(\lambda)+X) &= \sum_{ij}\int dx_1dx_2\, f_{i/\pi}(x_1)\, f_{j/N}(x_2) \\ &\quad\times\delta\left(1-\frac{M^2}{x_1x_2s}\right)\frac{\pi}{M^4}\overline{|A(ij\to\psi'(\lambda)+X)|^2} \\ &\equiv \sum_{ij}\Phi_{ij/\pi N}(M^2/s)\frac{\pi}{M^4}\overline{|A(ij\to\psi'(\lambda)+X)|^2}, \quad (11)\end{aligned}$$

where we neglected factorization-scale dependence. The contribution from the color-octet subprocesses (1), (2) and (3) simplifies to

$$\begin{aligned}&\sigma_{\rm octet}(\pi N\to\psi'(\lambda)+X) \\ &= \frac{\pi}{M^4}\Bigg\{\Phi_{gg/\pi N}(M^2/s)\left[\frac{10\pi^2\alpha_s^2 m_c}{9M^4} < 0|\mathcal{O}_8^{\psi'}({}^3P_J)|0 > (3-2\delta_{\lambda 0})\right. \\ &\qquad\left. + \frac{5\pi^2\alpha_s^2}{144 m_c} < 0|\mathcal{O}_8^{\psi'}({}^1S_0)|0 > (1-\delta_{\lambda 0})\right] \\ &\quad + \sum_q\left[\Phi_{q\bar{q}/\pi N}(M^2/s)+\Phi_{\bar{q}q/\pi N}(M^2/s)\right] \\ &\qquad\times\frac{32\pi^2\alpha_s^2 m_c}{54M^2} < 0|\mathcal{O}_8^{\psi'}({}^3S_1)|0 > (1-\delta_{\lambda 0})\Bigg\}. \quad (12)\end{aligned}$$

The difference between the measured cross section [13]

$$\sigma(\pi N\to\psi'+X; x_F>0) = 25 \text{ nb}$$

at $E_{lab}(\pi) = 300$ GeV and the color-singlet prediction [11]

$$\sigma_{\rm singlet}(\pi N\to\psi'+X; x_F>0) = 3.2 \text{ nb}$$

gives an experimental upper limit of the color-octet contribution (12). However, polarization measurements show that all of the "missing" part cannot be due to the lowest-order color-octet mechanisms. The octet contribution is dominantly transversely polarized; each of the three components alone corresponds to $\alpha = 1/2$, $\alpha = 1$ and $\alpha = 1$, respectively, in the angular distribution $1 + \alpha \cos^2\theta$ of the ψ' decay dileptons in the Gottfried-Jackson frame. On the other hand, the observed value is $\alpha = 0.028 \pm 0.004$ [15]. Hence the color-octet mechanism could at most contribute about half of the observed cross section, if the other half were due to a mechanism which produces longitudinally polarized ψ' (note that the leading-twist color-singlet mechanism gives $\alpha \approx 0.25$). We conclude that the leading-twist color-singlet and color-octet mechanisms are not sufficient to reproduce the observed polarization of the ψ' in pion-nucleon collisions.

In the color-singlet model, the ratio of the J/ψ and ψ' cross sections is predicted to be

$$\frac{\sigma(\psi')}{\sigma(J/\psi)} = \frac{M^3(J/\psi)\,\Gamma(\psi')}{M^3(\psi')\,\Gamma(J/\psi)} = 0.24, \tag{13}$$

where M and Γ are the masses and leptonic decay widths of the J/ψ and ψ'. The experimental photoproduction [17] and fixed-target hadroproduction [18] cross sections are consistent with eq. (13). This again suggests that the failure of the existing models in reproducing fixed-target data is due to neglected $Q\bar{Q}$ production mechanisms rather than to the neglected color-octet mechanisms of quarkonium formation.

Note that our results do not imply that the color-octet explanation of the CDF quarkonium surplus is wrong. Using the value [12]

$$< 0|\mathcal{O}_8^{\psi'}(^3S_1)|0 >= 0.0073 \text{ GeV}^3,$$

we find that the contribution from this non-perturbative transition to $\sigma_{\rm octet}$ of eq. (12) is only 0.7 nb $\times\,(1 - \delta_{\lambda 0})$. Such a small contribution, even though it is transversely polarized, does not contradict the existing fixed-target measurements.

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FIGURE CAPTIONS

Figure 1. Braaten and Fleming's color-octet fragmentation mechanism of ψ' production.

Figure 2. The Feynman diagrams which describe the lowest-order color-octet ψ' production mechanisms. We omit diagrams that correspond to vanishing amplitudes.