

Two-spin asymmetry for ψ' photoproduction with the color-octet mechanism

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We study the photoproduction of ψ' in the forward regions in polarized γp collisions at relevant (DESY) HERA energies. We find that this reaction is very effective to test the color-octet mechanism which is based on the NRQCD factorization formalism. Furthermore we find that the value of the NRQCD matrix elements can be severely constrained by measuring the two-spin asymmetry, though the process depends on the polarized gluon distribution $\Delta g(x)$.

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Heavy quarkonium productions and decays have been traditionally calculated in the framework of the color-singlet model [1]. However, it has been reported that the color-singlet model cannot explain the experimental data of J/ψ and ψ' hadroproductions [2]; the cross sections of prompt J/ψ and ψ' production in unpolarized $p\bar{p}$ collisions predicted by the color-singlet model were smaller than the Fermilab Tevatron data by more than one order of magnitude [3]. Furthermore, in the photoproduction of J/ψ , the color-singlet model cannot satisfactorily reproduce cross sections for inclusive J/ψ production at the recent DESY ep collider HERA experiment [4] even including next-to-leading order corrections [5]. In order to solve these serious problems, a new color-octet model has been advocated by several people [6] as one of the most promising candidates that can possibly remove such big discrepancies between the experimental data and the theoretical prediction by the color-singlet model.

A rigorous formulation of the color-octet model has been introduced based on an effective field theory called nonrelativistic QCD (NRQCD), in which the $\mathcal{O}(v)$ corrections of a relative velocity between the bound heavy quarks can be systematically calculated [7]. The NRQCD factorization approach separates the effects of short distances that are comparable to or smaller than the inverse of heavy quark mass, from the effects of longer distance scales of hadronization. A heavy $Q\bar{Q}$ pair is first produced in a virtual color-octet intermediate state of the NRQCD higher Fock state, and then hadronizes into a detected color-singlet particle via the emission or absorption of dynamical gluons. Production cross sections of heavy quarkonium H can be factorized into a product of a short distance coefficient C_n which can be computed using perturbative QCD, and a long distance part $\langle \mathcal{O}_n^H(2S+1L_J) \rangle$ which is described by nonperturbative NRQCD matrix elements whose values should be determined from experiments or lattice gauge theory,

$$\sum_X d\sigma(AB \rightarrow H+X) = \frac{1}{\Phi} d\Gamma \sum_n C_n \langle \mathcal{O}_n^H(2S+1L_J) \rangle, \quad (1)$$

where Φ and Γ show a flux and a phase space factor, respectively. The label n denotes color and angular momentum numbers. In this factorization approach, there are two long distance parameters which are essentially the vacuum expectation values of the color-singlet and -octet NRQCD matrix elements $\langle \mathcal{O}_{1,8}^H \rangle$, whose relative importance is determined by the velocity scaling rules [8]. Physics of the color-octet model is now one of the most interesting topics on heavy quarkonium productions at high energy. However, although the color-octet model is quite successful in explaining the Tevatron data, it looks problematic for the process $\gamma + p \rightarrow J/\psi + X$; using the long distance matrix elements extracted from the Tevatron data, the color-octet model largely overestimates the HERA data [9]. Since the color-singlet matrix elements is related to the radial wave functions at the origin, their values are calculable using potential models [10]. On the other hand, the color-octet matrix elements can be extracted only from experiments at present. However, the present uncertainties on the color-octet matrix elements are still large and the discussion seems controversial. In order to confirm the validity of the NRQCD factorization approach, the universality of long distance parameters must be established for different processes with acceptable experimental error. So far, several processes have been already suggested for testing this factorization approach, such as polar angle distributions of J/ψ in e^+e^- annihilation into $J/\psi + X$ [11], Z^0 decays at the CERN e^+e^- collider LEP [12], leptoproduction of J/ψ [13], and so on.

In this paper, as another test of the color-octet model, we propose the ψ' photoproduction at small- p_T regions,

$$\vec{\gamma} + \vec{p} \rightarrow \psi' + X, \quad (2)$$

which might be observed in the forthcoming polarized HERA experiment, where the arrow attached to particles means that these particles are polarized in a parallel or antiparallel direction to the running direction of each particle. In this work, we do not consider the contribution of elastic diffractive mechanisms and other reducible background processes, since they can be eliminated with appropriate cuts [14]. If the color-octet mechanism works, the process is dominated by the color-octet subprocess $\gamma + g \rightarrow (c\bar{c})_{octet}$ at small- p_T regions. In addition, there can be the contribution from the conventional color-singlet subprocess $\gamma + g$

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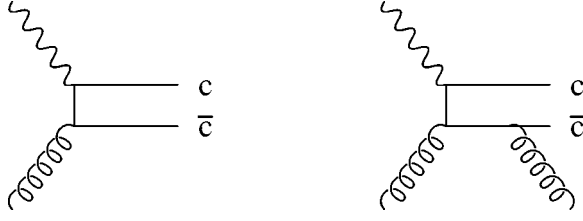


FIG. 1. Feynman diagrams for the leading order of the color-octet subprocess $\gamma + p \rightarrow (c\bar{c})_{octet}$ and the color-singlet subprocess $\gamma + p \rightarrow (c\bar{c})_{singlet} + g$. Initial γ and proton are polarized.

$\rightarrow (c\bar{c})_{singlet} + g$ which appears only as a second order of the strong coupling constant α_s . Feynman diagrams for these subprocesses are illustrated in Fig. 1. The main contribution to the leading color-octet mechanism comes from the color-octet $^1S_0^{(8)}$ and $^3P_{J=0,2}^{(8)}$ states, whereas the color-singlet mechanism originates from $^3S_1^{(1)}$ state. The process involves the NRQCD long distance parameters corresponding to such states. In particular, for the color-octet mechanism the cross

section is proportional only to the linear combination of the NRQCD long distance parameters, $\langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle$ and $\langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle$, owing to the NRQCD spin symmetry relation, as described later. We show that to measure the spin-dependent cross section and two-spin asymmetry for this process is very effective not only for testing of the color-octet model but also for extracting the values of the color-octet long distance matrix elements. Furthermore, since the process is dominantly produced in photon-gluon fusion, the cross section must be sensitive to the gluon density in a proton and thus one can get good information on the spin-dependent gluon distribution function by analyzing this polarized process. A related subject has been recently investigated by Japardize *et al.* [15]. They have calculated the two-spin asymmetry of J/ψ photoproduction at large- p_T regions in polarized γp scattering and discussed the sensitivity of the long distance parameters to the asymmetry. They have insisted that the process is effective for testing the color-octet model.

The spin-independent total cross section due to these mechanisms for small- p_T regions is given by [16]

$$\begin{aligned} \sigma(\gamma p \rightarrow \psi' + X) &= \sigma_{\underline{8}}(\gamma p \rightarrow \psi' + X) + \sigma_{\underline{1}}(\gamma p \rightarrow \psi' + X) \\ &= \int dx g(x) \left(\sum \hat{\sigma}(\gamma g \rightarrow c\bar{c}[^{2S+1}L_J^{(8)}]) \langle \mathcal{O}_8^{\psi'}(^{2S+1}L_J) \rangle + \hat{\sigma}(\gamma g \rightarrow c\bar{c}[^3S_1^{(1)}]g) \langle \mathcal{O}_1^{\psi'}(^3S_1) \rangle \right) \\ &= \frac{\pi^2 \alpha_e m_e^2}{m_c^3} \int dx g(x) \left(\pi \alpha_s \delta(4m_c^2 - \hat{s}) \Theta \right. \\ &\quad \left. + \int d\hat{t} \frac{64\alpha_s^2 m_c^4 |R_{\psi'}(0)|^2}{3\hat{s}^2} \frac{\hat{s}^2(\hat{s} - 4m_c^2)^2 + \hat{t}^2(\hat{t} - 4m_c^2)^2 + \hat{u}^2(\hat{u} - 4m_c^2)^2}{(\hat{s} - 4m_c^2)^2(\hat{t} - 4m_c^2)^2(\hat{u} - 4m_c^2)^2} \right), \end{aligned} \quad (3)$$

where $g(x)$ is the unpolarized gluon distribution function, and \hat{s} , \hat{t} , and \hat{u} are the usual Mandelstam variables for the subprocess. The labels $\underline{1}$ and $\underline{8}$ for the cross sections denote the contribution from the color-singlet and -octet state, respectively. The sum in the first term is taken over $^3P_{0,2}^{(8)}$ and $^1S_0^{(8)}$ states and Θ is the linear combination of color-octet matrix elements for these states,

$$\Theta \equiv \langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle + \frac{7}{m_c^2} \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle. \quad (4)$$

$R_{\psi'}(0)$ is a radial wave function at the origin and is related to the color-singlet matrix element as

$$\langle \mathcal{O}_1^{\psi'}(^3S_1) \rangle \sim \frac{9}{2\pi} |R_{\psi'}(0)|^2 (1 + \mathcal{O}(v^2)), \quad (5)$$

which can be well determined from the leptonic decay width of ψ' , though its value cannot be calculated perturbatively.

The spin-dependent cross section can be obtained by replacing the unpolarized subprocess cross section by the polarized one, and furthermore by the following replacement:

$$g(x) \rightarrow \Delta g(x) \quad (\Delta \text{ means "polarized"}), \quad (6)$$

$$\Theta \rightarrow \tilde{\Theta} \equiv \langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle - \frac{1}{m_c^2} \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle. \quad (7)$$

In the present calculation, we used the 1996 Gehrmann-Stirling (GS96) (set A and set B) [17] and 1996 Glück-Reya-Stratmann-Vogelsang (GRSV96) [18] parametrizations for the polarized gluon distribution and the 1995 Glück-Reya-Vogt (GRV95) parametrization [19] for the unpolarized one. Color-octet matrix elements were taken from the recent analysis on charmonium hadroproduction data: $\langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle + (7/m_c^2) \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle \approx 5.2 \times 10^{-3} [\text{GeV}^3]$ [20] and $\frac{1}{3} \langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle + (1/m_c^2) \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle \approx (5.9 \pm 1.9) \times 10^{-3} [\text{GeV}^3]$ [21], which lead to

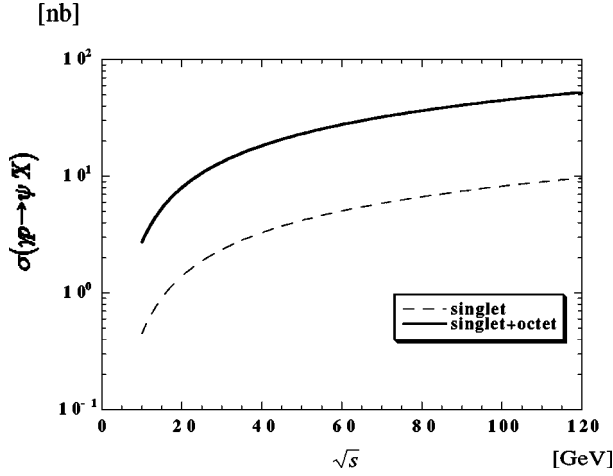


FIG. 2. The spin-independent total cross section as a function of \sqrt{s} . The solid line represents the sum of the color-singlet and octet contributions, while the dashed line represents the color-singlet contribution only.

$$\frac{\tilde{\Theta}}{\Theta} \equiv \frac{\langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle - 1/m_c^2 \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle}{\langle \mathcal{O}_8^{\psi'}(^1S_0) \rangle + 7/m_c^2 \langle \mathcal{O}_8^{\psi'}(^3P_0) \rangle} \approx 3.6 \sim 8.0. \quad (8)$$

Calculated cross sections are presented in Fig. 2 and Fig. 3. We see that the color-octet contribution is larger than the color-singlet one by one and two order of magnitude for the unpolarized and polarized cross sections, respectively. It is remarkable that the difference due to different gluon polarization models is not so large. As is well known, the photo-production of heavy quarkonium in the framework of the NRQCD factorization approach has an important issue on kinematic enhancement in the region $z \rightarrow 1$ arising from higher order terms in the NRQCD velocity expansion. However, as discussed by Beneke *et al.* [22], the singular region

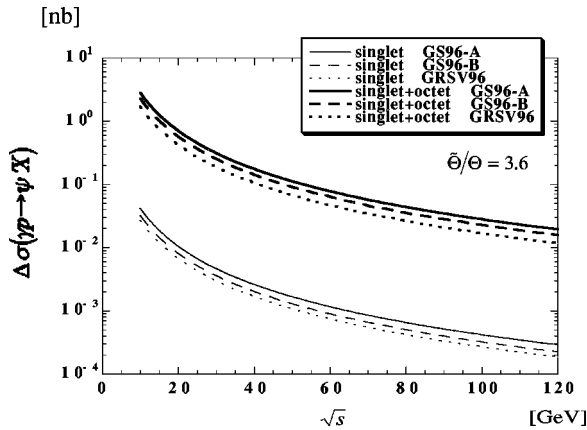


FIG. 3. The spin-dependent total cross section with the parameter $\tilde{\Theta}/\Theta = 3.6$ as a function of \sqrt{s} . The solid, dashed and dotted lines show the case of set A of GS96 [17], set B of GS96 [17] and the “standard scenario” of GRSV96 [18], respectively. Upper bold lines represent the sum of the color-singlet and -octet contributions, while lower lines represent the color-singlet contribution only.

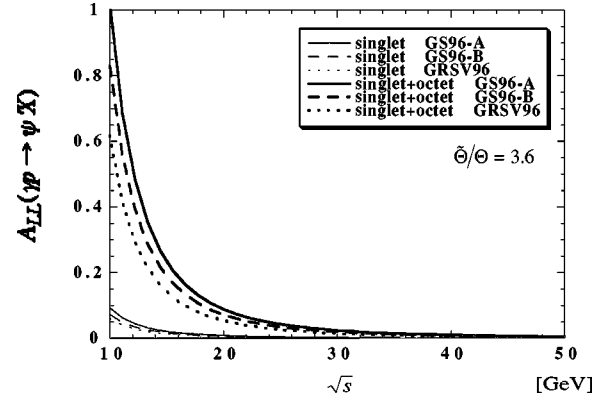


FIG. 4. The two-spin asymmetry $A_{LL}(\gamma p \rightarrow \psi' X)$ with the parameter $\tilde{\Theta}/\Theta = 3.6$ as a function of \sqrt{s} . Various lines show the same as in Fig. 3. Upper bold lines represent the color-singlet plus octet contribution, while lower lines represent the color-singlet contributions only.

is smeared out by integrating over z and the information of the complicated shape function is lost. Since here we discuss only the integrated cross sections of the process, we do not worry about such singular effects.

Now we move to the analysis on a two-spin asymmetry for ψ' production in the polarized reaction defined by

$$A_{LL} \equiv \frac{[d\sigma_{++} - d\sigma_{+-} + d\sigma_{--} - d\sigma_{-+}]}{[d\sigma_{++} + d\sigma_{+-} + d\sigma_{--} + d\sigma_{-+}]} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\Delta\sigma_8 + d\Delta\sigma_\perp}{d\sigma_8 + d\sigma_\perp}, \quad (9)$$

where $d\sigma_{+-}$, for instance, denotes that the helicity of photon is positive and the one of proton is negative. From Eq. (9), we see that if only the color-octet contribution which is the lowest order process in α_s works, the asymmetry A_{LL} can be written by a simple formula

$$A_{LL}^{\psi'}(\gamma p)_{lowest} = \frac{d\Delta\sigma_8}{d\sigma_8} = \frac{\Delta g(x, Q^2)}{g(x, Q^2)} \frac{\tilde{\Theta}}{\Theta}, \quad (10)$$

which is just a product of the ratio of polarized and unpolarized gluon densities and the one of color-octet matrix elements.

Taking $Q^2 = 4m_c^2$ with a charm mass $m_c = 1.5$ GeV, the calculated A_{LL} at relevant HERA energies are presented in Fig. 4. As shown in Fig. 4, if the color-octet process works, then the A_{LL} becomes quite large in the rather smaller \sqrt{s} region, comparing with the one for the color-singlet mechanism only. The difference of A_{LL} due to the color-octet and -singlet mechanism is larger than the uncertainties due to the polarized gluon distribution functions. Hence we can sufficiently test the color-octet contribution in this reaction. Furthermore, since the A_{LL} strongly depends on the value of $\tilde{\Theta}/\Theta$, one can constrain its magnitude from the value of A_{LL} as follows; if we take the GS96 or GRSV96 parametrization which are widely used, the maximum value of $\Delta g(x)/g(x)$ becomes roughly 0.35 for GS96 and 0.2 for GRSV96 and

then, with this value on the ratio of gluon distributions, we can constrain the maximum value of the ratio of NRQCD matrix elements as

$$\frac{\tilde{\Theta}}{\Theta} \leq 2.9 \quad \text{for GS96,} \quad (11)$$

$$\leq 5.0 \quad \text{for GRSV96,} \quad (12)$$

from the requirement that the A_{LL} should be less than 1. Actually, the uncertainty of matrix elements seems to be larger than that of gluon distribution, because the value of matrix elements obtained from the Tevatron data which we used here does not include the contributions of higher order QCD corrections. In Ref. [23], Kniehl and Kramer have approximately taken into account the effect from higher order QCD corrections due to multiple-gluon initial state radiation and improved the values of long distance parameters for J/ψ meson as smaller. They have insisted that it is possible to explain both Tevatron and HERA data by using such a “small” set of long distance parameters. In any case we can say that our process is very effective not only for testing the NRQCD factorization approach but also for constraining the value of long distance parameters, though the result depends on the polarized gluon distribution function. On the contrary, if the NRQCD factorization approach is confirmed enough with the long distance matrix elements with acceptable the-

oretical and experimental uncertainties, we can get good information on the polarized gluon distribution function in rather smaller \sqrt{s} regions.

Finally, let us discuss the sensitivity on our results. In order to examine the experimental feasibility of the forthcoming HERA experiments, we have estimated the experimental sensitivity of the A_{LL} for 100-day experiments at various \sqrt{s} in the manner of Nowak [24], using the expected data of beam or target polarization ($P_B, P_T \sim 70\%$), the integrated luminosity ($\mathcal{L} \cdot T \sim 66 \text{ pb}^{-1}$), and the combined trigger and reconstruction efficiency ($C \sim 50\%$) together with the value of unpolarized total cross sections. As a result we found that the experimental sensitivity δA_{LL} is order of magnitude $\sim 10^{-3}$, which is very small. Hence our predictions are expected to be actually tested in the future polarized HERA experiments.

In summary, to test the color-octet model we have proposed the photoproduction of ψ' at small- p_T regions in polarized γp scattering which might be available in the forthcoming polarized HERA experiments. We have calculated two-spin asymmetry A_{LL} for various parameter regions $\tilde{\Theta}/\Theta = 3.6 \sim 8.0$, and found that the A_{LL} becomes quite large in the regions $\sqrt{s} = 10\text{--}20 \text{ GeV}$. Therefore we can sufficiently test the color-octet model in this process. In addition, the measurement of A_{LL} is very effective to severely constrain the value of NRQCD matrix elements, though it depends on the polarized gluon distribution $\Delta g(x)$.

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