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ψ' production as a test of color-octet mechanism

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To test the color-octet model of heavy quarkonium production, we propose ψ' production at small-p_T regions in polarized pp collisions for the forthcoming BNL RHIC polarized experiments, whose experimental test at $\sqrt{s}=50$ GeV might be very promising.
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Traditionally, heavy quarkonium production has been calculated so far in the color-singlet model [1], which is essentially a nonrelativistic model. However, with this model one cannot quantitatively estimate various uncertainties originating from the higher order QCD corrections, the quarkonium binding effects, and the corrections due to relativistic effects of quarkonium. Recently, it has been reported that the cross sections of prompt J/ψ and ψ' production in unpolarized $p\bar{p}$ collisions measured by the Collider Detector at Fermilab (CDF) Collaboration are largely inconsistent with the calculation by the QCD lowest order process with the color-singlet mechanism alone [2]. This suggests that we need some other mechanisms beyond the color-singlet model.

In the last few years, a new color-octet model has been advocated by several people [3] as one of the most promising candidates that could remove such a big discrepancy between the experimental data and the prediction of the color-singlet model. The model is quite successful in explaining the CDF data for large-p_T heavy quarkonium production. About the same time, a rigorous formulation of such a new model has been presented in terms of a beautiful effective theory called nonrelativistic QCD (NRQCD), in which the $\mathcal{O}(v)$ corrections of the relative velocity between the bound heavy quarks can be systematically calculated [4]. Physics of the color-octet model is now one of the most interesting topics for heavy quarkonium production at high energy. Several processes have been already suggested for testing the color-octet model, such as transversely polarized prompt J/ψ and ψ' hadroproduction at high energy collisions [5], polar angle distributions of the J/ψ in e^+e^- annihilation into $J/\psi+X$ [6], Z^0 decays at the CERN e^+e^- collider LEP [7], and so on. However, the prediction of the color-octet model on $\gamma+p\rightarrow J/\psi+X$ is at variance with recent data at the DESY ep collider HERA [8], and thus the discussion seems still controversial. To go beyond the present theoretical understanding, it is necessary to study other processes.

In this paper, as another test of the color-octet model, we propose a different process, ψ' hadroproduction at small-p_T regions in longitudinally-polarized-proton–longitudinally-polarized-proton collisions which will be observed in the forthcoming experiment at the BNL Relativistic Heavy Ion Collider (RHIC). The process is of great advantage to clearly test the color-octet model as described in the following. Since the process is dominated by the s-channel gluon-gluon fusion, there is no direct productions of the color-singlet ψ' because of charge conjugation. For this process, only two states are expected to contribute to ψ' production in the final state: (1) a color-octet state, where a $c\bar{c}$ pair is produced at short distances in a color-octet state which subsequently evolves nonperturbatively into a physical quarkonium [3], and (2) a radially excited color-singlet $2\,^3P_2$ state ($\approx$3.9–4.0 GeV) decaying into $\psi'+\gamma$, where the decay into DD, DD^* is suppressed by the D-wave phase space and dynamical effects [9,10]. The contribution of the $2\,^3P_0$ state is considered to be small because the branching ratio of the $2\,^3P_0$ into $\psi'+\gamma$ is expected to be very small by analogy of the tiny branching ratio of $1\,^3P_0$ into $J/\psi+\gamma$, $B(1\,^3P_0\rightarrow J/\psi+\gamma)=(6.6\pm1.8)\times10^{-3}$ [11] and, thus, can be safely neglected here. The $2\,^3P_1$ state ($\approx$3.9 GeV), does not contribute to this process because of Yang's theorem, though this state might contribute to large-p_T ψ' production. Note that in the case of J/ψ production, in addition to radiative decays of $1\,^3P_2$ and $2\,^3P_2$ states, $\psi'\rightarrow J/\psi+X$ contributes to the J/ψ production in the final states and hence the analysis must be complicated. Furthermore, since the ψ' is dominantly produced in gluon fusion, the cross section is sensitive to the gluon density in the proton and thus one can get good information on the spin-dependent gluon distribution in the proton by analyzing this polarized process, which is also a hot current topic. A related subject has been studied recently by Teryaev and Tkabladze [12]: They have calculated the two-spin asymmetry of the J/ψ production at large-p_T (>1.5 GeV) regions in polarized pp collisions and insisted that the color-octet mechanism dominantly contributes to the asymmetry.

Let us introduce a two-spin asymmetry A_{LL} for this process:

$$A_{LL}=\frac{[d\sigma_{++}-d\sigma_{+-}+d\sigma_{--}-d\sigma_{-+}]}{[d\sigma_{++}+d\sigma_{+-}+d\sigma_{--}+d\sigma_{-+}]}=\frac{d\Delta\sigma}{d\sigma}, \qquad (1)$$

where $d\sigma_{+-}$, for instance, denotes that the helicity of one beam particle is positive and the other is negative.

The spin-dependent and spin-independent differential cross sections of small-p_T ψ' production via the color-octet state are given by [13]

$$\frac{d\Delta\sigma_{\rm CO}}{dx_L}=\frac{d\sigma_{++}}{dx_L}-\frac{d\sigma_{+-}}{dx_L}+\frac{d\sigma_{--}}{dx_L}-\frac{d\sigma_{-+}}{dx_L}$$
$$=\frac{\tau_c}{\sqrt{x_L^2+4\tau_c}}\left[\frac{\pi^3\alpha_s^2}{144m_c^5}\left\{\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle-\frac{1}{m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle\right\}\Delta g(x_a,Q^2)\Delta g(x_b,Q^2)\right.$$
$$-\frac{\pi^3\alpha_s^2}{54m_c^5}\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$$
$$\left.\times\{\Delta q(x_a,Q^2)\Delta\overline{q}(x_b,Q^2)+\Delta q\leftrightarrow\Delta\overline{q}\}\right], \qquad (2)$$

$$\frac{d\sigma_{\rm CO}}{dx_L}=\frac{\tau_c}{\sqrt{x_L^2+4\tau_c}}\left[\frac{\pi^3\alpha_s^2}{144m_c^5}\left\{\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle+\frac{7}{m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle\right\}\right.$$
$$\times g(x_a,Q^2)g(x_b,Q^2)$$
$$+\frac{\pi^3\alpha_s^2}{54m_c^5}\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$$
$$\left.\times\{q(x_a,Q^2)\overline{q}(x_b,Q^2)+q\leftrightarrow\overline{q}\}\right], \qquad (3)$$

where x_a and x_b are the momentum fraction in a proton and are given as

$$x_a=\frac{x_L+\sqrt{x_L^2+4\tau_c}}{2}, \quad x_b=\frac{-x_L+\sqrt{x_L^2+4\tau_c}}{2},$$

$$x_L\equiv\frac{2p_L}{\sqrt{s}}, \quad \tau_c\equiv\frac{4m_c^2}{s}, \qquad (4)$$

with longitudinal momentum p_L of the produced particle. $\Delta g(x,Q^2)$ and $\Delta q(x,Q^2)$ are the spin-dependent gluon and quark density with the momentum fraction x at any Q^2, respectively. $\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle$, $\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$, and $\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle$ are nonperturbative long-distance factors associated with the production of a $c\overline{c}$ pair in a color-octet $^1S_0$, $^3S_1$, and $^3P_0$ states, respectively. From a recent analysis on charmonium hadroproduction, the values of $\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$ and of the combination are given as $\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle\approx4.6\times10^{-3}$ [GeV^3], $\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle+(7/m_c^2)\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle\approx5.2\times10^{-3}$ [GeV^3] [14], and another combination $\frac{1}{3}\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle+(1/m_c^2)\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle\approx(5.9\pm1.9)\times10^{-3}$ [GeV^3] [15]. Then we find the ratio as

$$\frac{\widetilde{\Theta}}{\Theta}\equiv\frac{\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle-\frac{1}{m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle}{\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle+\frac{7}{m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle}\approx8.0\text{–}3.6.$$

The A_{LL}, due to the color-octet state alone, has been numerically calculated using various proton distributions, and we found that it becomes positive in the entire x_L region if $\Delta g(x,Q^2)$ does not change its sign in $0<x<1.0$, though its value largely depends on $\widetilde{\Theta}/\Theta$.

The spin-dependent differential cross section of small-p_T ψ' production via the $2\,^3P_2$ state can be given by [16]

$$\frac{d\Delta\sigma_{2^3P_2}}{dx_L}=\frac{d\sigma_{++}}{dx_L}-\frac{d\sigma_{+-}}{dx_L}+\frac{d\sigma_{--}}{dx_L}-\frac{d\sigma_{-+}}{dx_L}$$
$$=B(2^3P_2\to\psi'+\gamma)\,\frac{-16\pi^2\alpha_s^2|R'_{2^3P_2}(0)|^2}{M^7}$$
$$\times\frac{\tau}{\sqrt{x_L^2+4\tau}}\Delta g(x_a,Q^2)\Delta g(x_b,Q^2), \qquad (5)$$

where x_a and x_b are given by replacing τ_c in Eq. (4) by $\tau\equiv M^2/s$. The spin-independent cross section is given by replacing $\Delta g(x,Q^2)$ by $g(x,Q^2)$. As shown from Eq. (5), the A_{LL} due to the radiative decay of the $2\,^3P_2$ state becomes negative, though its magnitude depends on $|R'_{2\,^3P_2}(0)|$ whose value has been calculated using various potential models as $|R'_{2\,^3P_2}(0)|^2=0.076$, 0.102, 0.131, and 0.186 GeV^5, for the logarithmic, Buchmüller-Tye, power-low, and Cornell potentials, respectively [17].

The Relativistic Heavy Ion Collider (RHIC), which is designed to have a luminosity of 2×10^{32} cm^{-2} sec^{-1}, an energy of $\sqrt{s}=50$–500 GeV, and a beam polarization of about 70%, is now under construction at Brookhaven National Laboratory (BNL) and, hopefully in a few years, will produce fruitful data on high energy polarized pp collisions. Expecting the forthcoming RHIC experiments, we have calculated the A_{LL} for these energies. In this calculation, we need information on $\Delta g(x)$ and, in addition, $\Delta q(x)$ and $\Delta\overline{q}(x)$ for the case of the color-octet model. So far, many people have suggested various kinds of different spin-dependent gluon distributions from the analysis of data on nucleon spin structure functions [18–20]. Among many models of $\Delta g(x,Q^2)$, we take here typical three types of $\Delta g(x,Q^2)$: (a) set A of the Gehrmann-Stirling (GS) parametrization [18], (b) the Brodsky-Burkardt-Schmidt (BBS) parametrization [19], and (c) the Glück-Reya-Vogt (GRV) parametrization [20], which are shown in Fig. 1, and calcu-

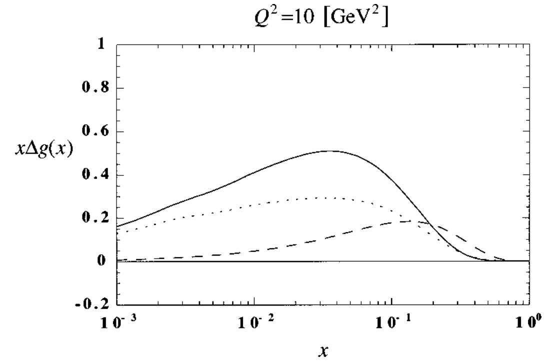

FIG. 1. The x dependence of $x\Delta g(x,Q^2)$ at $Q^2=10$ GeV^2 for various types of spin-dependent gluon distributions. The solid, dashed, and dotted lines indicate set A of Refs. [18], [19], and [20], respectively.

late the A_{LL} for ψ' production as a function of x_L at RHIC energies. In calculating for the color-octet model, we have taken $\Delta q(x)$ and $\Delta \overline{q}(x)$ from respective models of GS [18], BBS [19], and GRV [20] and found that the contribution of $q\overline{q}\to c\overline{c}$ is considerably smaller than the one of $gg\to c\overline{c}$ for $x_L<0.5$. As for the spin-independent parton distributions, we have used the GRV parametrization [21] for (a) and (c), and the BBS parametrization [19] for (b).

Fixing Q^2 as $4m_c^2$ with $m_c=1.5$ GeV and taking the mass $M_{2\,^3P_2}=3.98$ GeV and $B(2\,^3P_2\to\psi'+\gamma)=0.08$ [22], we have studied the parameter dependence of

$$A_{LL}=\frac{d\Delta\sigma_{\rm CO}/dx_L+d\Delta\sigma_{2\,^3P_2}/dx_L}{d\sigma_{\rm CO}/dx_L+d\sigma_{2\,^3P_2}/dx_L}$$

on $\widetilde{\Theta}/\Theta$ and $|R'_{2\,^3P_2}(0)|^2$ at relevant RHIC energies and found that the A_{LL} becomes larger for the larger $\widetilde{\Theta}/\Theta$ and smaller $|R'_{2\,^3P_2}(0)|^2$. We found that the A_{LL} became positive in all regions of $\widetilde{\Theta}/\Theta$ and $|R'_{2\,^3P_2}(0)|^2$ given above for $\sqrt{s}=50$–500 GeV. The A_{LL} is also largely dependent on $\Delta g(x,Q^2)$. The results calculated at $\sqrt{s}=50$ GeV for two extreme cases, (A) $\widetilde{\Theta}/\Theta=8.0$, $|R'_{2\,^3P_2}(0)|^2=0.076$ GeV^5 and (B) $\widetilde{\Theta}/\Theta=3.6$, $|R'_{2\,^3P_2}(0)|^2=0.186$ GeV^5, are presented in Fig. 2. Since the A_{LL} is rather large, it must be easy to test the color-octet model in the future experiment. To see the energy dependence, we have calculated the A_{LL} at the highest RHIC energy, $\sqrt{s}=500$ GeV, which becomes very small as shown in Fig. 3. This is due to the fact that at larger $\sqrt{s}$, x_a and x_b $(=x_a-x_L)$ defined by Eq. (4) take smaller value and hence $\Delta g(x_a)/g(x_a)\times\Delta g(x_b)/g(x_b)$ becomes smaller. Now, it is important to note that without color-octet contributions, we can never expect a positive A_{LL}. Therefore, if we observe a positive A_{LL} in the forthcoming RHIC experiment, we can definitely say that the color-octet mechanism really contributes to this process. Our results suggest that the observation of the A_{LL} is very effective for testing the color-octet model and, in practice, the experiment at $\sqrt{s}=50$ GeV is very promising. Since the results significantly

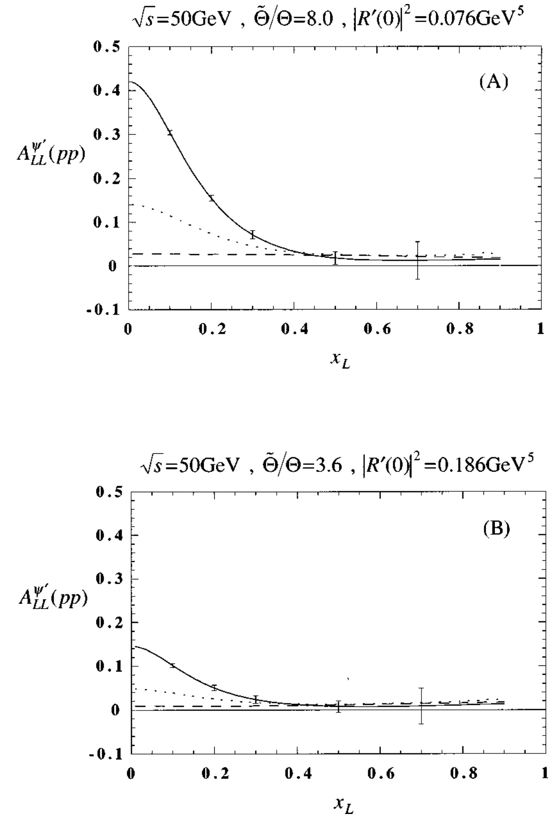

FIG. 2. The two-spin asymmetry $A_{LL}^{\psi'}(pp)$ for (A) $\widetilde{\Theta}/\Theta=8.0$, $|R'_{2\,^3P_2}(0)|^2=0.076$ GeV^5 and (B) $\widetilde{\Theta}/\Theta=3.6$, $|R'_{2\,^3P_2}(0)|^2=0.186$ GeV^5 at $\sqrt{s}=50$ GeV, calculated with various types of $\Delta g(x)$, as a function of longitudinal momentum fraction x_L of ψ'. Various lines represent the same as in Fig. 1. Error bars for the solid line denote the experimental sensitivity (see text).

depend on the value of $\widetilde{\Theta}/\Theta$, it is very important to determine this value from other experiments to give a better prediction.

Some comments are in order. One is on how the results could be affected by possible backgrounds such as intrinsic p_T and higher twist effects. There are several discussions that higher twists become important at high-x_L regions [23]. However, here we are interested in rather smaller-x_L regions

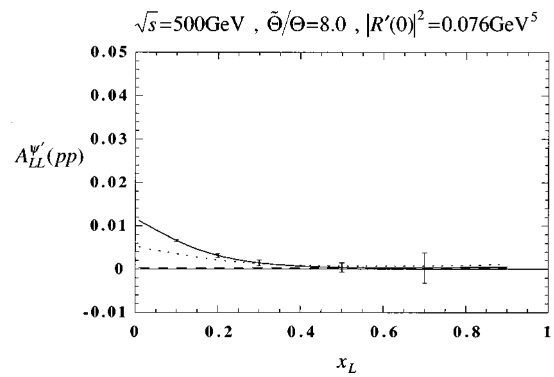

FIG. 3. The two-spin asymmetry $A_{LL}^{\psi'}(pp)$ for $\widetilde{\Theta}/\Theta=8.0$ and $|R'_{2\,^3P_2}(0)|^2=0.076$ GeV^5 at $\sqrt{s}=500$ GeV. Various lines represent the same as in Fig. 1. Error bars for the solid line denote the experimental sensitivity (see text).

where the dependence of A_{LL} on the shapes of $\Delta g(x)$ is large. Thus we do not need to worry about the higher twist effects to A_{LL}, in particular, for smaller x_L regions, $x_L < 0.2$. As for the intrinsic p_T effect, we have calculated the magnitude of such effects according to Contogouris *et al.* [24] and found that the effect was also negligible, although both the numerator and the denominator decrease a little owing to intrinsic p_T effects. Another comment is on the experimental sensitivity of the results. In order to examine if the experimental accuracy of the forthcoming RHIC experiments can really test our calculated results, we have estimated the experimental sensitivity for 100-day experiments at $\sqrt{s}=50$ and 500 GeV in the manner of Nowak [25], using the designed data of the beam polarization ($P=70\%$), the luminosity [$\mathcal{L}=8\times10^{30}$ (2×10^{32}) $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ for $\sqrt{s}=50$ (500) GeV], and the combined trigger and reconstruction efficiency ($C=50\%$) together with the values of unpolarized cross sections. The results are shown in Figs. 2 and 3 for the case of the GS parametrization (solid lines), where the BBS and GRV cases are not presented because they are almost the same. Because of the rather good sensitivity, our predictions are expected to be actually tested in the RHIC experiments, in particular, for smaller x_L regions like $x_L < 0.2$.

In summary, we have proposed small-p_T ψ' productions in longitudinal-proton–longitudinal-proton collisions whose experimental test will be available in the forthcoming RHIC experiments. The process can be dominated by two-gluon fusion in the lowest order, and thus we have only two mechanisms, i.e., color-octet and $2\,{}^3P_2$ state productions. Since each of them shows distinct behavior of the A_{LL} with opposite signs between the color-octet and $2\,{}^3P_2$ state, the process allows us to give a clean test of the color-octet model. Practically, the experimental test at $\sqrt{s}=50$ GeV might be the most promising. Furthermore, the process is effective for testing the spin-dependent gluon distribution in the proton because its cross section is directly proportional to the product of $\Delta g(x)$ in both protons.

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