Hard Processes with Spin–Dependent Parton Distributions

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ABSTRACT

To test a possible color–octet contribution of heavy quarkonium productions, we propose $\psi'$–productions for small–$p_T$ regions, where the color–singlet $\psi'$ state cannot be produced by the gluon–gluon fusion owing to charge conjugation. We also point out that these processes are very useful to deduce informations of spin–dependent gluon distributions $\Delta g$.

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Recently, it has been reported that the cross sections of heavy quarkonium productions measured in unpolarized $p\bar{p}$ collisions by the CDF collaboration are inconsistent with the calculation with the lowest order processes alone. Several groups have proposed new mechanisms: the production proceeds with not only color–singlet but also color–octet quarkonium states and this new mechanism dominates over the lowest order processes for large–$p_T$ quarkonium productions. But it does not seem to work for $\gamma + p \rightarrow J/\psi + X$. The discussion on the color–octet contribution is still controversial. Thus, it is important to test this mechanism in other experiments.

On the other hand, measurements of the spin–dependent structure functions of a nucleon $g_1(x,Q^2)$ for polarized deep inelastic scatterings (PDIS) imply a surprising result that the amount of the proton spin carried by quarks, ($\sim 30\%$), is much smaller than expected.
from the quark–parton model\(^4\). One of keys to solve this spin puzzle is to directly measure the spin–dependent gluon distributions \(\Delta g\) and study the behavior of them. Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), which will start early in the next decade, could offer such a possibility and will give us fruitful informations on the nucleon spin structure.

In this talk, to test a possible color–octet contribution to charmonium productions\(^2\) and furthermore to deduce informations of the spin–dependent gluon distributions, we suggest \(\psi'\)–productions for small–\(p_T\) regions at RHIC energies, where the color–singlet \(\psi'\) state does not contribute to the process due to charge conjugation. This process proceeds via the gluon–gluon fusion in the lowest order. Although there are several charmonium states, the detection for \(\psi'\) is easier than that for other charmonium states.

Let us introduce a two–spin asymmetry \(A_{LL}\) for this process,

\[
A_{LL} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{d\Delta\sigma}{d\sigma}, \quad (1)
\]

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 are

\[
\frac{d\Delta\sigma}{dx_L} = \frac{\tau}{\sqrt{x_L^2 + 4\tau}} \left[ \pi^2 \alpha_s^2 \left\{ \langle O_{S}^{\psi'} (1S_0) \rangle - \frac{1}{m_c^2} \langle O_{S}^{\psi'} (3P_0) \rangle \right\} \Delta g(x_a, Q^2) \Delta g(x_b, Q^2) - \frac{\pi^2 \alpha_s^2}{54 m_c^2} \langle O_{S}^{\psi'} (3S_1) \rangle \{ \Delta q(x_a, Q^2) \Delta \bar{q}(x_b, Q^2) + \Delta q \leftrightarrow \Delta \bar{q} \} \right], \quad (2)
\]

\[
\frac{d\sigma}{dx_L} = \frac{\tau}{\sqrt{x_L^2 + 4\tau}} \left[ \pi^2 \alpha_s^2 \left\{ \langle O_{S}^{\psi'} (1S_0) \rangle + \frac{7}{m_c^2} \langle O_{S}^{\psi'} (3P_0) \rangle \right\} g(x_a, Q^2) g(x_b, Q^2) + \frac{\pi^2 \alpha_s^2}{54 m_c^2} \langle O_{S}^{\psi'} (3S_1) \rangle \{ q(x_a, Q^2) \bar{q}(x_b, Q^2) + q \leftrightarrow \bar{q} \} \right], \quad (3)
\]

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

\[
x_a = \frac{x_L + \sqrt{x_L^2 + 4\tau}}{2}, \quad x_b = \frac{-x_L + \sqrt{x_L^2 + 4\tau}}{2}, \quad x_L \equiv \frac{2 p_L}{\sqrt{s}}, \quad \tau \equiv \frac{M^2}{s}, \quad (4)
\]

with longitudinal momentum \(p_L\) of the produced particle. \(\langle O_{S}^{\psi'} (1S_0) \rangle\), \(\langle O_{S}^{\psi'} (3S_1) \rangle\) and \(\langle O_{S}^{\psi'} (3P_0) \rangle\) are nonperturbative long–distance factors associated with the production of a \(c\bar{c}\) pair in a color–octet \(1S_0\), \(3S_1\) and \(3P_0\) states, respectively. From recent analysis for charmonium hadroproductions, the value of \(\langle O_{S}^{\psi'} (3S_1) \rangle\) and of the combination are given as \(\langle O_{S}^{\psi'} (3S_1) \rangle \sim\)
\[
4.6 \times 10^{-3} \text{ [GeV}^3\text{]}, \quad \langle O_{8}^\psi (1 S_{0}) \rangle + \frac{7}{m_c^2} \langle O_{8}^\psi (3 P_{0}) \rangle \sim 5.2 \times 10^{-3} \text{ [GeV}^3\text{]}\], and another combination \[
\frac{1}{3} \langle O_{8}^\psi (1 S_{0}) \rangle + \frac{1}{m_c^2} \langle O_{8}^\psi (3 P_{0}) \rangle \sim (5.9 \pm 1.9) \times 10^{-3} \text{ [GeV}^3\text{]}\]. Then we find the ratio as \[
\Theta = \frac{\langle O_{8}^\psi (1 S_{0}) \rangle - \frac{7}{m_c^2} \langle O_{8}^\psi (3 P_{0}) \rangle}{\langle O_{8}^\psi (1 S_{0}) \rangle + \frac{1}{m_c^2} \langle O_{8}^\psi (3 P_{0}) \rangle} \sim 0.69 \div 1.63.
\]

In order to study how the two–spin asymmetry \( A_{LL}^\psi \) is affect by the spin–dependent gluon distribution \( \Delta g(x) \), we take a model of \( \Delta g(x) \). So far, many people have suggested various kinds of \( \Delta g(x) \) from the analysis of the data on \( g_1(x, Q^2) \)[10, 11, 12]. The \( x \)–dependence of \( x\Delta g(x, Q^2) \) at \( Q^2 = 10\text{GeV}^2 \) is shown in fig.1. We estimate the \( A_{LL}^\psi (pp) \) as a function of \( x_L \) for \( \psi' \)–products at relevant RHIC energies, \( \sqrt{s} = 50 \) and 500GeV, by using these spin–dependent gluon distributions together with the spin–independent parton distribution of the Owens parametrization [10] for (a), the BBS parametrization [8] for (b), and the GRV92 LO parametrization [11] for (c), and taking \( Q^2 \) as 4\( m_c^2 \) with \( m_c = 1.5\text{GeV} \). Putting the ratio \( \Theta = 1 \), we show the results of \( A_{LL}^\psi (pp) \) at \( \sqrt{s} = 50 \) and 500GeV in figs.2 and 3, respectively. For \( \sqrt{s} = 50\text{GeV} \), we find that \( A_{LL}^\psi (pp) \) is very effective for examining not only the magnitude but also the behavior of the gluon polarization. But at \( \sqrt{s} = 500\text{GeV} \) we need rather precise data on \( A_{LL}^\psi (pp) \) to test \( \Delta g(x) \). There is a tendency that the smaller the \( \sqrt{s} \) is, the larger the \( A_{LL}^\psi (pp) \) become. 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 so \( g(x_a) \) and \( g(x_b) \) at \( \sqrt{s} = 500\text{GeV} \) become large. Accordingly, \( \Delta g(x_a)/g(x_a) \times \Delta g(x_b)/g(x_b) \) at \( \sqrt{s} = 500\text{GeV} \) become smaller than that at \( \sqrt{s} = 50\text{GeV} \).

In summary, observation of \( A_{LL}^\psi (pp) \) at small–\( p_T \) regions can largely contribute for the confirmation of the color–octet mechanism. At present, we do not know the exact value of \( \Theta = 0.69 \div 1.63 \). It is interesting to fix this value from other experiments in order to make a precise prediction of \( A_{LL}^\psi (pp) \). Furthermore, the small–\( p_T \) \( \psi' \)–production allow us to give a rather clean test as a probe of the magnitude and \( x \)–dependence of the gluon polarization.

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**Figure captions**

**Fig. 1:** The $x$ dependence of $x\Delta g(x,Q^2)$ at $Q^2 = 10\text{GeV}^2$ for various types of spin–dependent gluon distributions. The solid, dash–dotted, dotted, dashed and broken lines indicate the set A, B, C of ref.[7], ref.[8] and the ‘standard senrio’ of ref.[9], respectively.

**Fig. 2:** The two–spin asymmetry $A_{LL}^{\psi'}(pp)$ for $\bar{\Theta}/\Theta = 1$ and $\sqrt{s} = 50\text{GeV}$, calculated with various types of $\Delta g(x)$, as a function of longitudinal momentum fraction $x_L$ of $\psi'$. Various lines represent the same as in fig.1.

**Fig. 3:** The two–spin asymmetry $A_{LL}^{\psi'}(pp)$ for $\bar{\Theta}/\Theta = 1$ and $\sqrt{s} = 500\text{GeV}$. Various lines represent the same as in fig.1.
$Q^2 = 10 \text{[GeV}^2]\text{]}

Fig. 1

$\Theta / \Theta = 1.0$

Fig. 2
\[ \bar{\Theta} / \Theta = 1.0 \]

**Fig. 3**

The graph shows the variation of \( A_L^\psi (pp) \) as a function of \( x_L \). The y-axis represents \( A_L^\psi (pp) \) ranging from -0.001 to 0.006, while the x-axis represents \( x_L \) ranging from 0.0 to 1.0. The curves indicate different scenarios or conditions, with \( \bar{\Theta} / \Theta = 1.0 \) being a notable condition, as highlighted in the figure.