Single Diffractive $\Lambda_c^+$ Production in Polarized $pp$ Scattering with Polarized Gluon Distribution in the Proton

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ABSTRACT

Based on the hard-scattering factorization which decomposes the diffractive structure function into a pomeron flux and a pomeron structure function, we study the single diffractive $\Lambda_c^+$ production in polarized $pp$ scattering: $p + \bar{p} \rightarrow p + \Lambda_c^+ + X$, which will be observed at forthcoming RHIC experiment. By analyzing the cross section and correlation of the spin polarization between the initial proton and produced $\Lambda_c^+$, we found that the process might be effective for testing both hard-scattering factorization and models of the polarized gluon distribution in the proton.

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As is well known, the diffractive interaction which is characterized by a large rapidity gap event is described by pomeron exchange in the Regge theory \[1\]. Although the pomeron carrying the vacuum quantum number plays a crucial role in diffractive scattering, nature of the pomeron is still mysterious in the framework of quantum chromodynamics (QCD). Ingelman and Schlein suggested that the single pomeron exchange in proton-proton interaction can be probed as a hard scattering process between a hard parton in the pomeron emitted from a proton and a parton in another proton \[2\]. The evidence of the hard partonic structure of the pomeron was first reported by the UA8 Collaboration at CERN \(p\bar{p}\) collider at \(\sqrt{s} = 630\) GeV by observing diffractive dijet production \[3\]. This result has been confirmed by further experiments \[4, 5, 6\]. In addition, recent experiment found the hard-gluon fraction in the pomeron to be \(0.7 \pm 0.2\) \[6\], which means the pomeron being an almost gluonic object. Those results suggest us to apply the factorization theorem to diffractive hard process as well as to usual inclusive processes. However, Collins proved that the factorization theorem for diffractive deep inelastic scattering (DDIS) is not expected to be applicable to hadron-hadron collisions, though this theorem works for the lepton and direct photon induced hard DDIS \[7\]. In fact, the predicted cross sections for hadron-hadron collisions are several times larger than the experimental data, and hence the hard factorization for DDIS does not work well for the hadron-hadron collision \[8, 9\]. In order to overcome such difficulty, Goulianos proposed a phenomenological model in which the structure of the pomeron is derived from the structure of the parent hadron \[8\]; he introduced a renormalized pomeron flux factor which was given by renormalizing the standard pomeron flux carried by a proton to be unity (renormalized pomeron flux model). Although the prediction by this model seems to be in agreement with experimental data \[8, 9\], further tests of this model are necessary for various processes \[10\].

On the other hand, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) will start soon. One of the important purposes of RHIC experiment is to extract information about the polarized gluon distribution.
in the proton. That information is a key to understand the proton spin puzzle which is still one of the most challenging current topics in the nuclear and particle physics \[11\]. So far there are many models of the polarized parton distribution in the proton, which are extracted from a fit to the data on \(g_1(x, Q^2)\) \[12, 13\]. Those models can excellently reproduce experimental data on the polarized structure function of nucleons. However the behavior of the polarized gluon distributions is quite different among these models. In other words, the data on polarized structure functions of nucleon and deuteron alone are not enough to distinguish the model of gluon distribution functions. Although various processes have been proposed so far to test the models of the polarized gluon, knowledge of it is still poor.

In this work, we propose another diffractive semi-inclusive process: \(p + \vec{p} \rightarrow p + \Lambda_c^+ + X\) (left side of Fig. 1), which can be a test of the renormalized pomeron flux model and also the polarized gluon distribution function. In this process, \(\Lambda_c^+\) is dominantly produced via gluon-gluon fusion at the lowest order as shown in the right side of Fig. 1\#1, where one of the 2 gluons is originated from the pomeron. Moreover, since \(\Lambda_c^+\) is composed of a heavy quark \(c\) and antisymmetrically combined light \(u\) and \(d\) quarks, the spin of \(\Lambda_c^+\) is expected to be carried by the \(c\) quark and thus, the production of \(\Lambda_c^+\) in polarized proton-proton collisions gives us an interesting information about polarized gluons in the initial proton \[14, 15, 16\]. To test the hard-scattering factorization and polarized gluon distribution model for this attractive process:

\[
p (p_A) + \vec{p} (p_B) \rightarrow p (p'_A) + \overline{\Lambda}_c^+ (p_{\Lambda^+_c}) + X, \tag{1}
\]

whose lowest order subprocess is\#2

\[
g(p_a) + \vec{g}(p_b) \rightarrow \bar{c}(p_c) + \bar{c}(p_c), \tag{2}
\]

where \(p_i\) \((i = A, B, a, b, c, \bar{c}, \Lambda_c^+)\) in the parentheses denote the four-momentum of each particle and the over-arrow means that an initial gluon with momentum

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\#1 Since the charm quark content is extremely tiny and furthermore the pomeron is dominantly composed of gluons \[3\], the gluon-gluon fusion is the dominant process for charm quark pair production.

\#2 A subprocess in this model is a hard gluon-gluon scattering in the pomeron-proton system, as shown in Fig. 1.
Figure 1: The diagram for \( p + \bar{p} \to p + \Lambda_c^+ + X \) at the lowest order in the framework of hard-scattering factorization (left side) and its subprocess diagrams (right side). In the left side, the particles with arrows are polarized. \( \Pi P \) denotes the pomeron.

\( p_b \) and a produced \( c \) quark with momentum \( p_c \) are polarized, we introduce two useful observables; one is the \( d\Delta\sigma/dp_T \) defined in Eq. (3), which we call hereafter the polarized differential cross section, and the other is the \( A_{LL} \) defined in Eq. (4), which we call the spin correlation asymmetry;

\[
\frac{d\Delta\sigma}{dp_T} \equiv \frac{d\sigma(++) - d\sigma(-+) + d\sigma(--) - d\sigma(+-)}{dp_T},
\]

\[
A_{LL} \equiv \frac{[d\sigma(++) - d\sigma(-+) + d\sigma(--) - d\sigma(+-)]}{[d\sigma(++) + d\sigma(-+) + d\sigma(--) + d\sigma(+-)]} \frac{1}{dp_T},
\]

where \( d\sigma(+-)/dp_T \), for example, denotes the spin-dependent differential cross section with positive helicity of the target proton and negative helicity of the produced \( \Lambda_c^+ \).

Let us consider the process in the proton-proton center-of-mass frame. In this frame, we can take four-momenta of \( p_i \) as follows;

\[
p_{A,B} = \frac{\sqrt{s}}{2} (1, \mp \beta, \vec{0}) \text{ with } \beta \equiv \sqrt{1 - \frac{4m_P^2}{s}},
\]

\[
p_{\Lambda^+_c} = (E_{\Lambda^+_c}, p_L, \vec{p}_T)
\]

\[
= (\sqrt{m_{\Lambda^+_c}^2 + p_T^2 \csc^2 \Theta}, p_T \cot \Theta, \vec{p}_T),
\]

\[
p_{p} = \xi p_A, \quad p_a = x_a p_{p}, \quad p_b = x_b p_B, \quad p_c = \frac{p_{\Lambda^+_c}}{z}.
\]
where the first, second and third components in parentheses are the energy, the longitudinal momentum and the transverse momentum, respectively. \( m_i \) is the mass of the \( i \)-particle. The polarized differential cross section, \( d\Delta\sigma/dp_T \), can be calculated as follows:

\[
\frac{d\Delta\sigma}{dp_T} = \int_{-1}^{0} dt \int_{\xi_{\text{min}}}^{\xi_{\text{max}}} d\xi \int_{\Theta_{\text{min}}}^{\Theta_{\text{max}}} d\Theta \int_{x_{a_{\text{min}}}}^{1} dx_a \int_{x_{b_{\text{min}}}}^{1} dx_b \times f_{\gamma^* p}(\xi, t) f_{g/\gamma^*}(x_a, Q^2) \Delta G_{g/p}(x_b, Q^2) \\
\times \frac{d\Delta\hat{\sigma}}{d\hat{t}} J \Delta D_{\hat{\Lambda} + /c}(z),
\]

where \( t \) is the square of the four-momentum transfer of the proton which emits the pomeron. \( J \) is the Jacobian which transforms the variables \( z \) and \( \hat{t} \) into \( \Theta \) and \( p_T \). \( f_{g/\gamma^*}(x_a, Q^2) \) and \( f_{\gamma^* p}(\xi, t) \) are the hard gluon distribution function in the pomeron and the renormalized pomeron flux in the proton, respectively. The renormalized pomeron flux which was proposed by Goulianos to predict the observed single diffractive cross section [8], is defined by

\[
f_{\gamma^* p}^{\text{RN}}(\xi, t) \equiv D f_{\gamma^* p}(\xi, t),
\]

where \( f_{\gamma^* p}(\xi, t) \) and \( D \) are the standard pomeron flux and renormalization factor, respectively. \( f_{\gamma^* p}(\xi, t) \) is given by

\[
f_{\gamma^* p}(\xi, t) = K \xi^{1-2\alpha(t)} F^2(t),
\]

with the parameters which are chosen as [8]

\[
K = 0.73 \text{ GeV}^2, \quad \alpha(t) = 1 + 0.115 + 0.26[\text{GeV}^{-2}]t, \\
F^2(t) = e^{4.6t}.
\]

The renormalization factor \( D \) is defined as [8]

\[
D = \min(1, \frac{1}{N})
\]

with

\[
N = \int_{M_0^2/s}^{0.1} d\xi \int_{t=0}^{t=\infty} f_{\gamma^* p}(\xi, t) dt
\]
where \( M_0^2 \) is 1.5 GeV\(^2\) being the effective diffractive threshold and the upper limit for the \( \xi \) integration is a coherence limit. In addition, \( \Delta G_{\bar{g}/p}(x_b, Q^2) \) and \( \Delta D_{\Lambda^+_c/c}(z) \) represent the polarized gluon distribution function in the proton and the polarized fragmentation function of the outgoing charm quark decaying into a polarized \( \bar{\Lambda}_c^+ \), respectively.

Since the subprocesses considered here are the same with the ones discussed in Ref. [14], here we repeat some important formulas for reader’s convenience. By using the kinematical variables in Eq. (5), the polarized differential cross section, \( d\hat{\sigma}/d\hat{t} \), for the subprocess is calculated to be

\[
\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}} \left[ \frac{m_c^2}{24} \left( \frac{9\hat{t}_1 - 19\hat{u}_1}{\hat{t}_1\hat{u}_1} + \frac{8\hat{s}}{\hat{u}_1^2} \right) \right. \\
\left. + \frac{\hat{s}}{6} \left( \frac{\hat{t}_1 - \hat{u}_1}{\hat{t}_1\hat{u}_1} \right) - \frac{3}{8} \left( \frac{2\hat{t}}{\hat{s}} + 1 \right) \right],
\]

(11)

where \( \hat{s} \), \( \hat{t}_1 \) and \( \hat{u}_1 \) are defined as \( \hat{s} \equiv (p_a + p_b)^2 \), \( \hat{t}_1 \equiv (p_b - p_c)^2 - m_c^2 \) and \( \hat{u}_1 \equiv (p_a - p_c)^2 - m_c^2 \), respectively. The Jacobian \( J \) is given by

\[
J = \frac{2s\beta p_t^2 \cosec^2\Theta}{z(s - 2m_p^2)\sqrt{m_{\Lambda^+_c}^2 + p_t^2\cosec^2\Theta}},
\]

(12)

where \( s \) and \( z \) are defined as \( s \equiv (p_A + p_B)^2 \) and \( z \equiv \frac{x_1}{x_a} + \frac{x_2}{x_b} \), respectively, with \( x_1 \equiv \frac{2p_B p_{\Lambda_c^+}}{s - 2m_p^2} \), \( x_2 \equiv \frac{2p_A p_{\Lambda_c^+}}{s - 2m_p^2} \).

In order to estimate the asymmetry, \( A_{LL} \), we need the unpolarized cross section which can be obtained by replacing polarized functions, \( \Delta G_{\bar{g}/p}, \Delta \hat{\sigma}/d\hat{t} \) and \( \Delta D_{\Lambda^+_c/c} \) by unpolarized functions, \( G_{\bar{g}/p}, \hat{\sigma}/d\hat{t} \) and \( D_{\Lambda^+_c/c} \), respectively, in Eq. (6). The explicit formula of the unpolarized differential cross section for this subprocess was given by Babcock et al. [17]. As for the gluon distributions, we take the AAC [13] and the GRSV01 [18] parameterization models for the polarized distribution and the GRV98 [19] model for the unpolarized one. Here, we set \( Q^2 \) as \( (2m_c)^2 \) for each models. As for the unpolarized fragmentation function, we use Peterson fragmentation function \( D_{c \rightarrow \Lambda^+_c}(z) \). However, unfortunately at present there are no established polarized fragmentation function \( \Delta D_{c \rightarrow \Lambda^+_c}(z) \) because of lack of experimental data. Thus, by analogy with the study on \( \Lambda \) polarization [21], we take the following ansatz:

\[
\Delta D_{\bar{c} \rightarrow \bar{\Lambda}_c^+}(z) = C_{c \rightarrow \Lambda^+_c} D_{c \rightarrow \Lambda^+_c},
\]
where \( C_{c \to \Lambda_c^+} \) is scale-independent spin transfer coefficient. Here we apply the analysis on \( \Lambda \) production to \( \Lambda_c^+ \) production and choose the following two typical models:

(i) \( C_{c \to \Lambda_c^+} = 1 \) (non-relativistic quark model),
(ii) \( C_{c \to \Lambda_c^+} = z \) (Jet fragmentation model \[22\]).

For the hard gluon distribution function of the pomeron, we use \[6, 23\];

\[
xf_{g/P}(x, Q^2) = f_g 6x(1 - x), \quad f_g = 0.7 \pm 0.2, \quad (13)
\]

where \( f_g \) is the hard gluon fraction in the pomeron. To determine the value of the renormalization factor \( D \) given by Eq.\((7)\), we estimated the value of \( N \) defined by Eq.\((10)\) to be \( N = 3.4 \) (5.0) for \( \sqrt{s} = 200 \) (500) GeV using Eq.\((8)\) \[9\].

For numerical calculation, we use, as input parameters, \( m_c = 1.25 \) GeV, \( m_p = 0.938 \) GeV and \( m_{\Lambda_c^+} = 2.285 \) GeV \[24\]. In numerically integrating Eq. \((8)\), the minimum values of \( \xi, x_a \) and \( x_b \) are given by \( \xi_{\text{min}} = \frac{x}{1-x_2}, \quad x_{a \text{min}} = \frac{x_1}{\xi(1-x_2)} \) and \( x_{b \text{min}} = \frac{\xi x_1 x_2}{\xi x_a - x_1} \), respectively. In addition, to reduce possible non-pomeron contribution, we set \( \xi_{\text{max}} = 0.05 \) as usual \[8, 9, 10\]. Furthermore, in order to get rid of the produced \( \Lambda_c^+ \) entering the beam pipe, we limit the integration region of \( \Theta \) for produced \( \Lambda_c^+ \) as \( \frac{\pi}{6} \leq \Theta \leq \frac{5\pi}{6} \). \( p_T \) region is kinematically constrained from the condition of the diffractive production.

We show the \( p_T \) distribution of \( |d(\Delta)\sigma/dp_T| \) and \( A_{LL} \) in Fig. \[4\] for \( \sqrt{s} = 200 \) GeV and in Fig. \[3\] for \( \sqrt{s} = 500 \) GeV, respectively. Notice that the absolute value of \( d\Delta\sigma/dp_T \) is presented in these figures, because the negative value of \( d\Delta\sigma/dp_T \) cannot be depicted in the figure which has an ordinate with logarithmic scale. Actually, the value of \( d\Delta\sigma/dp_T \) is negative for \( p_T \) region larger than the value corresponding to the apparent sharp dip shown in Fig. \[2\]. Information on the dip is expected to be useful for distinguishing the models of the polarized gluon distribution functions because each parameterization model has a dip at different \( p_T \) as shown in the left panel of Figs. \[2\]. At \( \sqrt{s} = 500 \) GeV, the dip is not seen as shown in the left panel of Fig. \[3\] because the dip is in the region smaller than \( p_T = 1 \) GeV for the case of \( \sqrt{s} = 500 \) GeV. Thus, the polarized differential cross section are actually negative in the kinematical region presented in Fig. \[3\]. From
Figure 2: The unpolarized and polarized differential cross section (left panel) and the spin correlation asymmetry (right panel) as a function of $p_T$ at $\sqrt{s} = 200$ GeV. The solid line in the left panel represents the unpolarized differential cross section with the GRV98 model for the unpolarized gluon distribution. The long-dashed and dashed lines show the polarized differential cross section calculated with $C_{c \to \Lambda^+_c} = 1$ and $C_{c \to \Lambda^+_c} = z$, respectively, for AAC and GRSV01 models of polarized gluon distributions. The value of $d\Delta\sigma/dp_T$ is negative for $p_T$ region larger than the value corresponding to the apparent sharp dip. The same combination of the models for polarized gluon distributions and polarized fragmentation functions is adopted in the right panel.

Figure 3: The same as in Fig. 2 but for $\sqrt{s} = 500$ GeV.
the right panel of Figs. 2 and 3, it seems that the $A_{LL}$ is an effective observable to distinguish various models of polarized gluon distribution functions, even if there are uncertainties of the spin-dependent fragmentation function. Notice that if the renormalized pomeron flux model is not taken into account for the present process, the polarized differential cross section and unpolarized differential cross section become 3.4 (5.0) times larger than our calculation for $\sqrt{s} = 200(500)$ GeV. Therefore, measurement of those cross sections can be a good test of the renormalized pomeron flux model, though the $A_{LL}$ is not useful for testing the renormalized flux model because the renormalized flux factors are canceled out between the numerator and the denominator of Eq. (4).

Finally, some comments are in order, regarding uncertainty of the calculated result on the value of $m_c$ and the choice of $Q^2$. We have examined the variation of $A_{LL}$ on $m_c$ for the region of $1.15 \text{GeV} \leq m_c \leq 1.35 \text{GeV}$ and found that the result remain to be unchanged. We also found that the $Q^2$ dependence is rather insensitive; we have examined the 3 cases, (i) $Q^2 = (2m_c)^2$, (ii) $Q^2 = p_T^2$ and (iii) $Q^2 = m_{\Lambda_c^+}^2 + p_T^2$, without much difference.

In summary, we have calculated the polarized differential cross section, $d\Delta\sigma/dp_T$, and the spin correlation asymmetry, $A_{LL}$, for the single diffractive $\Lambda_c^+$ production in polarized $pp$ reactions at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV, based on the hard-scattering factorization with the renormalized pomeron flux. We found that $d\Delta\sigma/dp_T$ and $A_{LL}$ largely depend on the model of the polarized gluon distribution function. Therefore, the process looks promising for testing the models of polarized gluon distribution function. Moreover, it is expected that the measurement of $d(\Delta)\sigma/dp_T$ is quite effective for testing the renormalized pomeron flux model. In order to get more reliable prediction, the next-to-leading order calculation and error estimation might be necessary, which will be given in the forthcoming paper. In addition, since our prediction somewhat depends on the model of polarized fragmentation function, further experimental and theoretical study on polarized fragmentation functions is necessary for getting more reliable predictions.

Although the present calculation is confined in the leading order, the results are interesting and we hope our prediction will be tested in the forthcoming RHIC
experiment.

The authors thanks N. Saito for informing the physical parameters and condition of the RHIC experiment. We are also deeply grateful to M. Reya and W. Vogelsang for sending Fortran program of GRSV01. One of the authors (T.M.) would like to thank for the financial support by the Grant-in-Aid for Scientific Research, Ministry of Education, Science and Culture, Japan (No.11694081).

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