Charmed Hadron Production in Polarized $pp$ Collisions†

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ABSTRACT

To extract information about polarized gluons in the proton, production of charmed hadrons, in particular, $\Lambda_c^+$ baryon in $pp$ collisions was studied. We calculated the transverse momentum distribution and the pseudo-rapidity distribution of the spin correlation asymmetry $A_{LL}$ between the initial proton and the produced $\Lambda_c^+$. Those statistical sensitivities were also calculated under the condition of RHIC experiment. We found that the pseudo-rapidity distribution of $A_{LL}$ is promising for testing the model of polarized gluons in the proton and also the spin-dependent fragmentation model of a charm quark decaying into $\Lambda_c^+$ baryon.

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1 Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has just started to explore the internal structure of proton. One of the important purposes of those RHIC experiments is to study the behavior of polarized gluons in the proton. As is well known, the proton spin is given by the sum of the spin carried by quarks $\Delta \Sigma$ and gluons $\Delta G$, and their orbital angular momenta $\langle L_z \rangle$. In these years, a great deal of efforts have been made for extracting those components from polarized structure functions of nucleons\cite{1}. Based on the next-to-leading order QCD analyses on the polarized structure functions $g_1(x)$, the contribution of quarks to the proton spin is well known. However, knowledge on polarized gluons in the proton is still poor. To understand the origin of the nucleon spin, it is very important to know how gluons polarize in the nucleon. So far, several interesting processes have been proposed for extracting $\Delta G$. Here we also propose a different process to obtain more detailed information on polarized gluons, expecting the forthcoming RHIC experiment. The processes which we propose here are the polarized charmed hadron production, i.e. $p\bar{p} \rightarrow \Lambda_c^+ X$ and $p\bar{p} \rightarrow D^* X$, in the polarized proton–unpolarized proton collision\cite{21}, which will be observed at the RHIC experiment. We study which observables are useful for extracting information about polarized gluons in the proton and also discuss its sensitivity.

2 $\Lambda_c^+$ Baryon Production in Proton–Proton Collision

In the process on which we focus here, the $\Lambda_c^+$ baryon is expected to have some advantageous properties for probing behavior of polarized gluons in the proton. Those properties are as follows;

1. A charm quark which is one of constituents of the $\Lambda_c^+$ baryon is dominantly produced via gluon-gluon fusion in $pp$ reaction, because charm quarks are tiny contents in the proton. Thus, the cross section of this process is directly proportional to the gluon distribution in the proton.

\footnote{Though we have calculated even for $D^*$ production, we focus only on the $\Lambda_c^+$ production in this report, because the main point of the result remain unchanged.}
2. Since the $\Lambda_c^+$ baryon is composed of a charm quark and antisymmetrically combined light up and down quarks, the spin of $\Lambda_c^+$ baryon is expected to be almost equal to the spin of its constituent charm quark.

3. Since a charm quark is heavy, it must be very rare for the charm quark to change its spin arrangement during its fragmentation into a $\Lambda_c^+$ baryon. In other words, the spin direction of the charm quark produced in the subprocess is expected to be kept in the $\Lambda_c^+$ baryon produced in the final state.

After all, the spin of the $\Lambda_c^+$ is in strong correlation to the polarization of gluons in the proton. Therefore, by observing the spin correlation between the polarized proton in the initial state and the polarized $\Lambda_c^+$ in the final state, we can get, rather clearly, information on the polarized gluon in the proton.

3 Spin Correlation Asymmetry and its Statistical Sensitivity

To study the polarized gluon distribution in the proton, we introduced the spin correlation asymmetry of the target polarized-proton and produced $\Lambda_c^+$ baryon [2];

$$A_{L \ell} = \frac{d\sigma_{++} - d\sigma_{+\ell} + d\sigma_{-\ell} - d\sigma_{--}}{d\sigma_{++} + d\sigma_{+\ell} + d\sigma_{-\ell} + d\sigma_{--}}$$

$$\equiv \frac{d\Delta\sigma/dX}{d\sigma/dX}, \quad (X = p_T \text{ or } \eta),$$

(1)

where $d\sigma_{\pm\ell}$, for example, denotes the spin-dependent differential cross section with the positive helicity of the target proton and the negative helicity of the produced $\Lambda_c^+$ baryon. $p_T$ and $\eta$, which are represented by $X$ in Eq.(1), are transverse momentum and pseudo-rapidity of produced $\Lambda_c^+$, respectively.

According to the quark-parton model, $d\Delta\sigma/dX$ can be expressed as

$$\frac{d\Delta\sigma}{dX} = \int_{Y_{\text{min}}}^{Y_{\text{max}}} \int_{x_{\text{min}}^a}^{1} \int_{x_{\text{min}}^b}^{1} G_{p,a} \rightarrow g_{a}(x_a, Q^2) \Delta G_{p,B} \rightarrow g_{b}(x_b, Q^2) \Delta D_{c \rightarrow \Lambda_c^+}(z)$$

$$\times \frac{d\Delta\hat{\sigma}}{dt} J dx_a dx_b dY, \quad (X, Y = \eta \text{ or } p_T \quad (X \neq Y)),$$

(2)

with

$$J = \frac{2s\beta p_T^2 \cosh \eta}{z \sqrt{m_c^2 + p_T^2 \cosh^2 \eta}}, \quad \beta = \sqrt{1 - \frac{4m_c^2}{s}}$$
where $G_{p_A \to g_a}(x_a, Q^2)$, $\Delta G_{\bar{p}_B \to \bar{g}_b}(x_b, Q^2)$ and $\Delta D_{\bar{c} \to \bar{\Lambda}_c^+}(z)$ represent the unpolarized gluon distribution function, the polarized gluon distribution function and the spin-dependent fragmentation function of the outgoing charm quark decaying into a polarized $\bar{\Lambda}_c^+$, respectively. $d\Delta\hat{s}/d\hat{t}$ is the spin-dependent differential cross section of the subprocess and $J$ is the Jacobian which transforms the variables $z$ and $\hat{t}$ into $p_T$ and $\eta$. In the expression of Eq.(2), $p_T$ and $\eta$ are described as $X$ or $Y$.

Statistical sensitivities of $A_{LL}$ for the $p_T$ and $\eta$ distribution are estimated by using the following formula:

$$\delta A_{LL} \simeq \frac{1}{P} \frac{1}{\sqrt{b_{\Lambda_c^+}} \epsilon L T} \sigma.$$ (3)

To numerically estimate the value of $\delta A_{LL}$, here we use following parameters: operating time; $T = 100$-day, the beam polarization; $P = 70\%$, a luminosity; $L = 8 \times 10^{31} (2 \times 10^{32})$ cm$^{-2}$ sec$^{-1}$ for $\sqrt{s} = 200 (500)$ GeV, the trigger efficiency; $\epsilon = 10\%$ for detecting produced $\Lambda_c^+$ events and a branching ratio; $b_{\Lambda_c^+} \equiv \text{Br}(\Lambda_c^+ \to pK^-\pi^+) \simeq 5\%$ [3]. The purely charged decay mode is needed to measure the polarization of produced $\Lambda_c^+$. $\sigma$ denotes the unpolarized cross section integrated over suitable $p_T$ or $\eta$ region.

### 4 Numerical Calculations

To carry out the numerical calculation of $A_{LL}$, we used, as input parameters, $m_c = 1.20$ GeV, $m_p = 0.938$ GeV and $m_{\Lambda_c^+} = 2.28$ GeV[3]. We limited the integration region of $\eta$ and $p_T$ of produced $\Lambda_c^+$ as $-1.3 \leq \eta \leq 1.3$ and $3$ GeV $\leq p_T \leq 15(40)$ GeV, respectively, for $\sqrt{s} = 200(500)$ GeV. The range of $\eta$ and the lower limit of $p_T$ were selected in order to get rid of the contribution from the diffractive $\Lambda_c^+$ production. As for the upper limit of $p_T$, we took it as described above, for simplicity, though the kinematical maximum of $p_T$ of produced $\Lambda_c^+$ is slightly larger than 15 GeV and 40 GeV for $\sqrt{s} = 200$ GeV and 500 GeV, respectively. In addition, we took the AAC[4] and GRSV01 [5] parameterization models for the polarized gluon distribution function and the GRV98 [6] model for the unpolarized one. Though both of AAC and GRSV01 models excellently reproduce the experimental data on the polarized structure function of nucleons $g_1(x)$, the polarized gluon distributions for those models are quite different. In other words, the data on polarized structure function of nucleons $g_1(x)$ alone are not enough to distinguish the model of gluon distributions. Since the process is semi-inclusive, the
fragmentation function of a charm quark to $\Lambda_c^+$ is necessary to carry out numerical calculations. For the unpolarized fragmentation function, we used Peterson fragmentation function, $D_{c \rightarrow \Lambda_c^+}(z)$ [3, 7]. However, since we have no data, at present, about polarized fragmentation functions for the polarized $\Lambda_c^+$ production, we took the following ansatz for the polarized fragmentation function $\Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}(x)$,

$$\Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}(z) = C_{c \rightarrow \Lambda_c^+} D_{c \rightarrow \Lambda_c^+}, \quad (4)$$

where $C_{c \rightarrow \Lambda_c^+}$ is a scale-independent spin transfer coefficient. In this analysis, we studied two cases: (A) $C_{c \rightarrow \Lambda_c^+} = 1$ (non-relativistic quark model) and (B) $C_{c \rightarrow \Lambda_c^+} = z$ (Jet fragmentation model [8]). As we discussed before, if the spin of $\Lambda_c^+$ is same as the spin of charm quark produced in subprocess, the model (A) might be a reasonable scenario.

Numerical results of $A_{LL}$ are shown in Fig. 1 and Fig. 2. In those figures, statistical sensitivities, $\delta A_{LL}$, are also attached to the solid line of $A_{LL}$ which is calculated for the case of the GRSV01 parametrization model of polarized gluon and the non-relativistic fragmentation model.\(^2\) From these results, we see that the $\eta$ distributions of $A_{LL}$ are more effective observables than the $p_T$ distributions at $\sqrt{s} = 200$ GeV and 500 GeV. As shown in the right panel of Fig. 2 given at $\sqrt{s} = 500$ GeV, we could distinguish the parametrization models of polarized gluon as well as the models of the spin-dependent fragmentation function though the magnitude of $A_{LL}$ is rather small. At $\sqrt{s} = 200$ GeV, the magnitude of $A_{LL}$ for $\eta$ distribution becomes larger, though statistical sensitivities are not so small. If the integrated luminosity at $\sqrt{s} = 200$ GeV could be large and the detection efficiency, $\epsilon$, is improved, this observable could be promising to distinguish not only the models of $\Delta G(x)$ but also the models of $\Delta D(z)$. For the $p_T$ distribution of $A_{LL}$, $\delta A_{LL}$ become rapidly larger with increasing $p_T$ and we cannot say anything from those region. However, if we confine the kinematical region in rather small $p_T$ range like $p_T = 3 \sim 5(10)$ GeV at $\sqrt{s} = 200(500)$ GeV, it might be still effective.

5 Concluding Remark

To extract information on the polarized gluon distribution in the proton, the charmed hadron production processes at RHIC experiments have been proposed.\(^2\)

\(^2\)Note that as shown from Eq.(4), $\delta A_{LL}$ does not depend on both of the model of polarized gluons and the model of fragmentation functions.
Figure 1: $A_{LL}$ as a function of $p_T$ (left panel) and $\eta$ (right panel) at $\sqrt{s} = 200$ GeV.

Figure 2: The same as in Fig. 1, but for $\sqrt{s} = 500$ GeV.

(Actually, only $\Lambda_c^+$ process was discussed in this report.) The spin correlation asymmetry $A_{LL}$ between the initial proton and the produced $\Lambda_c^+$ was calculated for $p_T$ and $\eta$ distributions with statistical sensitivities which were estimated using RHIC parameters. We found that $A_{LL}$ is rather sensitive to the model of $\Delta G(x)$ and $\Delta D(z)$. The $\eta$ distribution of $A_{LL}$ could be promising for distinguishing the parametrization model of polarized gluons as well as the model of spin-dependent fragmentation of a charm quark into $\Lambda_c^+$. 

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