Semi–inclusive $\Lambda_c^+$ Leptoproductions and Polarized Gluon Distributions

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Abstract

In order to extract the behavior and magnitude of the spin–dependent gluon distribution, we propose a semi–inclusive $\Lambda_c^+$ production using unpolarized lepton beams and polarized proton targets. The correlation between the target proton spin and the spin of $\Lambda_c^+$ produced in the target fragmentation region might be very effective for testing various models of polarized gluons.

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The analysis of abundant experimental data on deep inelastic scatterings at large momentum transfer squared $Q^2$ indicates that a proton has structure and is composed of constituents called partons which are identified as massless quarks and gluons. The quantum number of the proton is carried by those constituents. For instance, the proton spin is given by the sum of the spin of those constituents and their orbital angular momenta,

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + \langle L_Z \rangle_{q+g},$$

where $\Delta \Sigma$ and $\Delta g$ are the amount of the proton spin carried by quarks and gluons, respectively, and $\langle L_Z \rangle_{q+g}$ implies the orbital angular momenta of quarks and gluons.

Recent measurement of spin–dependent structure functions of nucleons $g_1(x, Q^2)$, carried by EMC and SMC at CERN and E142, E143 and E154 at SLAC for polarized deep inelastic scatterings (DIS), has been widely interpreted as evidence of a breakdown of the simple quark–parton model of nucleons, with a surprising result that a little of the proton spin is carried by quarks, $\Delta \Sigma \sim 0.30$\cite{1}. Several competing explanations for this result have been proposed so far. Among them, there exist two most common interpretations: either the strange sea–quark (s–quark) of the proton is significantly polarized, or gluons contribute to the spin–dependent proton structure function through a flavor singlet current with subtle anomaly effects. In order to understand the underlying dynamics of the spin sum rule of eq.(1), it is important to know the behavior of polarized s–quarks and gluons in a proton. Many people have proposed various polarized parton distributions (PPDs) from a fit to recent data on $g_1(x, Q^2)$ based on above interpretations\cite{2, 3, 4}. From these analyses, one can see that the polarized distribution function of gluons can be largely different among various models as shown in fig.1, whereas those models mostly reproduce the valence quark polarization in a nucleon as well\cite{5}. The values of $\Delta g$ are large or small, depending on models. Far from that, some people have discussed about the possibility of even negatively polarized gluons\cite{6, 7}. In any case, at present the behavior and magnitude of the gluon polariza-
tion in a proton is still obscure. In order to understand the nucleon spin structure, their experimental determination is urgent. However, from measurement of $g_1(x, Q^2)$ alone, one cannot constrain the behavior of polarized gluons and test their models. Even if $g_1(x, Q^2)$ is measured with much higher precision, the situation cannot be improved as long as we remain in the polarized inclusive processes, $\ell \bar{p} \to \ell' X$, alone. Therefore, we are forced to proceed to other processes such as polarized proton–polarized proton collisions or semi–inclusive lepton–nucleon collisions for polarized DIS, $\ell \bar{p} \to \ell' hX$.

On the other hand, a large acceptance and high luminosity measurement of identified hadrons in DIS of polarized muons on polarized solid targets is now proposed by COMPASS Collaboration at CERN[8]. One of purposes of COMPASS experiments is to extract the spin-dependent distribution of individual partons from these semi-inclusive processes, in particular, by analyzing charmed hadron productions whose dominant processes are photon–gluon fusion. In the scattering of polarized lepton beams on polarized proton targets, photon–gluon fusion for heavy quark productions such as $J/\psi$ productions, open charm productions and so on, is generally a good process for testing gluon polarizations and many people have discussed interesting analyses so far[9].

In this letter, we propose a different process to test the gluon polarization in a proton, which is a semi–inclusive production of polarized $\Lambda_c^+$ baryons from a polarized proton, $\ell \bar{p} \to \ell' \Lambda_c^+ X$, using unpolarized lepton beams. Since a process of a charm quark decaying into $\Lambda_c^+$ almost carries the semi–inclusive production of $\Lambda_c^+$ and a contribution of photon–light quark processes is smaller than the case of open charm productions, the ambiguity of this process might be less than the case of open charm productions[10]. In addition, determining the polarization of $\Lambda_c^+$ is considerably easier because $\Lambda_c^+$ works as a self–analyzing particle. As is well known, the spin of $\Lambda_c^+$ is carried by a charm quark. Since a charm is created by a gluon via photon–gluon fusion as shown in fig.2 and thus has a spin parallel to the gluon spin, the direction of the $\Lambda_c^+$ spin which preserves the
charm quark spin, depends on that of the gluon spin. Therefore, if gluons are largely positively–polarized in a nucleon, the correlation between the target proton spin and the spin of $\Lambda_c^+$ produced in the target fragmentation region $x_F < 0$ along the target polarization axis is expected to become positive because the process can occur only via photon–gluon fusion in the lowest order. This suggests that the spin correlation between the target proton and produced $\Lambda_c^+$ can give a good information on gluon polarization in a proton.

Now, we define a spin correlation asymmetry $A_{LL}$ as an interesting observable parameter,

$$A_{LL} = \frac{[d\sigma_{++} - d\sigma_{+-} + d\sigma_{-+} - d\sigma_{--}]}{[d\sigma_{++} + d\sigma_{+-} + d\sigma_{-+} + d\sigma_{--}]} = \frac{d\Delta\sigma/dy}{d\sigma/dy}, \quad (2)$$

where $d\sigma_{+-}$, for instance, denotes that the spin of the target proton and produced $\Lambda_c^+$ is positive and negative, respectively. The spin–dependent differential cross section for $\gamma^*\vec{p} \rightarrow \vec{\Lambda}_c^+ X$ which is related to that for $\ell\vec{p} \rightarrow \ell' \vec{\Lambda}_c^+ X$ is given by

$$\frac{d\Delta\sigma_{\gamma^*\vec{p} \rightarrow \vec{\Lambda}_c^+ X}}{dy}(s,Q^2) = \int_{p_{t\min}^2}^{p_{t\max}^2} \int_{x_{\min}}^{1} dp_t^2 dx \; \Delta g(x,Q^2) \; \Delta D_{\Lambda_c^+/c}(z) \; f(s,Q^2) \times \frac{d\Delta\hat{\sigma}_{\gamma^*\vec{g} \rightarrow \vec{c}\bar{c}}}{dt}(\hat{s},\hat{t},\hat{u}), \quad (3)$$

with

$$f(s,Q^2) = \frac{x\sqrt{s(s + Q^2)}}{(M_{\Lambda_c^+}^2 + p_t^2)^2[se^y + \{xs - Q^2(1 - x)e^{-y}\}e^{-y}]} \quad (4)$$

where $\Delta g(x,Q^2)$ and $\Delta D_{\Lambda_c^+/c}(z)$ represent the polarized gluon distribution and spin–dependent fragmentation function of an outgoing charm quark decaying into a polarized $\Lambda_c^+$ with momentum fraction $z$, respectively. Unfortunately, at present the spin–dependent fragmentation function $\Delta D_{\Lambda_c^+/c}(z)$ is not known for lack of experimental data though we have some knowledge of the spin–independent one $D_{\Lambda_c^+/c}(z)$ \cite{11, 12}. However, since a charm quark is heavy, it might not be unreasonable to use $D_{\Lambda_c^+/c}(z)$
for \( \Delta D^{\Lambda^+}_{\Lambda^+}(z) \). Here we use \( D^{\Lambda^+}_{\Lambda^+}(z) \) suggested in ref.\[12\] for \( \Delta D^{\Lambda^+}_{\Lambda^+}(z) \). The spin-independent cross section is given by just replacing \( \Delta g(x, Q^2) \) and \( d\Delta \sigma/d\hat{t}(\hat{s}, \hat{t}, \hat{u}) \) in eq.(3) by \( g(x, Q^2) \) and \( d\sigma/d\hat{t}(\hat{s}, \hat{t}, \hat{u}) \), respectively. The perturbative QCD allows to calculate the subprocess cross section of photon–gluon fusion, \( \gamma^* g \to c\bar{c} \). Since the spin-independent subprocess cross section has been already presented in ref.\[13\], we here show only the spin-dependent one

\[
\frac{d\Delta \sigma}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}) = \frac{\pi \alpha_s e^2}{2 \hat{s}^2} \left[ \frac{-\hat{s}(A + B)}{\hat{s} + Q^2} \left( \frac{\hat{u}_1 + \hat{t}_1}{\hat{t}_1} + 2 \right) \right] + (A - B)(\hat{s} + Q^2) \left\{ \frac{\hat{s} + \hat{u}_1 + 2m_c^2}{\hat{t}_1} + \frac{2m_c^2 - \hat{u}_1}{\hat{u}_1} + \frac{2(2m_c^2 - \hat{s})}{\hat{t}_1} \right\},
\]

with

\[
\hat{t}_1 = \hat{t} - m_c^2, \quad \hat{u}_1 = \hat{u} - m_c^2,
\]

\[
A = \cos \theta_c \approx \cos \theta^{\Lambda^+}_c = \frac{(M_{\Lambda^+}^2 + p_T^2)^{\frac{1}{2}}(e^y - e^{-y})}{\left\{ M_{\Lambda^+}^2(e^y - e^{-y})^2 + p_T^2(e^y + e^{-y})^2 \right\}^{\frac{1}{2}}}, \quad \frac{1}{B} = \left( 1 - \frac{4m_c^2}{\hat{s}} \right)^{\frac{1}{2}}.
\]

Here we take approximately \( \theta_c \approx \theta^{\Lambda^+}_c \) for the scattering angle of the charm quark and that of produced \( \Lambda^+_c \), which can be expressed in terms of the transverse momentum and rapidity of produced \( \Lambda^+_c \).

In order to examine how the observed parameter is sensitive to the behavior of polarized gluon distributions, we calculate \( A_{LL} \) by using four typical examples of \( \Delta g(x, Q^2) \) presented in fig.1. At a CMS energy of the virtual photon–proton collision, \( \sqrt{s} = 10\text{GeV} \) (which corresponds to \( \gamma^* \) energy \( \nu = 56\text{GeV} \)) and a momentum transfer squared \( Q^2 = 10\text{GeV}^2 \), whose kinematical region can be covered by COMPASS experiments, we have calculated the asymmetry \( A_{LL} \) and shown it in fig.3 as a function of rapidity \( y \) of \( \Lambda^+_c \). In figs.3 and 4, to calculate unpolarized cross sections, we have used an unpolarized gluon distribution of ref.\[14\] for the solid and dotted lines, the one of ref.\[3\] for the dash-dotted line and the one of ref.\[15\] for the dashed line. One can see that the \( A_{LL} \) significantly depends on the behavior and magnitude of polarized gluon distributions. It is remarkable that although the lower limit of the integration
variable $x$ for the differential cross section in eq.(3) is $x_{\text{min}} = 0.29$ for $\sqrt{s} = 10\text{GeV}$ and $Q^2 = 10\text{GeV}^2$ at $y = -0.5$ and the difference of $\Delta g(x)$ among various models taken up here is not so big for the region larger than $x \approx 0.3$, the difference of $A_{LL}$ becomes conspicuous. This implies that the process might be very promising to distinguish various models of polarized gluons.

Some comments are in order. (1) In order to determine the polarization of $\Lambda_c^+$ in experiment, one must observe the processes of $\Lambda_c^+ \rightarrow \Lambda \pi^+$ or $\Lambda e^+\nu_e$, whose branching ratios are $(7.9 \pm 1.8) \times 10^{-3}$ or $1.4 \pm 0.5\%$, respectively. Since the spin-dependent and spin–independent cross sections are not so large, being an order of $10^{-2}\text{nb}$ and $10^{-1}\text{nb}$, respectively, at $\sqrt{s} = 10\text{GeV}$ and $Q^2 = 10\text{GeV}^2$ as shown in fig.4, we need rather high luminosity, which can be hopefully obtained. (2) For the semi–inclusive $\Lambda_c^+$ production, there might be other processes in addition to the process calculated here: a vector meson dominance process, a diffractive dissociation and a compton scattering process due to an intrinsic charm component. However, by constraining a kinematical region as $x_F < 0$ for produced $\Lambda_c^+$, we can pick up the photon–gluon fusion mechanism which dominantly contributes to $\ell \vec{p} \rightarrow \ell' \Lambda_c^+ X$. In such a region, the value of spin correlations between the target proton and produced $\Lambda_c^+$ can give a good information on gluon polarizations in a proton. (3) Some people have discussed that measurement of polarization of $\Lambda$ produced in the target fragmentation region for unpolarized lepton scatterings off a polarized proton target could determine whether $s$–quarks polarized negatively or gluons polarized positively in a proton [16]. In this reaction, one can expect that for the latter case the correlation between the target proton spin and the spin of $\Lambda$ produced along the target polarization axis becomes positive, while that should be negative for the former case. Our prediction is deeply related to their prediction. Experimental test of both predictions would lead us to a good understanding of the spin structure of a proton.

In summary, we have calculated the spin correlation asymmetry $A_{LL}$ for the
process with unpolarized lepton beams and polarized proton targets, $\ell \vec{p} \rightarrow \ell' \vec{\Lambda}^+_c X$, and found that the behaviour of $A_{LL}$ is sensitive to the form of $\Delta g$. We hope the present prediction can be tested in the forthcoming experiment.

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Figure captions

Fig. 1: The $x$–dependence of polarized gluon distributions at $Q^2 = 10 \text{GeV}^2$. The solid, dotted, dash–dotted and dashed lines indicate the set A, C of ref.[2], ref.[3] and the ‘standard scenario’ of ref.[4], respectively.

Fig. 2: The lowest order QCD diagram for $\Lambda_c^+$ leptoproductions in unpolarized lepton–polarized proton scatterings.

Fig. 3: The spin correlation asymmetry $A_{LL}$ as a function of rapidty $y$ at $\sqrt{s} = 10 \text{GeV}$ and $Q^2 = 10 \text{GeV}^2$. Various lines represent the same as in fig.1.

Fig. 4: The spin–dependent and spin–independent differential cross sections as a function of $y$ at $\sqrt{s} = 10 \text{GeV}$ and $Q^2 = 10 \text{GeV}^2$. Various lines represent the same as in fig.1.
\[ Q^2 = 10 \text{ [GeV}^2 \text{]} \]

Fig. 1

Fig. 2
