Charmed Hadron Production in Neutrino Reactions and Polarized $s$–quark Distribution

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Abstract

In order to obtain information about the polarized strange quark distribution, we studied the semi–inclusive $\Lambda^+_c/\bar{\Lambda}_c^+$ production in neutrino and polarized proton collisions. We found that these reactions are effective to clearly extract the polarization of strange quark by measuring the spin correlation between the target proton and the produced $\Lambda^+_c/\bar{\Lambda}_c^+$ baryon.

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Proton spin puzzle is currently one of the most challenging topics in high energy spin physics. As is well known, proton spin is composed of the spin and orbital angular momentum of quarks and gluons which constitute proton. The polarized parton distribution plays an important role on the spin structure of proton. However, knowledge of the polarized sea quark distribution remain still poor. In order to understand the spin structure of proton, we need more information about the polarized sea quark distribution functions. Recently, HERMES group has reported \cite{1} that direct measurement of the strange sea is required to explain the violation of the Ellis–Jaffe sum rule \cite{2}. So far, there are several parametrization models of the strange quark distribution. Though the most simplest case is to assume the flavor SU(3)$_f$, a new parametrization taken account of the violation of SU(3)$_f$ is also recently proposed \cite{3}.

Here we focus on the polarized $s/\bar{s}$ quark distribution. To examine the polarized $s/\bar{s}$ quark distribution, we have studied semi–inclusive $\Lambda^+_c/\bar{\Lambda}^+_c$ neutrino production; $\nu+\bar{p}\to l^-+\bar{\Lambda}^+_c+X$, $\bar{\nu}+p\to l^++\Lambda^+_c+X$, which might be observed at the planned factory, where arrows attached to particles mean that these particles are polarized. Since in the naive quark model, the $\Lambda^+_c$ baryon is composed of a heavy $c$–quark and anti–symmetrically combined light $u$ and $d$–quarks, we can assume the polarization of $\Lambda^+_c$ baryon to be the one of $c$–quark. In addition, $\Lambda^+_c$ is dominantly produced by the fragmentation of $c$–quark which is originated from $s$–quark through the $t$–channel $W$ exchange at the leading order. Therefore, there can be a correlation between the $s$–quark polarization and the produced $c$–quark polarization. Hence we can expect that the measurement of the spin correlation between the incident proton and the produced $\Lambda^+_c/\bar{\Lambda}^+_c$ gives us information about the polarized $s/\bar{s}$–quark distribution in proton.

For above processes, we calculated the double spin asymmetry $A^H_{LL}$ for final state hadron specified by $H$ ($\Lambda^+_c$ or $\bar{\Lambda}^+_c$), which is given by

$$A^H_{LL} = \frac{d\Delta\sigma/dp_T}{d\sigma/dp_T},$$

where $p_T$ is a transverse momentum of final hadron $H$. $d\Delta\sigma$ represents the spin–dependent differential cross section and is defined in terms of $d\sigma_{hh'}$ as

$$d\Delta\sigma \equiv \frac{1}{4}[d\sigma_{++} - d\sigma_{+-} + d\sigma_{-+} - d\sigma_{--}],$$
with definite helicities $h$ and $h'$ for incoming proton and outgoing $\Lambda_c^+ / \bar{\Lambda}_c^+$, respectively.

For $\Lambda_c^+$ production, the spin–dependent differential cross section is given

$$d\Delta\sigma(\nu p \to l^- \Lambda_c^+ X) = \left\{ U_{cs}^2 \Delta s(x) + U_{cd}^2 \Delta d(x) \right\} dx \left( \frac{d\Delta\hat{\sigma}}{dt} \right) d\hat{t} \Delta D^{\Lambda_c^+}_{cs}(z)dz,$$

(3)

where $\Delta s(x)$ and $\Delta d(x)$ are the polarized $s$–quark and $d$–quark distribution functions, respectively. $U_{cs}$ and $U_{cd}$ are CKM parameters. $\Delta D^{\Lambda_c^+}_{cs}(z)$ is the polarized fragmentation function of outgoing charm quark decaying into $\Lambda_c^+$.

We used the model of Peterson et al. [4] as the unpolarized fragmentation function, which is given by [5]

$$D^{\Lambda_c^+}_{cs}(z) = \frac{1}{z[1 - \frac{1}{z} - \frac{\epsilon_p}{1-z}]^2}$$

$\epsilon_p \sim 0.25$ for $\Lambda_c^+$. (4)

Unfortunately, the polarized fragmentation function is not yet established because of lack of experimental data. By analogy with the study on $\Lambda$ polarization [3], we took the following ansatz:

$$\Delta D^{\Lambda_c^+}_{cs}(z) = C^{\Lambda_c^+}_{cs}(z) D^{\Lambda_c^+}_{cs}(z),$$

(5)

where $C^{\Lambda_c^+}_{cs}(z)$ is the scale–independent spin transfer coefficient. Here we apply the analysis on $\Lambda$ production to $\Lambda_c^+$ production and choose the following two models; $C^{\Lambda_c^+}_{cs}(z) = 1$ (the naive nonrelativistic quark model) and $C^{\Lambda_c^+}_{cs}(z) = z$ (the jet fragmentation models [7]). The double spin asymmetry $A^{\Lambda_c^+}_{LL}$ is described in terms of the spin transfer coefficient $C^{\Lambda_c^+}_{cs}(z)$ and the ratio of the parton distribution functions as

$$A^{\Lambda_c^+}_{LL} \propto C^{\Lambda_c^+}_{cs}(z) \frac{U_{cs}^2 \Delta s(x) + U_{cd}^2 \Delta d(x)}{U_{cs}^2 s(x) + U_{cd}^2 d(x)}.$$

(6)

Thus $A^{\Lambda_c^+}_{LL}$ is proportional to linear combination of the polarized $s$–quark and $d$–quark distribution function. Therefore, $\Lambda_c^+$ production is not so good process for clearly extracting the $s$–quark distribution, since the contribution from the valence $d$–quark is large.
On the contrary, $A_{LL}^{\Lambda^+}$ in $\bar{\Lambda}_c^+$ production can be represented as

$$A_{LL}^{\Lambda^+} \propto C_c^{\Lambda^+}(z) \frac{U_{cs}^2 \Delta \bar{s}(x) + U_{cd}^2 \Delta \bar{d}(x)}{U_{cs}^2 \bar{s}(x) + U_{cd}^2 \bar{d}(x)} = C_c^{\Lambda^+}(z) \frac{\Delta \bar{s}(x)}{\bar{s}(x)} = C_c^{\Lambda^+}(z) \frac{\Delta s(x)}{s(x)},$$

in which the $\bar{d}$–quark contribution can be eliminated and thus $A_{LL}^{\Lambda^+}$ is directly proportional to the strange quark distribution function. Therefore, we can clearly extract the polarized strange quark distribution $\Delta s(x)$. Note that above equation is derived in both the flavor SU(3)$_f$ case ($\Delta \bar{u}(x) = \Delta \bar{d}(x) = \Delta \bar{s}(x)$) and the non–SU(3)$_f$ case ($\Delta \bar{u}(x) = \Delta \bar{d}(x) = \lambda \Delta \bar{s}(x)$).

Setting a charm quark mass $m_c = 1.5$ GeV and the relevant collider energy $\sqrt{s} = 50$ GeV, we numerically calculated the spin–independent and dependent differential cross sections and the double spin asymmetry. As for the parton distribution functions, we used the GRV98 [8] parametrization as the unpolarized parton distribution function, and the AAC [4] and “standard scenario” of GRSV00 [10] parametrizations for the polarized one.

We show the double spin asymmetry in Fig. 1 as a function of $p_T$ at $\sqrt{s} = 50$ GeV for $\Lambda_c^+$ production (left panel) and for $\bar{\Lambda}_c^+$ production (right panel). In order to suppress the contributions from the diffractive process and higher twist corrections, we have imposed the kinematical cut on $p_T$ as $p_T > 2$ GeV in numerical calculations. In figures, the bold and normal lines show the case of AAC parametrization and “standard scenario” of GRSV00 parametrization, respectively. The solid lines represent the spin transfer coefficient $C_c^{\Lambda_c^+}(z) = 1$ case, while the dashed lines represent $C_c^{\Lambda_c^+}(z) = z$ case.

As shown in figures, $A_{LL}^{\Lambda_c^+}$ in the smaller $p_T$ regions does not depend on the model of polarized parton distribution functions, and is strongly affected by the shape of the spin transfer coefficient $C_c^{\Lambda_c^+}(z)$. Therefore, The $\Lambda_c^+$ production is effective for extracting information about the polarized fragmentation function $\Delta D_{\Lambda_c^+}(z)$. On the other hand, measuring $A_{LL}^{\Lambda_c^+}$ in larger $p_T$ regions is quite effective for testing the model of polarized parton distribution functions, since the ambiguity of the polarized fragmentation function is small and we see a big difference between two parametrization models.

*λ represent a degree of SU(3)$_f$ violation and is a parameter which should be determined from experiments [3].
In summary, to extract information about the polarized strange quark distribution in proton, the semi-inclusive $\Lambda^+_c/\bar{\Lambda}^+_c$ production in neutrino-polarized proton collisions was studied. $\bar{\Lambda}^+_c$ production is most promising not only for testing but also for directly extracting the polarized strange quark distribution $\Delta s(x)$ by measuring $A_{LL}^{\bar{\Lambda}^+_c}$.

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