Influence of Heavy Quark Recombination on the Nucleon Strangeness Asymmetry

Puze Gao
Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China

Bo-Qiang Ma*
School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

The nucleon strange and anti-strange distribution asymmetry is an important issue in the study of the nucleon structure. In this work, we show that the heavy quark recombination processes from a perturbative QCD picture can give a sizable influence on the measurement of the nucleon strangeness asymmetry from charged-current charm production processes, such as the CCFR and NuTeV dimuon measurements. When the influence of heavy quark recombination is considered, a positive effective strangeness asymmetry should be added to the initially extracted strangeness asymmetry to be relevant to the NuTeV anomaly within the framework of the standard model. Perturbative QCD at three-loops can also generate a strangeness asymmetry, however, the obtained magnitude is one order smaller to be relevant to the NuTeV anomaly.

The nucleon strange and anti-strange distributions are important quantities in the study of the nucleon structure, and a clear knowledge of them helps for a better understanding of some related phenomena in experiments. The nucleon strange quark-antiquark distribution asymmetry is predicted naturally by some non-perturbative models, and a positive strange asymmetry $S^- = \int dx [s(x) - \bar{s}(x)] x$ has been shown to be a promising mechanism to explain the NuTeV anomaly within the framework of the standard model. Perturbative QCD at three-loops can also generate a strangeness asymmetry, however, the obtained magnitude is one order smaller to be relevant to the NuTeV anomaly.

In the measurement of the nucleon strangeness asymmetry, some valuable works have been done, though no conclusive result has been reached. Since strangeness asymmetry should be a very small quantity in inclusive deep inelastic scattering (DIS) cross sections, it is difficult to be extracted precisely. However, (anti-)neutrino induced charged current production processes are quite sensitive to the (anti-)strange distribution, and thus can provide valuable information on the strangeness asymmetry. CCFR and NuTeV dimuon measurements are of such experiments. Although earlier analysis of dimuon data did not show support of the nucleon strangeness asymmetry, a recent next to leading order (NLO) analysis of the NuTeV data with improved method does show some evidence of the nucleon strange asymmetry $S^- = 0.00196 \pm 0.00046$ (stat) $\pm 0.00045$ (syst) $\pm 0.00128$ (external). Meanwhile, global analysis have indicated positive strange asymmetry, such as the most recent work of Lai et al., who include both CCFR and NuTeV dimuon data sets in their analysis, and produce the allowed range of $-0.001 < S^- < 0.005$ at 90% confidence level. These analysis suggest that $S^-$ is likely positive.

In this work, we aim at checking the measurement of the nucleon strangeness asymmetry by including a perturbatively calculable QCD effect. We find that the heavy quark recombination processes can produce a sizable influence on the measurements with charged-current charm production process such as the CCFR and NuTeV dimuon measurements.

Heavy quark recombination combines a heavy quark, e.g., $c$ quark, with a light antiquark $\bar{q}$ to form a D meson. Refs. employ simple perturbative QCD pictures and explain the charm photoproduction asymmetry and the leading particle effect successfully. In the following, we show how the heavy quark recombination influences the measurement of the nucleon strangeness asymmetry.

The CCFR and NuTeV dimuon measurements have provided important information on the strangeness degrees of freedom in the parton structure of the nucleon. These measurements both rely on the (anti-)neutrino induced charged-current charm production processes, with the leading order (LO) subprocesses being $\nu + s(d) \rightarrow \mu^- + c$ and $\bar{\nu} + \bar{s}(d) \rightarrow \mu^+ + \bar{c}$. The produced $c(\bar{c})$ quark hadronizes and then decays partially into $\mu^+(\mu^-)$ to form a second $\mu$. The oppositely signed dimuon events in experiment are then recorded for analysis of the nucleon strange distributions.

The CCFR and NuTeV experiments use iron as their target, and for simplicity, we take it as an isoscalar target. The strange quark antiquark distribution asymmetry is directly related to the difference between neutrino and anti-neutrino induced dimuon differential cross section.
where $d\sigma_{D(c\bar{q})}$ denotes the cross section for the subprocess $(2)$, which is identical to the cross section of subprocess $(3)$ from charge symmetry. $B_{D(c\bar{q})}$ is the branching ratio for $D(c\bar{q}) \to \mu^+X$. $q$ denotes a light quark flavor from the nucleon, which could be $u$ or $d$, and the $D(c\bar{q})$ meson could be either a scalar $^1S_0$ state or a vector $^3S_1$ state.

Such a contribution as Eq. (4) serves as an additional part in the extracted strange distribution asymmetry, such as the NLO analysis of the NuTuV dimuon data [13], because the recombination processes as FIG. 1 are not included in the analysis. Thus the realistic strange distribution asymmetry $S_{\text{real}}^-(\xi)$ should be the analysed result $S_{\text{analy}}^-(\xi)$ minus the contribution from heavy quark recombination processes, which is a negative quantity from Eq. (4) since the nucleon structure ensures $\bar{q}(x) - q(x) < 0$ for $q = u, d$. From Eq. (11) and Eq. (4), one gets

\[ S_{\text{real}}^-(\xi) = S_{\text{analy}}^-(\xi) + \delta S_{\text{HR}}^-(\xi), \]  

(5)

with

\[ \delta S_{\text{HR}}^-(\xi) \approx \frac{\pi r_w^2}{G_F^2 S f_c B_c |V_{cd}|^2} \times \sum_{q,D} \int dx[q(x) - \bar{q}(x)] \frac{d^2\sigma_{D(c\bar{q})}}{d\xi dy} B_{D(c\bar{q})}, \]  

(6)

where $\delta S_{\text{HR}}^-(\xi) > 0$ since to minus a negative quantity is equivalent to plus a positive quantity. Thus the realistic strangeness asymmetry $S_{\text{real}}^-(\xi)$ should be larger than the experimentally extracted value according to the contribution from the unaccounted recombination processes.

Now we proceed to estimate the size of $\delta S_{\text{HR}}^-(\xi)$. We follow the method in Ref. [13] to calculate the heavy quark recombination process. For the color singlet $^1S_0$ $D(c\bar{q})$ production, the following substitution is made in the parton amplitude:

\[ v_j(p_q)\bar{q} c(p_c) \to x_q \rho c(\xi) (\gamma^\mu \varepsilon^\nu (p_c - m_c)\gamma_5). \]  

(7)

Then set $p_q = x_q p_c$ in the amplitude and take the limit $x_q \to 0$. Thus the amplitude for color singlet $^1S_0$ state $D(c\bar{q})$ production is (diagrams in FIG. 1(a)(b)):

\[ M_{\text{in}} = \frac{16\pi G_F^2 x_q m_c \delta_{ij} f_c}{9\sqrt{2} r_w^2 (2l^2 - p_c)} L^\mu \bar{\tau}(l) \gamma^\nu (\gamma - m_c) \gamma_5 \]  

\[ \times \{\gamma_\mu (p - k - k_0)^2 - m_c^2/2\} (1 - \gamma_5) + \gamma_\nu (1 - \gamma_5) \frac{\gamma - k_0}{l^2 - k_0^2} \gamma^\nu \varepsilon(k_0), \]  

(8)
where $L^\mu = \overline{\psi}(k)\gamma^\mu(1 - \gamma_5)u(p)$ is the lepton current.

The $\delta_j$ in Eq. (7) is the color factor for color-singlet state, which is replaced by $\sqrt{\frac{2}{3}}f^i_j$ for color-octet state together with the nonperturbative parameter $f_+$ replaced by $f^3_+$. $\rho_1 = f^i_+ + ps$ and $\rho_8 = (f^3_+)^2$ will appear in cross sections to characterize the probability for a color-singlet and a color-octet $1^3S_0(1^3f)$ state to hadronize into a state including a $1^1S_0$ state $D(\overline{c}f)$ meson. The subprocess cross section for $1^3S_0$ state $D(\overline{c}f)$ meson production thus can be expressed as

$$d\sigma_{D(\overline{c}f)} = d\hat{\sigma}[\overline{c}f(1^3S_01^1f)] \cdot \rho_1 + d\hat{\sigma}[\overline{c}f(1^3S_0s)] \cdot \rho_8.$$  (9)

The $d\hat{\sigma}[\overline{c}f(1^3S_0s)]$ can be calculated to be different from $d\hat{\sigma}[\overline{c}f(1^3S_01^1f)]$ by a single color factor of $1/8$. Thus, $d\hat{\sigma}_{D(\overline{c}f)}$ of Eq. (9) can be expressed as

$$d\sigma_{D(\overline{c}f)} = d\sigma[\overline{c}f(1^3S_01^1f)] \cdot \rho_{ef}[\overline{c}f(1^3S_01^1f) \to D(\overline{c}f)],$$  (10)

with $\rho_{ef} = \rho_1 + \rho_8/8$.

For $1^3S_1$ state production of vector meson $D^*(\overline{c}f)$, similar substitution as Eq. (7) with the $\gamma_5$ replaced by $\gamma$ is made in the parton amplitude, where $\epsilon$ is the polarization vector for the $1^3S_1$ state. Similar expression as Eq. (10) can be obtained for the subprocess cross section of vector $D^*(\overline{c}f)$ meson production, and spin-flipped transitions such as $\overline{c}f(1^3S_01^3f) \to D^*(\overline{c}f)$. While we have neglected such transitions, partly because the calculation of charm photoproduction and the leading particle effect have both set $\rho_{ef} = 0$, and partly because the inclusion of these transitions will not affect our result, since both $D(\overline{c}f)$ and $D^*(\overline{c}f)$ meson will decay similarly to $\mu^+$. The flavor-changing transitions, such as $\epsilon \to D^*(\overline{c}f)$, are also neglected as Refs. 19, 20, because these transitions are relatively suppressed in the large $N_c$ limit of QCD, and also because the inclusion of such transitions will not affect our result notted.

The number of free parameters can be greatly reduced from symmetries of the strong interaction. As discussed in Ref. 19, heavy quark spin symmetry implies

$$\rho_{ef}[\overline{c}f(1^3S_01^3f) \to D(\overline{c}f)] = \rho_{ef}[\overline{c}f(1^3S_1) \to D^*(\overline{c}f)],$$  (12)

and SU(3) light quark flavor symmetry indicates, for example,

$$\rho_{ef}[\overline{c}f(1^3S_0) \to D^0] = \rho_{ef}[\overline{c}f(1^3S_0) \to D^+].$$  (13)

Thus, only one parameter is left:

$$\rho_{\text{sm}} = \rho_{ef}[\overline{c}f(1^3S_0) \to D^+] = \rho_{ef}[\overline{c}f(1^3S_1) \to D^{**}].$$  (14)

Thus, for isoscalar target, the $\delta S_{\text{HR}}^{-}(\xi)$ of Eq. (8) can be expressed as

$$\delta S_{\text{HR}}^{-}(\xi) \approx \frac{\pi v^{2}}{G_{F}^{2}f_{\text{c}}|V_{c\overline{c}}|^{2}B_{\text{c}}^{2}} \int \frac{dz}{u_{\text{c}}(x) + d_{\text{c}}(x)} \times \left[ \frac{d\hat{\sigma}[\overline{c}f(1^3S_01^1f)]_{b_1} + d\hat{\sigma}[\overline{c}f(1^3S_1)1^1f]}{d\xi dy} \right] \cdot \rho_{\text{sm}}.$$  (15)

where $b_1 = (B_{D^{++}} + B_{D^{0}})/2$ and $b_2 = (B_{D^{0}} + B_{D^{+}})/2$.

The subprocess cross section can be calculated straight forward from the parton amplitudes (with the parameter $f_+$ extracted out for $\rho_{\text{sm}}$). Since the subprocess is a $2 \to 3$ process, there are five independent variables in the subprocess cross section. From the symmetry of the scattered $\mu^+$ around the incident direction, four independent variables are left, where two variables are transformed to $\xi$ and $y$ (or $Q^2$) and the other two are integrated out. Thus for $\delta S_{\text{HR}}^{-}(\xi)$ of fixed $Q^2$, the integration is totally of 3 dimensions including the integral on $x$ in Eq. (15). The boundaries of the integration are determined from the allowed physical phase space.

We use the CTEQ6L parton distributions for the nucleon, and the running coupling constant $\alpha_s$ is as specified in CTEQ6L. We take $m_{c} = 1.5$ GeV and set the factorization scale to be $\sqrt{p_{T}^{2} + m_{c}^{2}}$. Since the two muons in NuTeV experiment are required to have energy greater than 5 GeV, we try similar cuts for the produced $\mu$ and the charmed meson in our integration. We find that the cross section from heavy quark recombination process decreases very slowly with the increase of the cut on the energy of the produced charmed meson. Thus the recombination processes are not suppressed by the cuts in experiments.

FIG. 2 shows our result of $\delta S_{\text{HR}}^{-}(\xi)$ for $E_{\mu} = 160$ GeV, $Q^2 = 20$ GeV and $\rho_{\text{sm}} = 0.15$. Such $E_{\mu}$ and $Q^2$ are approximate averaged incident energy and $Q^2$ in the NuTeV dimuon experiment, $\rho_{\text{sm}}$ is the nonperturbative parameter for the heavy quark recombination and $\rho_{\text{sm}} = 0.15$ is the LO fitted result from charm photoproduction asymmetry. The branching ratios and $|V_{c\overline{c}}|$ are taken to be the central values from Ref. 27.

From FIG. 2, one sees that $\delta S_{\text{HR}}^{-}(\xi)$ is a valence-like distribution, with its peak in the range of $\xi = 0.1 \sim 0.3$. From Eq. (5), the realistic strange distribution asymmetry is the sum of the analysed result of dimuon experiments and the effective contribution from heavy quark recombination $\delta S_{\text{HR}}^{-}(\xi)$. We can estimate $\delta S_{\text{HR}}^{-}(\xi)$ over $\xi$, and get $\delta S_{\text{HR}}^{-} \approx 0.0023$ for $\rho_{\text{sm}} = 0.15$.

Such a value of $\delta S_{\text{HR}}^{-}$ significantly enhances the measured strangeness asymmetry to a larger positive value, since $S_{\text{real}} = S_{\text{analy}} + \delta S_{\text{HR}}^{-}$. Recent NLO analysis of the NuTeV dimuon data provides positive strangeness asymmetry centered at $0.00196_{-0.0015}^{+0.0023}$. With the correction of the heavy quark recombination, the central value of the realistic strangeness asymmetry could be $S_{\text{real}} \approx 0.0043$. 

Thus, for isoscalar target, the $\delta S_{\text{HR}}^{-}(\xi)$ of Eq. (8) can be expressed as

$$\delta S_{\text{HR}}^{-}(\xi) \approx \frac{\pi v^{2}}{G_{F}^{2}f_{\text{c}}|V_{c\overline{c}}|^{2}B_{\text{c}}^{2}} \int \frac{dz}{u_{\text{c}}(x) + d_{\text{c}}(x)} \times \left[ \frac{d\hat{\sigma}[\overline{c}f(1^3S_01^1f)]_{b_1} + d\hat{\sigma}[\overline{c}f(1^3S_1)1^1f]}{d\xi dy} \right] \cdot \rho_{\text{sm}}.$$  (15)
Such a value of the strangeness asymmetry can explain the NuTeV anomaly to a large extent. NuTeV anomaly arises from the large discrepancy of the NuTeV measurement of the sin $\theta_w$ with the standard model prediction, and becomes a hot debated area in recent years. The NuTeV measurement of the sin $\theta_w$ relies on the hypothesis that strange and anti-strange distributions are symmetric. When this assumption is violated, their result on the NuTeV anomaly to a large extent. NuTeV anomaly.

Our work implies the significance of using heavy quark recombination mechanism [18, 19], i.e., a perturbatively calculable QCD effect, to reveal the strangeness asymmetry. Let us recall that a previous LO analysis [9] of nucleon strangeness asymmetry by NuTeV collaboration reported a negative value $S^{−} = −0.0027 ± 0.0013$, whereas their new NLO analysis [15] gave a positive value centered at 0.00196 as mentioned above. The difference between the two values is 0.0047, which is of the same order as the $S^{−}_{HR}$ estimated in this work. This again supports our work to take higher order effects into account.

In summary, we investigated the influence of heavy quark recombination in (anti-)neutrino induced charged current charm photoproduction processes on the measurement of the nucleon strange distribution asymmetry. Our result shows that the influence could be quite sizable and the realistic strangeness asymmetry $S^{−}$ should be larger than the initially experimental results. From our investigation and the result of recent experimental analysis, the nucleon strange asymmetry $S^{−}$ should be positive and could be large enough to explain the NuTeV anomaly.

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