$\Lambda/\bar{\Lambda}$ Longitudinal Spin Transfer from Asymmetric Nucleon $s/\bar{s}$ Distribution

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We investigate quark to Λ and $\bar{\Lambda}$ longitudinal spin transfers in the light-cone SU(6) quark septetator-diquark model and try to analyze the possible origins for the spin transfer difference between them measured by the COMPASS collaboration. The intermediate heavier hyperon decay processes are considered, while the final hadron transverse momentum is also included. We find that after taking into account the asymmetric nucleon $s/\bar{s}$ distribution effect, the results we get are qualitatively comparable with the difference of the COMPASS experimental data.

Keywords: Hyperons; Baryon production; Fragmentation into hadrons; Polarization in interactions and scattering.

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1. Introduction

The nucleon structures in terms of quarks and gluons have received a lot of attention in recent years. Due to the nonperturbative nature of quantum chromodynamics (QCD), it is almost impossible to calculate the low-energy properties and structures of the nucleon from the QCD Lagrangian directly. Although it is well

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known that hadrons are composite state of quarks and gluons, our knowledge on the detailed hadron structure is still limited. For example, the proton spin crisis¹⁻⁴ why quarks carry only about 30% of the proton spin puzzles the whole society, and how the rest spin can be divided between gluons and orbital angular momentum is still not clear.⁵ Even till now, we have no model-independent relations to measure orbital angular momentum in experiments.^{6,7} Another important problem lies in the strange content of the nucleon. Earlier studies commonly assumed the distributions of strange quark and antiquark are symmetric, but researches from both perturbative and nonperturbative aspects indicate it can be asymmetric.⁸⁻¹³ The contribution of the asymmetric strange quark-antiquark sea can remove the discrepancy between the NuTeV result and other determinations of $\sin^2\theta_W$ in a large extent.¹⁴⁻¹⁶ The study of the final hyperons polarization in semi-inclusive deep inelastic scattering (SIDIS) process can serve as a tool to help us understand the hadron structures.¹⁷⁻²⁰

In this report, we provide a systematic study of the longitudinal spin transfers of Λ and $\bar{\Lambda}$ and try to analyze the possible origins for the spin transfer difference between them measured by the COMPASS experiment at CERN,²¹ which may be related to the quark-antiquark asymmetry in the nucleon sea.²² The content of this report is about our previous studies, and the work has been published in Ref. 24.

2. The $\Lambda/\bar{\Lambda}$ longitudinal spin transfers and asymmetric nucleon $s/\bar{s}$ distribution

In a general lepton-nucleon SIDIS process $\ell p \rightarrow \ell h X$, the longitudinal spin transfer can be effectively expressed as

$$A(x, y, z) = \frac{\frac{S_x}{Q^4} \sum_q e_q^2 f_q^p(x, Q^2) \Delta D_q^h(z, Q^2) + (q \rightarrow \bar{q})}{\frac{S_x}{Q^4} \sum_q e_q^2 f_q^p(x, Q^2) D_q^h(z, Q^2) + (q \rightarrow \bar{q})}, \quad (1)$$

where S and Q^2 are squared energy in the lepton-proton center of mass frame and squared 4-momentum transfer of the virtual photon, f_q^p is the unpolarized parton distribution function of proton, D_q^h and ΔD_q^h are the unpolarized and polarized parton fragmentation functions respectively. After replacing h by $\bar{h}$ and q by $\bar{q}$ in Eq. (1), one can obtain the longitudinal spin transfer for the antihyperon.

To get the longitudinal spin transfer dependence on the Feynman variable x_F , we parameterize x_F as a function of x, y and z variables through a kinematic transformation²⁴

$$x_F = \frac{Syz}{M[M^2 + Sy(1-x)]} \left[\left(M + \frac{Sy}{2M} \right) \times \sqrt{\frac{1 - [4M^2(M_h^2 + P_{h\perp}^2)]}{(Syz)^2}} - \sqrt{\frac{S^2 y^2}{4M^2} + Sxy} \right]. \quad (2)$$

Fig. 1. The results of the x_F on the y and z kinematical variable dependences. The plot region of the x_F variable is 0.05 $\sim$ 0.50.

Figure 1 shows the counter plots of the Feynman variable x_F on the y and z variable dependences under the COMPASS experimental conditions, where S is 320 GeV². As observed from the figure, with the increasing value of the $P_{h\perp}$ and x , the region of the z variable is significantly right shifted at the same x_F numerical value.

Because of the nonperturbative nature of quark fragments process, the fragmentation function appearing in Eq.(2) cannot be calculated through the perturbative QCD. One can only constrain the shape of the fragmentation functions with the help of phenomenological models. Gribov and Lipatov pointed out that quark fragmentation and distribution functions can be related by the phenomenological relation(GL relation)^{25, 26}

$$D_q^h(z) \sim zq_h(z). \quad (3)$$

Though this relation is known to be only valid near $z \rightarrow 1$, it provides a reasonable guidance for us to parameterize the quark fragmentation functions. The quark distribution functions of the octet baryons can be calculated in the light-cone SU(6) quark-diquark model, and their exact forms can be referred to Refs. 27. The quark distribution functions of Σ^* can be referred to Ref. 24.

The unpolarized and polarized fragmentation functions of $D_\Lambda^q(z, Q^2)$ and $\Delta D_\Lambda^q(z, Q^2)$ in Eq. (1) can be expressed as²³

$$\begin{aligned} D_\Lambda^{q(\bar{q})}(z, Q^2) &= a_1 D_{q(\bar{q})}^{\Lambda(\text{direct})}(z, Q^2) + a_2 D_{q(\bar{q})}^{\Sigma^0}(z', Q^2) \\ &+ a_3 D_{q(\bar{q})}^{\Sigma^*}(z', Q^2) + a_4 D_{q(\bar{q})}^{\Xi}(z', Q^2), \end{aligned} \quad (4)$$

and

$$\begin{aligned} \Delta D_\Lambda^q(z, Q^2) &= a_1 \Delta D_q^{\Lambda(\text{direct})}(z, Q^2) + a_2 \Delta D_q^{\Sigma^0}(z', Q^2) \alpha_{\Sigma^0 \Lambda} \\ &+ a_3 \Delta D_q^{\Sigma^*}(z', Q^2) \alpha_{\Sigma^* \Lambda} + a_4 \Delta D_q^{\Xi}(z', Q^2) \alpha_{\Xi \Lambda}, \end{aligned} \quad (5)$$

when the intermediate heavier hyperon decay processes are considered. The values of a 's and α 's can be referred to Ref. 24.

The antiquark distributions were considered using SU(3) flavor symmetry relation between octet baryons. The CTEQ5 parametrization(ctq5l) for proton is used

as an input:²⁸

$$q_v^\Lambda(x) = \frac{q_v^{\Lambda,\text{th}}(x)}{u_v^{p,\text{th}}(x)} * u_v^{\text{ctq}}(x), \Delta q_v^\Lambda(x) = \frac{\Delta q_v^{\Lambda,\text{th}}(x)}{u_v^{p,\text{th}}(x)} * u_v^{\text{ctq}}(x),$$

$$d_s^\Lambda(x) = u_s^\Lambda(x) = \bar{u}^\Lambda(x) = \frac{1}{2}(\bar{u}^{\text{ctq}}(x) + \bar{d}^{\text{ctq}}(x)), s_s^\Lambda(x) = \bar{s}^\Lambda(x) = \bar{d}^{\text{ctq}}(x), \quad (6)$$

where $u_v^{\text{ctq}}(x)$ means the PDF for the valence u quark inside the proton from the CTEQ5L parametrization, $q_v^{\Lambda,\text{th}}(x)$ means the PDF for the valence q quark inside the Λ from the light-cone SU(6) quark-diquark model. Having all the quark distributions of the baryons appearing in Eq. (4) and (5), we can use the GL relation to get the quark fragmentation functions.

As for the inputs of the distribution functions in Eq. (1), the non-strange quark distribution functions of proton are directly from the CTEQ5L parametrization. For the strange quark distribution functions, the fluctuation model can give an asymmetric intrinsic strange sea distribution without the QCD evolution effect. To reflect the QCD evolution effect, a reasonable asymmetric $s/\bar{s}$ distribution input is expressed as

$$s^p(x) = \frac{2s^{\text{th}}(x)}{s^{\text{th}}(x) + \bar{s}^{\text{th}}(x)} s^{\text{ctq}}(x),$$

$$\bar{s}^p(x) = \frac{2\bar{s}^{\text{th}}(x)}{s^{\text{th}}(x) + \bar{s}^{\text{th}}(x)} s^{\text{ctq}}(x), \quad (7)$$

where s^{th} and $\bar{s}^{\text{th}}$ are strange and antistrange quark distribution functions from the baryon-meson fluctuation model.⁸

The numerical results of the longitudinal spin transfers on the x and Feynman variable x_F dependences are presented in Figs. 2–3. All our results are obtained under the COMPASS experimental cuts: $1 \text{ GeV}^2 < Q^2 < 50 \text{ GeV}^2$, $0.005 < x < 0.65$, $0.2 < y < 0.9$ and $0.05 < x_F < 0.5$. Figs. 2(a)–2(c) are obtained by considering the asymmetric strange sea input while the nonzero $P_{h\perp}$ values are taken into account step by step. Figs. 2(d)–2(f) are similar to Figs. 2(a)–2(c) except the input of the proton strange sea is symmetric. As we can see, the asymmetric strange sea input can give a more proper trend to the Λ and $\bar{\Lambda}$ longitudinal spin transfer difference measured by the COMPASS collaboration. And with the increasing of the $P_{h\perp}$ value, the difference get enlarged. At $P_{h\perp}$ value equals 3.0 GeV, our results are qualitatively comparable with the COMPASS experimental data. Figs. 2(d)–2(f) tell us that without the asymmetric strange sea input, the contribution to the spin transfer difference from the nonzero $P_{h\perp}$ value is non-neglected but still too small. The similar situation is observed in Figs. 3(a)–3(f) on the Feynman variable x_F dependence.

Fig. 2. The results of the x -dependent longitudinal spin transfer for the Λ and $\bar{\Lambda}$ hyperons. The data are taken from COMPASS.

Fig. 3. The results of the x_F -dependent longitudinal spin transfer for the Λ and $\bar{\Lambda}$ hyperons. The data are taken from COMPASS.

3. Summary

We investigate quark to Λ and $\bar{\Lambda}$ longitudinal spin transfers in the SU(6) quark-spectator-diquark model. Our calculation includes the intermediate hyperon decay processes and the antiquark fragmentation processes. We find that after taking into account the asymmetric nucleon $s/\bar{s}$ distribution effect and the nonzero final hadron transverse momentum, which can provide a natural constraint to the final hadron z range, our result is qualitatively comparable with the difference of the COMPASS experimental data. From figure 1 we can see that the large z region is more sensitive to the asymmetric strange sea input. So the measurement of the production of the Λ and $\bar{\Lambda}$ in the large z region can give a more precise examination of the existence of the nucleon strange sea asymmetry.

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