Accessing directly the strange quark content of the proton at HERA

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We investigate a double-spin asymmetry for the semi-inclusive Λ hyperon production in the longitudinal deeply inelastic lepton-proton scattering, the sign of which can provide us with useful information about the strange quark helicity distribution in the proton. On the basis of the interpretation of the longitudinal deep inelastic lepton-nucleon scattering data as a negative strange quark polarization in the proton and the preliminary results on the measurement of the longitudinal Λ polarization at the Z resonance in electron-positron annihilation, we predict a minus sign for the suggested observable. The experimental condition required for our suggestion is met by the HERA facilities, so the considered asymmetry can be measured by the HERMES experiments at HERA in the near future.

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Since the announcement of the famous European Muon Collaboration (EMC) experiment results [1], the extensive interest in the physics community has been attracted [2] by the proton spin structure. Besides the EMC data, the ensuing experiments [3] also indicate that the strange quarks and antiquarks in the proton possess a net negative polarization opposite to the proton spin. However, other possible interpretations such as the polarized gluons in the proton [4] have been competing with this allegement. Therefore, it is indeed imperative to invent some machineries to access independently the strange contents of the proton. Recently, Alberg, Ellis, and Kharzeev [5] pointed out that the measurement of target spin depolarization parameter in the $\bar{p}p \to \bar{\Lambda}\Lambda$ may construct a test of the polarization state of the strange quarks in the proton. Later, Ellis, Kharzeev and Kontzinian [6] made predictions, by using their polarized strange quark model, for the polarization of the Λ hyperons semi-inclusively detected in the deeply inelastic scattering of polarized muons on both unpolarized and polarized nucleon targets. At the same time, Lu and Ma [7] found that the sign of the polarization of the Λ particles produced in the current fragmentation region, in the case of unpolarized lepton beam and longitudinally polarized proton target, may supply us with the clear information about the strange quark spin in the proton, provided that one can use as inputs the longitudinal spin-dependent $s \to \Lambda$ fragmentation function measured at CERN LEP-I.

At present, the most promising deeply inelastic scattering experiments are being done at DESY HERA, where both the lepton beam and nucleon target are longitudinally polarized. Therefore, it is desirable to search for some observables experimentally operatable for the HERA experimets to probe the strange quark spin in the proton. The HEAR experiments are performed [8] by keeping the beam polarization unchanged and reversing the target polarization as required. In this Letter, we completely conform to such experimental conditions and investigate the implications of the possible negative strange quark polarization to the semi-inclusively detected Λ particles. Our findings are positive, i.e., there exists a spin asymmetry for the semi-inclusive Λ hyperon production when both the lepton beam and proton target are longitudinally polarized. The sign of this quantity is contingent on that of the strange quark polarization in the proton.

More generally, we consider the semi-inclusive Λ production by the longitudinally deep inelastic lepton-nucleon scattering

$$l(p_l, s_l) + N(p_N, s_N) \to l(p_l') + \Lambda(p_\Lambda, s_\Lambda) + X,$$

where the particle momenta and covariant spin vectors are self-explanatory. As a first approximation, we adopt the one-photon exchange approximation, in which the proton structure is probed by a virtual photon of momentum $q = p_l - p_l'$. Then, the cross section is related to the Lorentz contraction between the leptonic tensor and hadronic tensor.

As usual, the leptonic tensors is taken as

$$L^{\mu\nu}(q, p_l, s_l) = \frac{q^2}{2} g^{\mu\nu} + 2p_l^\mu p_l^\nu - p_l^\mu q^\nu - q^\mu p_l^\nu + 2im_e \varepsilon^{\mu\nu\tau\rho} q_\tau s_{l\rho}, \tag{1}$$

while the hadronic tensor is defined

$$W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda) \equiv \frac{1}{4\pi} \sum_X \int d^4\xi \exp(iq\cdot\xi) \\ \times \langle p_N, s_N | j^\mu(0) | \Lambda(p_\Lambda, s_\Lambda), X\rangle \langle \Lambda(p_\Lambda, s_\Lambda), X | j^\nu(\xi) | p_N, s_N\rangle, \tag{2}$$

where the electromagnetic current is defined as $j_\mu = \sum\limits_a e_a \bar{\psi}_a \gamma_\mu \psi_a$ with a the quark flavor index and e_a the quark charge in unit of the electron charge. We normalize the spin vector as $s \cdot s = -1$ for the pure state of a spin-half fermion. In the forthcoming presentation, the longitudinal spin four-vector s is related to the particle helicity h via

$$\text{limit}_{m\to 0}\ m s^\mu = h p^\mu. \tag{3}$$

We adopt the conventional scalar variables:

$$x_B = \frac{-q^2}{2p_N \cdot q},\ y = \frac{p_N \cdot q}{p_N \cdot p_l},\ z = \frac{p_N \cdot p_\Lambda}{p_N \cdot q}. \tag{4}$$

Correspondingly, the cross section can be written as

$$\frac{d\sigma(s_l, s_N, s_\Lambda)}{dx_B dy dz d^2\mathbf{p}_{\Lambda\perp}} = \frac{\alpha^2 y}{8\pi^2 z Q^4} L_{\mu\nu}(q, p_l, s_l) W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda), \tag{5}$$

where $Q = \sqrt{-q^2}$ and $\mathbf{p}_{\Lambda\perp}$ is the components of the transverse Λ momentum relative to the axis of the quark fragmentation jet.

The hadronic tensor contains all the information about the proton structure and Λ hyperon production. Because of the lack of methods to treat nonperturbative effects, the general strategy so far is to factorize [9] the hadronic tensor into the long- and short-distance parts. The long-distance matrix elements encode the information on the proton structure and the hyperon production by parton hadronization whereas the short-distance coefficients describes the hard partonic interaction. We will work at the leading twist factorization, which is equivalent to the quark-parton model prescription without including any higher-order effects, so the corresponding nonperturbative matrix elements can be interpreted as the quark distribution and fragmentation functions in the quark parton model. For our purpose to elucidate the main physics, it is enough to adopt such a lowest-order approximation.

At the leading order and leading twist, only the lowest-order diagram shown in Fig. 1 makes contributions to the hadronic tensor:

$$\int W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda)\frac{d^3 p_\Lambda}{2E_\Lambda(2\pi)^3} = \frac{1}{4\pi}\int \frac{d^4 p_\Lambda}{(2\pi)^4}(2\pi)\delta(p_\Lambda^2 - M_\Lambda^2) \times \int \frac{d^4 k}{(2\pi)^4}\sum_a e_a^2 \mathrm{Tr}\left[T_N^a(k, p_N, s_N)\gamma_\mu T_\Lambda^a(k+q, p_\Lambda, s_\Lambda)\gamma_\nu\right], \quad (6)$$

where two nonperturbative matrices (in the Dirac space) are defined as

$$T_N^a(k, p_N, s_N)_{\alpha\beta} = \int d^4\xi \exp(ik\cdot\xi)\langle p_N, s_N|\bar{\psi}_\beta^a(0)\psi_\alpha^a(\xi)|p_N, s_N\rangle, \quad (7)$$

$$T_\Lambda^a(k, p_\Lambda, s_\Lambda)_{\alpha\beta} = \sum_X \int d^4\xi \exp(-ik\cdot\xi)\langle 0|\psi_\alpha^a(0)|\Lambda(p_\Lambda, s_\Lambda), X\rangle\langle\Lambda(p_\Lambda, s_\Lambda), X|\bar{\psi}_\beta^a(\xi)|0\rangle. \quad (8)$$

For the lowest-order diagram, its leading twist contributions can be extracted most efficiently by use of the collinear expansion technique [10], i.e., carrying out an expansion of parton momenta with respect to their components collinear with the corresponding hadron momenta. In this work, we restrict ourselves with the Λ production in the current fragmentation region so that the effects of the Λ hyperon mass can be ignored and the transverse Λ momentum can be safely integrated out. Undergoing the standard procedure [11,12] to separate the nonperturbative matrix elements from the hard partonic interaction part, we obtain the following leading twist factorization results:

$$\int W^{\mu\nu}(q,p_N,h_N,p_\Lambda,h_\Lambda)d^2\mathbf{p}_{\Lambda\perp} = \frac{1}{2zp_N\cdot q}\sum_a e_a^2[f_1^a(x_B)\hat{f}_1^a(z)(-p_N\cdot p_\Lambda g^{\mu\nu}+p_N^\mu p_\Lambda^\nu+p_\Lambda^\mu p_N^\nu)$$
$$+ih_N g_1^a(x_B)\hat{f}_1^a(z)\varepsilon^{\mu\nu\lambda\sigma}q_\lambda p_{N\sigma}+ih_\Lambda f_1^a(x_B)\hat{g}_1^a(z)\varepsilon^{\mu\nu\lambda\sigma}q_\lambda p_{\Lambda\sigma}$$
$$+h_N h_\Lambda g_1^a(x_B)\hat{g}_1^a(z)(-p_N\cdot p_\Lambda g^{\mu\nu}+p_N^\mu p_\Lambda^\nu+p_\Lambda^\mu p_N^\nu)]. \qquad (9)$$

where $f_1(x)$ and $g_1(x)$ are the quark momentum distribution and quark helicity distribution in the proton, $\hat{f}_1(x)$ and $\hat{g}_1(x)$ are the spin-independent and longitudinal spin-dependent quark fragmentation functions for inclusive Λ production. (We follow Jaffe and Ji's notation about the quark distribution functions [11] and fragmentation [12] functions.) As a matter of fact, eq. (9) can also be derived from the quark-parton model.

Substituting eqs. (1) and (9) into (5), we deduce the following expression for the cross section:

$$\frac{d\sigma(h_l,h_N,h_\Lambda)}{dx_B dy dz} = \frac{\alpha^2}{16\pi^2 yzQ^2}\sum_q[((y^2-2y+2)f_1^a(x_B)\hat{f}_1^a(z))$$
$$+h_N h_\Lambda(y^2-2y+2)g_1^a(x_B)\hat{g}_1^a(z)+h_l h_N y(2-y)g_1(x_B)+h_l h_\Lambda y(2-y)\hat{g}_1(z)]. \quad (10)$$

For the HERA experimets, both the lepton beam and the target nucleon are in their helicity states. We consider the polarization of the detected Λ hyperons, which is defined as

$$P_\Lambda(h_l,h_N) \equiv \frac{d\sigma(h_l,h_N,+)-d\sigma(h_l,h_N,-)}{d\sigma(h_l,h_N,+)+d\sigma(h_l,h_N,-)}. \qquad (11)$$

From eq. (10), one can obtain

$$P_\Lambda(h_l,h_N) = \frac{\sum_a e_a^2[h_N(y^2-2y+2)g_1^a(x_B)\hat{g}_1^a(z)+h_l y(2-y)\hat{g}_1^a(z)]}{\sum_a e_a^2[(y^2-2y+2)f_1^a(x_B)\hat{f}_1^a(z)+h_l h_N y(2-y)g_1(x_B)]}. \qquad (12)$$

Obviously, the Λ polarization has two sources: spin transfers from the lepton beam and from the nucleon target, respectively.

Keeping in mind the valence quark configuration of the Λ hyperon, we may assume *a priori* that the Λ particle is predominantly produced by the current strange quark fragmentation. Then, the flavor summation can be dropped in the above formula and correspondingly we consider only the contributions associated with the strange quark. As Burkardt and Jaffe [13] have discussed, the measurement of the longitudinal Λ polarization around the Z resonance in electron-positron annihilation can allow the determination of the $s \to \Lambda$ fragmentation functions, both of $f_1^s(z)$ and $\hat{g}_1^s(z)$. Once we obtain such data, we can evolve them to the HERA energy scale by the Altarelli-Parisi equation [15]. Therefore, the measurement of the Λ polarization at HERA, at least in principle, will make possible an independent extraction of the strange quark helicity distribution $g_1(x)$. However, we still feel it is not an easy work because of the experimental complexities.

For our understanding of the strange quark contents in the proton, the sign of the net strange quark polarization may be more important than its precise x-dependence. We observed that by measuring the following double-spin asymmetry

$$A \equiv \frac{d\sigma(+,+,+) - d\sigma(+,+,-) - d\sigma(+,-,+) + d\sigma(+,+,-)}{d\sigma(+,+,+) + d\sigma(+,+,-) + d\sigma(+,-,+) + d\sigma(+,+,-)}, \tag{13}$$

it is possible to determine this important sign. To unravel its physical meaning, we cast A into the form

$$A = D(+,+)P(+,+) - D(+,-)P(+,-), \tag{14}$$

where

$$D(+,+) = \frac{d\sigma(+,+,+) + d\sigma(+,+,-)}{d\sigma(+,+,+) + d\sigma(+,+,-) + d\sigma(+,-,+) + d\sigma(+,+,-)}, \tag{15}$$

$$D(+,-) = \frac{d\sigma(+,-,+) + d\sigma(+,-,-)}{d\sigma(+,+,+) + d\sigma(+,+,-) + d\sigma(+,-,+) + d\sigma(+,+,-)}. \tag{16}$$

So, A can be schematically thought of as being the "asymmetry" of the Λ polarization when the helicity of the target nucleon is reversed. Inserting eq. (10) into (13), we arrive at a very simple formula

$$A = \frac{g_1^s(x_B)\hat{g}_1^s(z)}{f_1^s(x_B)\hat{f}_1^s(z)}, \tag{17}$$

where we again take into account the contributions relevant to the strange quark only.

The preliminary results [14] about the longitudinal Λ polarization at the Z resonance at LEP-I have already been existent, which implies that the longitudinal spin-dependent $s \to \Lambda$ fragmentation function is positive. Although the data are subjected to refinement, one can be confident that there will not be qualitative changes. If the interpretation is accepted of the longitudinal deeply inelastic scattering data as a net negative strange quark polarization in the proton, we can make a prediction that the considered double-spin asymmetry is negative. The experimental condition required for this spin asymmetry happens to be met at HERA, where one fixes the lepton beam polarization but reverse the target polarization as required so as to measure the longitudinal spin-dependent quark distributions.

In conclusion, we worked out a leading twist factorized expression for the hadronic tensor for the semi-inclusive Λ production in the longitudinally deep inelastic scattering of leptons off nucleons. For the case in which both the lepton beam and nucleon target are longitudinally polarized, we proposed an observable A, which is simply related to the strange quark distribution functions in the nucleon and the $s \to \Lambda$ fragmentation functions. Provided that the involved fragmentation functions are precisely measured at LEP in the near future, the measurement of the suggested quantity at HERA will allow the determination of the strange quark helicity distribution in the nucleon. Considering the large statistics needed in such experiments, we point out that even the accurate measurements cannot be done on A, its measured sign can still supply us with very useful information about the strange quark polarization in the proton.

The author thanks Professor P. Söding for useful conservations as well as for supplying a copy of Ref. [8].

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Figure Caption

Figure 1. The lowest-order diagram contributing to the hadronic tensor for the semi-inclusive Λ hyperon production in the deeply inelastic scattering of leptons off nucleons.