Helicity and transversity distributions of the nucleon and Λ hyperon from Λ fragmentation

Bo-Qiang Ma,[1,*] Ivan Schmidt,[2,†] Jacques Soffer,[3,‡] and Jian-Jun Yang[2,4,§]
[1]*Department of Physics, Peking University, Beijing 100871, China;*
CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China;
and Institute of Theoretical Physics, Academia Sinica, Beijing 100080, China
[2]*Departamento de Física, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile*
[3]*Centre de Physique Théorique, CNRS, Luminy Case 907, F-13288 Marseille Cedex 9, France*
[4]*Department of Physics, Nanjing Normal University, Nanjing 210097, China*
(Received 11 January 2001; revised manuscript received 8 March 2001; published 31 May 2001)

It is shown that Λ-hyperon fragmentation in charged lepton deep inelastic scattering on a polarized nucleon target can provide sensitive information concerning the quark helicity and transversity distributions for both the nucleon and Λ hyperon at large x. Numerical predictions are given for the spin transfers of the produced Λ, when the target nucleon is polarized either longitudinally or transversely, and with the nucleon and Λ quark distributions evaluated both in an SU(6) quark-spectator-diquark model and in a perturbative QCD based model. It is also shown that the predicted spin transfers have different behaviors for proton and neutron targets, and this can provide sensitive tests of different predictions for the quark helicity and transversity distributions of the d valence quark of the proton at large x.

DOI: 10.1103/PhysRevD.64.014017 PACS number(s): 14.20.−c, 13.85.Ni, 13.87.Fh, 13.88.+e

Trying to understand the spin content of hadrons is a very challenging research direction of high-energy physics, and so far many unexpected discoveries have been found in contrast with naive theoretical considerations. The quark helicity distributions of the proton $\Delta q(x)$ have been extensively explored in recent years and our knowledge of them has been considerably enriched. However, there are still some uncertainties concerning the flavor decomposition of the quark helicity distributions, especially for the less dominant d valence quark of the proton. For example, there are different theoretical predictions for the ratio $\Delta d(x)/d(x)$ at $x\to 1$: the perturbative QCD (PQCD) based counting rule analysis [1] predicts $\Delta d(x)/d(x)\to 1$, whereas the SU(6) quark-spectator-diquark model [2] predicts $\Delta d(x)/d(x)\to -1/3$. The available experimental data are not yet accurate enough to provide a decisive test of the above two different predictions. On the other hand, our knowledge of the quark transversity distributions $\delta q(x)$ is very poor, since it is difficult to measure such quantities experimentally, although there have been attempts in this direction recently [3]. Among some proposals for measuring the quark transversity distributions, Artru and Mekhfi [4], and later Jaffe [5], have noticed that the Λ-hyperon transverse polarization, in the current fragmentation region of charged lepton deep inelastic scattering (DIS) on the transversely polarized nucleon target, can provide information of the quark transversity distribution of the target. However, such a measurement needs the fragmentation functions of the transversely polarized quark to transversely polarized Λ. In the absence of any theoretical estimate of such a quantity, one possible analysis is to use positivity bounds [6], but here we will make more specific assumptions.

There has been a suggestion [7] for measuring the nucleon strange polarizations by the longitudinal Λ polarization in the current fragmentation region of charged lepton DIS on a longitudinally polarized nucleon target. Such a process, as pointed out by Jaffe [5], should be most suitable for extracting both the quark helicity distributions of the target and the fragmentation functions of the longitudinally polarized quark to longitudinally polarized Λ. Thus it is possible to make a systematic study of the quark helicity and transversity distributions of nucleons, and of the polarized quark to polarized Λ fragmentations, by using the available facilities, such as COMPASS, HERMES, and the Spin Muon Collaboration (SMC), on Λ fragmentation in charged lepton DIS on both longitudinally and transversely polarized nucleon targets. The target nucleon can be chosen to be a proton or a neutron (experimentally through ^{2}H and ^{3}He targets), respectively, and this can provide additional information for a clear distinction of different predictions.

We now look at the quark to Λ fragmentation functions $D_q^{\Lambda}(z)$. Recently there has been progress in understanding the quark to Λ fragmentations [8] by using the Gribov-Lipatov (GL) relation [9]

$$D_q^h(z)\sim z q_h(z) \tag{1}$$

in order to connect the fragmentation functions with the distribution functions. This relation, where $D_q^h(z)$ is the fragmentation function for a quark q splitting into a hadron h with longitudinal momentum fraction z, and $q_h(z)$ is the quark distribution of finding the quark q inside the hadron h carrying a momentum fraction $x=z$, is only known to be valid near $z\to 1$ on an energy scale Q_0^2 in leading-order approximation [10]. However, predictions of Λ polarizations [8] based on quark distributions of the Λ in the SU(6) quark-spectator-diquark model and in the PQCD based counting rule analysis have been found to be supported by all available data from longitudinally polarized Λ fragmentations in

*Email address: mabq@phy.pku.edu.cn
†Email address: ischmidt@fis.utfsm.cl
‡Email address: Jacques.Soffer@cpt.univ-mrs.fr
§Email address: jjyang@fis.utfsm.cl

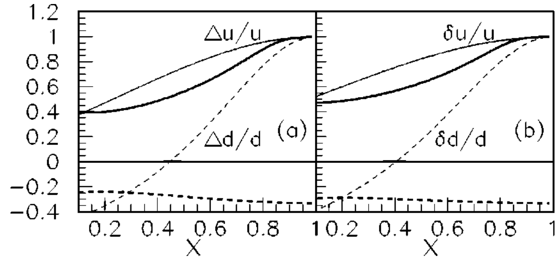

FIG. 1. The predicted ratios (a) $\Delta q(x)/q(x)$ and (b) $\delta q(x)/q(x)$ for proton in the quark-diquark model (thick curves) and the PQCD based model (thin curves). Solid curves are for u valence quarks and dashed curves are for d valence quarks.

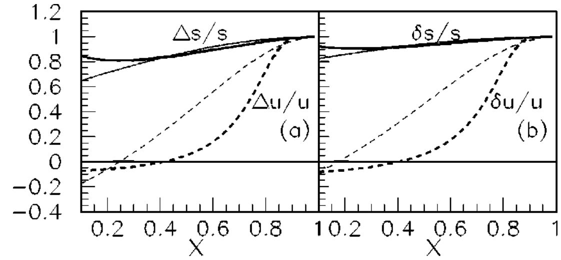

FIG. 2. The predicted ratios (a) $\Delta q(x)/q(x)$ and (b) $\delta q(x)/q(x)$ for Λ in the quark-diquark model (thick curves) and the PQCD based model (thin curves). Solid curves are for s valence quarks and dashed curves are for u and d valence quarks.

e^+e^- annihilation [11–13], polarized charged lepton DIS process [14,15], and most recently, neutrino (antineutrino) DIS process [16]. Thus it is natural to extend the same kind of analysis from longitudinally to transversely polarized cases, and then check the validity of the method by comparing theoretical predictions with experimental data. Such an analysis can also serve as a theoretical guidance to design future experiments.

The SU(6) quark-spectator-diquark model [2,17,18] starts from the three quark SU(6) quark model wave function of the baryon, and if any one of the quarks is probed, one reorganizes the other two quarks in terms of two quark wave functions with spin 0 or 1 (scalar and vector diquarks), i.e., the diquark serves as an effective particle, called the spectator. Some nonperturbative effects such as gluon exchanges between the two spectator quarks or other nonperturbative gluon effects in the hadronic debris can be effectively taken into account by the mass of the diquark spectator. The mass difference between the scalar and vector diquarks has been shown to be important for producing consistency with experimental observations of the ratio $F_2^n(x)/F_2^p(x)=1/4$ at $x\to 1$ found in the early experiments [17,18], and also for the proton and neutron polarized spin-dependent structure functions at large x [2,18]. The light-cone SU(6) quark-spectator-diquark model [2] is an extended version of this framework, taking into account the Melosh-Wigner rotation effects [19,20], in order to build up the quark helicity and transversity distributions of the nucleon. A detailed discussion of quark helicity and transversity distributions in the light-cone SU(6) quark-diquark model can be found in Ref. [21]. It has been also shown recently [22] that the predicted x-dependent transversity distributions are compatible with the available HERMES data for the azimuthal asymmetry [3]. The application of the model for discussing the quark helicity distributions of the Λ can be found in Ref. [8], where it is shown that the u and d quarks inside the Λ should be positively polarized at large x, although their net spin contributions to the Λ polarization might be zero or negative, and such a prediction was found [8] to be in good agreement with the experimental data. The extension of this framework to the quark transversity distributions is straightforward, since one only needs to replace the Melosh-Wigner rotation factor for helicity by that for transversity [20,21]. We found similar qualitative features between the helicity and transversity distributions for each quark flavor, as can be seen from Figs. 1 and 2, where the ratios $\Delta q(x)/q(x)$ and $\delta q(x)/q(x)$ for the valence quarks of both proton (Fig. 1) and Λ (Fig. 2) are presented.

We notice that the d quark in the proton is predicted to have a negative quark helicity distribution at $x\to 1$, and this feature is different from the PQCD counting rule prediction of ''helicity retention,'' which means that the helicity of a valence quark will match that of the parent hadron at large x. Explicitly, the quark helicity distributions of a hadron h have been shown to satisfy the counting rule [23],

$$q_h(x)\sim(1-x)^p, \tag{2}$$

where

$$p=2n-1+2\Delta S_z. \tag{3}$$

Here n is the minimal number of the spectator quarks, and $\Delta S_z=|S_z^q-S_z^h|=0$ or 1 for parallel or antiparallel quark and hadron helicities, respectively [1]. Therefore the antiparallel helicity quark distributions are suppressed by a relative factor $(1-x)^2$, and consequently $\Delta q(x)/q(x)\to 1$ as $x\to 1$. Taking only the leading term, we can write the quark helicity distributions of the valence quarks as

$$q_i^{\uparrow}(x)=\frac{\tilde{A}_{q_i}}{B_3}x^{-1/2}(1-x)^3;$$

$$q_i^{\downarrow}(x)=\frac{\tilde{C}_{q_i}}{B_5}x^{-1/2}(1-x)^5, \tag{4}$$

where $\tilde{A}_q+\tilde{C}_q=N_q$ is the valence quark number for quark q, $B_n=B(1/2,n+1)$ is the β function defined by $B(1-\alpha,n+1)=\int_0^1 x^{-\alpha}(1-x)^n dx$ for $\alpha=1/2$, and $B_3=32/35$ and $B_5=512/693$. The application of the PQCD counting rule analysis to discuss the unpolarized and polarized structure functions of nucleons can be found in Ref. [1], and the extension to the Λ can be found in Ref. [8]. The u and d quarks inside the Λ are also predicted to be positively polarized at large x [8], just as in the quark-diquark model prediction. It is interesting that the predictions based on the PQCD based counting rule analysis are also found [8] to be in agreement with the experimental data, after some adjustment to the parameters with higher-order terms included.

TABLE I. The parameters for quark distributions of the nucleon and Λ in the PQCD based model.

Baryon	q_1	q_2	$\tilde{A}_{q_1}$	$\tilde{C}_{q_1}$	$\tilde{A}_{q_2}$	$\tilde{C}_{q_2}$	$\hat{A}_{q_1}$	$\hat{C}_{q_1}$	$\hat{A}_{q_2}$	$\hat{C}_{q_2}$
p	u	d	1.375	0.625	0.275	0.725	1.52	0.48	0.305	0.695
n	d	u	1.375	0.625	0.275	0.725	1.52	0.48	0.305	0.695
Λ	s	$u(d)$	0.825	0.175	0.4125	0.5875	0.912	0.088	0.457	0.543

The quark transversity distributions are closely related to the quark helicity distributions. A useful inequality has been obtained [24], which constrains the quark transversity distributions by the quark unpolarized and polarized distributions, and there also exists an approximate relation [21] which connects the quark transversity distributions with the quark helicity and spin distributions. Two sum rules [21], connecting the integrated quark transversities with some measured quantities and two model correction factors with limited uncertainties, have been also recently obtained. For example, if we assume the saturation of the inequality [24]

$$2|\delta q(x)|\leqslant q(x)+\Delta q(x), \qquad (5)$$

then we obtain $\delta q=\frac{1}{2}[q(x)+\Delta q(x)]=q^{\uparrow}(x)$, and this suggests that in general we may express $\delta q(x)$ in terms of $q^{\uparrow}(x)$ and $q^{\downarrow}(x)$. All these considerations indicate that it is convenient to parametrize the valence quark transversity distributions in a similar form as the helicity distributions. Therefore we use as a second model

$$\delta q(x)=\frac{\hat{A}_q}{B_3}x^{-1/2}(1-x)^3-\frac{\hat{C}_q}{B_5}x^{-1/2}(1-x)^5, \qquad (6)$$

which clearly satisfies the inequality (5). These quark transversity distributions are constrained by $\delta Q=\int_0^1\delta q(x)\,dx$ from the two sum rules in Ref. [21]. We also take $\hat{A}_q+\hat{C}_q=N_q$ as in the case of the helicity distributions, in order to reduce the number of uncertain parameters. In addition, all quark distributions for the valence quarks of nucleons and the Λ are assumed to be connected between each other by the SU(3) symmetry relation

$$u^p=d^n=\frac{2}{3}u^{\Lambda}+\frac{4}{3}s^{\Lambda};$$

$$d^p=u^n=\frac{4}{3}u^{\Lambda}-\frac{1}{3}s^{\Lambda}. \qquad (7)$$

With the inputs of the quark helicity sum $\Sigma=\Delta U+\Delta D+\Delta S\approx 0.3$, the Bjorken sum rule $\Gamma^p-\Gamma^n=\frac{1}{6}(\Delta U-\Delta D)=\frac{1}{6}g_A/g_V\approx 0.2$, both obtained in charged lepton DIS experiments [21], and taking the two model correction factors both to be equal to 1 for the two sum rules of quark transversities [21], we obtain $\Delta U=0.75$, $\Delta D=-0.45$, $\delta U=1.04$, and $\delta D=-0.39$ for the proton, assuming $\Delta S=0$. Such a scenario should be able to reflect the bulk features of the valence quarks for the octet baryons, although it might be too rough for their sea content. The δU and δD so obtained are compatible with those from a chiral soliton model [25]. We may readjust the values when experimental constraints become available, or if we believe other models are more reasonable [21]. It is encouraging that the obtained transversity distributions for the nucleons have been found to give consistent descriptions [22] of the available HERMES data for the azimuthal asymmetry. The parameters for the nucleons and Λ quark distributions can be found in Table I. The ratios $\Delta q(x)/q(x)$ and $\delta q(x)/q(x)$ for the valence quarks of the proton and the Λ in the PQCD based model are also presented in Figs. 1 and 2, respectively. Notice that the helicity and transversity distributions are close to each other at large x. This comes from the fact that the Wigner-Melosh rotation factors reduce to 1 at the limit $x\to 1$.

For Λ production in the current fragmentation region along the virtual photon direction, the spin transfer to the longitudinal polarized Λ is written as [5,7]

$$A^{\Lambda}(x,z)=\frac{\sum_q e_q^2\Delta q^N(x,Q^2)\Delta D_q^{\Lambda}(z,Q^2)}{\sum_q e_q^2 q^N(x,Q^2)D_q^{\Lambda}(z,Q^2)} \qquad (8)$$

for charged lepton DIS on a longitudinally polarized nucleon N target, and that to the transversely polarized Λ is written as [4,5]

$$\hat{A}^{\Lambda}(x,z)=\frac{\sum_q e_q^2\delta q^N(x,Q^2)\delta D_q^{\Lambda}(z,Q^2)}{\sum_q e_q^2 q^N(x,Q^2)D_q^{\Lambda}(z,Q^2)} \qquad (9)$$

for charged lepton DIS on a transversely polarized nucleon N target. Now we have the quark distributions $q(x)$, $\Delta q(x)$, and $\delta q(x)$ for the valence quarks of nucleons and the Λ in both the SU(6) quark-diquark model and the PQCD inspired analysis. For the quark to Λ fragmentation functions $D_q^{\Lambda}(z)$, $\Delta D_q^{\Lambda}(z)$, and $\delta D_q^{\Lambda}(z)$, we use the Gribov-Lipatov relation Eq. (1), in order to connect them with the corresponding quark distributions of the Λ in the two models. Therefore we have the necessary inputs for a first numerical evaluation of the two spin transfers Eqs. (8) and (9) in the large x and z regions, where the valence quarks are dominant inside the baryons. Extension to the small x region requires the knowledge of quark helicity and transversity distributions of the target in this region, where we may use theoretical estimations or parametrizations from other kinds of experiments as inputs. Similarly, we can also use other experiments or theoretical considerations to constrain the various quark to Λ fragmentation functions, and extend our knowledge from the

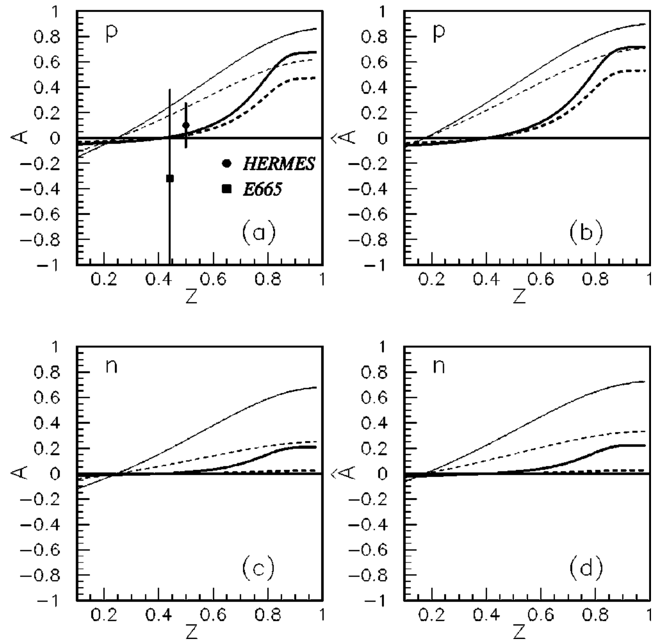

FIG. 3. The x-integrated spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ of Λ production in charged lepton DIS process on the longitudinally and transversely polarized proton and neutron targets, with the integrated x range of $0.6\rightarrow 1$ for the solid curves and $0.3\rightarrow 1$ for the dashed curves. The thick curves correspond to the results with quark distributions and fragmentation functions from the quark-diquark model and the thin curves correspond to these from the PQCD based model. The data are taken from E665 [15] and HERMES [14] Collaborations. Notice that the cuts of the data are slightly different from that of the prediction, but this does not change the qualitative trends.

large z region to the small z region. From the previous successful predictions [8] of longitudinal Λ polarizations, supported by all available data, we expect that our results will have some predictive power even in the small z region. Furthermore, by using the measured spin transfers for both $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$, we can double check our predictions from different models, and get a deeper insight into the spin structure of both nucleons and the Λ.

In the nucleon target, there are only u and d valence quarks, therefore the dominant contribution to the two spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ should come from the u and d quark contributions in the large x and z regions. In the specific case of the proton target, the u quarks are dominant inside the target, its squared charges is 4/9, larger than 1/4 of the d quark, and also the ratios $\Delta u(x)/u(x)$ and $\delta u(x)/u(x)$ are positive values close to 1, which causes the dominance of u quark contributions inside the target. Therefore the main features of the two spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ are mainly determined by the ratios $\Delta D_u^{\Lambda}(z)/D_u^{\Lambda}(z)$ and $\delta D_u^{\Lambda}(z)/D_u^{\Lambda}(z)$, as can be seen from Fig. 3. Thus we can check the predicted $\Delta D_u^{\Lambda}(z)/D_u^{\Lambda}(z)$ and $\delta D_u^{\Lambda}(z)/D_u^{\Lambda}(z)$ by the measured spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ from a proton target.

The two models have qualitatively similar features for the ratios $\Delta u(x)/u(x)$ and $\delta u(x)/u(x)$ for the Λ, and consequently, we have qualitatively similar $\Delta D_q^{\Lambda}(z)/D_q^{\Lambda}(z)$ and $\delta D_q^{\Lambda}(z)/D_q^{\Lambda}(z)$ for the inputs to Eqs. (8) and (9), as can be seen from Fig. 2. In the nonrelativistic model, the helicity and transversity distributions are the same as the quark spin distributions in the quark model. Therefore the difference between the helicity and transversity distributions reflects the quark relativistic motion inside the nucleon. As we mentioned before, the helicity and transversity distributions are close to each other at large x, because the Wigner-Melosh rotation factors reduces to 1 at the limit $x\rightarrow 1$. As a consequence we find not much difference between A and $\hat{A}$. However, at small and medium x when the sea quark contribution cannot be neglected, the different chiral properties between the helicity and transversity distributions will show up, and their difference is ideal in order to study the chiral properties of the nucleon.

Also we have $u\leftrightarrow d$ symmetry for the quark to Λ fragmentation functions. This implies that any big qualitative difference of our predictions between the proton and neutron targets are not mainly produced by the different inputs of various quark to Λ fragmentation functions in the two models, but by the u and d difference in the quark helicity and transversity distributions of the targets. Therefore the different trends between the predictions of the spin transfers for the proton and neutron targets, as can be seen in Fig. 3, come mainly from the difference of the quark helicity and transversity distributions for nucleons in the two models. This can be easily understood because the weights of squared charges are different for u and d quarks, and in the neutron target the less dominant u valence quark has more weight, therefore $\Delta u^n(x)/u^n(x)\rightarrow -1/3$ [which is $\Delta d^p(x)/d^p(x)$ from isospin symmetry] provides a bigger contribution than for the proton target. This indicates that the predicted spin transfers for the neutron target are more suppressed in the quark-diquark model, whereas they are less suppressed in the PQCD based model, as can be confirmed by Fig. 3. Thus we conclude that the spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ measured in both large x and large z regions for the proton and neutron targets can provide a check of the two different predictions of the quark helicity and transversity distributions for the less dominant d valence quark in the proton. They can also be used to test the prediction of positively polarized u and d quarks inside the Λ at large x for both models.

There are available data of the spin transfer to the longitudinal polarized Λ in charged lepton proton DIS scattering by E665 [15] and HERMES [14] Collaborations, respectively, and we can compare the data with our predictions as shown in Fig. 3(a). The precision of the data is still rough and the data are compatible with both model predictions at medium to large z range. High precision experiments are needed in order to make clear distinction between different predictions and we notice that the physics of the Λ polarization is strongly emphasized in the forthcoming COMPASS experiment [26]. We also present the spin transfers integrated over z in Fig. 4, and find that the x dependence is not strong for the proton target, especially for the quark-diquark model in which the x dependence of the ratios $\Delta q(x)/q(x)$ and $\delta q(x)/q(x)$ is not strong. Therefore we can use a wide

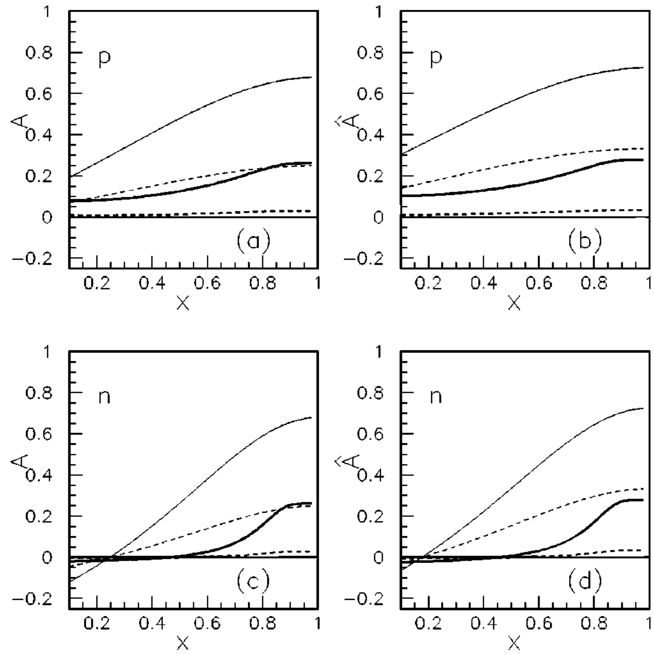

FIG. 4. The z-integrated spin transfers $A^{\Lambda}(x,z)$ and $\hat{A}^{\Lambda}(x,z)$ of Λ production in charged lepton DIS process on the longitudinally and transversely polarized proton and neutron targets, with the integrated z range of $0.6\rightarrow 1$ for the solid curves and $0.3\rightarrow 1$ for the dashed curves. The thick curves correspond to the results with quark distributions and fragmentation functions from the quark-diquark model and the thin curves correspond to these from the PQCD based model.

integrated x range to increase the statistics of the data. We should stress that our predictions should be considered to be valid more qualitatively than quantitatively, especially for the PQCD based model. In this case there is still freedom to include higher-order terms and to adjust the parameters of the PQCD based model from the constraints of the data. Varying x and z in different regions can provide us more information concerning the quark helicity and transversity distributions of the target, as well as the quark to Λ fragmentation functions. We would like to mention that a similar analysis can be also made for the spin transfers of other members of the octet baryons. The analysis and main conclusion for the spin transfers of the octet baryons fragmentation, when the target nucleon is polarized either longitudinally or transversely, should be similar to those found in hadron longitudinal polarizations of the octet baryons in polarized charged lepton DIS processes [8].

In conclusion, we showed in this paper that the Λ-hyperon fragmentation in charged lepton DIS on the polarized nucleon target can provide sensitive information concerning the quark helicity and transversity distributions for both nucleons and the Λ hyperon at large x. We calculated the spin transfers of the produced Λ when the target nucleon is polarized either longitudinally or transversely, with the nucleon and Λ quark distributions evaluated both in the SU(6) quark-spectator-diquark model and in a PQCD based model. We found that the predicted spin transfers have quite different behaviors for the proton and neutron targets in the two models, and this can provide a sensitive test of different predictions for the quark helicity and transversity distributions for the d valence quark of the proton at large x.

This work is partially supported by the National Natural Science Foundation of China under Grant Nos. 10025523, 19975052, and 19875024, by Fondecyt (Chile) under Grant No. 3990048, by the cooperation programs Ecos-Conicyt and CNRS-Conicyt between France and Chile, by Fondecyt (Chile) Grant Nos. 1990806 and 8000017, and by Cátedra (Chile).

[1] S. J. Brodsky, M. Burkardt, and I. Schmidt, Nucl. Phys. **B441**, 197 (1995).
[2] B.-Q. Ma, Phys. Lett. B **375**, 320 (1996).
[3] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **84**, 4047 (2000).
[4] X. Artru and M. Mekhfi, Z. Phys. C **45**, 669 (1990); Nucl. Phys. **A532**, 351c (1991).
[5] R. L. Jaffe, Phys. Rev. D **54**, R6581 (1996).
[6] D. de Florian, J. Soffer, M. Stratmann, and W. Vogelsang, Phys. Lett. B **439**, 176 (1998).
[7] W. Lu and B.-Q. Ma, Phys. Lett. B **357**, 419 (1995).
[8] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. D **61**, 034017 (2000); Phys. Lett. B **477**, 107 (2000); B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Eur. Phys. J. C **16**, 657 (2000); Phys. Lett. B **488**, 254 (2000); Phys. Rev. D **62**, 114009 (2000).
[9] V. N. Gribov and L. N. Lipatov, Phys. Lett. **37B**, 78 (1971); Yad. Fiz. **15**, 1218 (1972) [Sov. J. Nucl. Phys. **15**, 675 (1972)]; S. J. Brodsky and B.-Q. Ma, Phys. Lett. B **392**, 452 (1997).
[10] J. Blümlein, V. Radindran, and W. L. van Neerven, Nucl. Phys. **B589**, 349 (2000); V. Barone, A. Drago, and B.-Q. Ma, Phys. Rev. C **62**, 062201(R) (2000).
[11] ALEPH Collaboration, D. Buskulic *et al.*, Phys. Lett. B **374**, 319 (1996).
[12] DELPHI Collaboration, Report No. DELPHI 95-86 PHYS 521, CERN-PPE-95-172, presented at the EPS-HEP 95 Conference, Brussels, 1995.
[13] OPAL Collaboration, K. Ackerstaff *et al.*, Eur. Phys. J. C **2**, 49 (1998).
[14] HERMES Collaboration, A. Airapetian *et al.*, hep-ex/9911017.
[15] E665 Collaboration, M. R. Adams *et al.*, Eur. Phys. J. C **17**, 263 (2000).
[16] NOMAD Collaboration, Report No. CERN/SPSLC 91-121, SPSC/P261, 1991; C. Lachaud, Thèse de Doctorat Univ. Denis Diderot, Paris, 2000.
[17] R. P Feynman, *Photon Hadron Interactions* (Benjamin, New York, 1972), p. 150.
[18] F. E. Close, Phys. Lett. **43B**, 422 (1973); Nucl. Phys. **B80**, 269 (1974); R. Carlitz, Phys. Lett. **58B**, 345 (1975); J. Kaur, Nucl. Phys. **B128**, 219 (1977); A. Schäfer, Phys. Lett. B **208**, 175 (1988); F. E. Close and A. W. Thomas, *ibid.* **212**, 227 (1988);

N. Isgur, Phys. Rev. D **59**, 034013 (1999).
[19] B.-Q. Ma, J. Phys. G **17**, L53 (1991); B.-Q. Ma and Q.-R. Zhang, Z. Phys. C **58**, 479 (1993).
[20] I. Schmidt and J. Soffer, Phys. Lett. B **407**, 331 (1997).
[21] B.-Q. Ma, I. Schmidt, and J. Soffer, Phys. Lett. B **441**, 461 (1998); B.-Q. Ma and I. Schmidt, J. Phys. G **24**, L71 (1998); Phys. Rev. D **58**, 096008 (1998).
[22] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. D **63**, 037501 (2001).
[23] R. Blankenbecler and S. J. Brodsky, Phys. Rev. D **10**, 2973 (1974); J. F. Gunion, *ibid.* **10**, 242 (1974); S. J. Brodsky and G. P. Lepage, in Proceedings of the 1979 Summer Institute on Particle Physics, SLAC, 1979.
[24] J. Soffer, Phys. Rev. Lett. **74**, 1292 (1995).
[25] H.-C. Kim, M. V. Polyakov, and K. Goeke, Phys. Rev. D **53**, 4715 (1996); Phys. Lett. B **387**, 577 (1996).
[26] COMPASS Collaboration, CERN/SPSLC 96-14, SPSC/P297, 1996.