Anti-hyperon Polarization in $pA$ and $\Sigma^-A$ Collisions and Intrinsic Antidiquark State in Incident Baryon

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Abstract

We discuss the relation between the polarization of inclusively produced (anti-) hyperons and the incident baryon states in the framework of the constituent quark-diquark cascade model. We assume that there is an intrinsic diquark-antidiquark state in the incident baryon, in which the intrinsic diquark immediately fragments into a non-leading baryon and the antidiquark behaves as a valence constituent. It is also assumed that the valence (anti)diquark in the incident nucleon tends to combine selectively with a spin-down sea quark and, on the other hand, the spin-up valence quark in the projectile is chosen by a sea (anti)diquark in preference to the spin-down valence quark. It is found that the incident spin-1/2 baryon is mainly composed of a spin-0 valence diquark and a valence quark, and contains an intrinsic diquark-antidiquark state with a probability of about 7%.

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1 Introduction

It is well known that hyperons produced in unpolarized proton-proton and proton-nucleus \((pA)\) collisions are polarized transversely to the production plane. For example, the \(\Lambda\) is significantly negatively polarized and \(\bar{\Lambda}\) is not polarized\[1, 2, 3, 4, 5, 6\]. The polarizations of \(\Sigma^\pm\) and \(\Xi\) produced inclusively in proton beam in the soft hadronic interaction regions are positive and negative, respectively\[7, 8, 9, 10, 11, 12\]. Anti-hyperons are also polarized. The \(\bar{\Sigma}^-\) is polarized positively and \(\bar{\Xi}^+\) is polarized negatively\[13, 14\]. It is important to discuss the anti-hyperon polarization as well as the hyperon polarization. On the other hand, single-spin asymmetries of \(\pi^\pm\) in \(p^\uparrow p\) and \(\bar{p}^\uparrow p\) collisions have also been observed\[15, 16, 17, 18\]. The single-spin asymmetry is defined as \(A_N = (\sigma^\uparrow - \sigma^\downarrow)/(\sigma^\uparrow + \sigma^\downarrow)\), where \(\sigma^\uparrow (\sigma^\downarrow)\) denotes the cross section of \(\pi^+\) to go left (right) looking downstream in the \(p^\uparrow\) fragmentation region. The direction of transverse motion of the produced hadron depends on the polarization of the incident hadron. In the case of \(p^\uparrow p \rightarrow \pi^+ X\), the produced \(\pi^+\) tends to go left looking downstream, i.e., \(A_N > 0\).

Straightforward perturbative QCD (pQCD) and collinear factorization approaches underestimate the hyperon polarization in unpolarized \(pA\) collisions and single-spin asymmetry\[19, 20, 21\]. The single-spin asymmetry was analyzed by the pQCD with the higher twist terms\[22, 23\] or with the inclusion of spin and transverse-momentum effects in parton distribution\[24, 25, 26\]. The pQCD approach with polarizing fragmentation functions was applied to \(\Lambda\) and \(\bar{\Lambda}\) polarizations at \(p_T > 1\) GeV/c\[27, 28\]. While a number of different approaches have been proposed and applied to the hyperon polarization and the single-spin asymmetry\[29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39\]. However, they do not explain the data on hyperon and anti-hyperon polarizations satisfactorily. In them, C. Boros, L. Zuo-tang and D. Hui pointed out that it is important to consider the correlation between the spin of the fragmenting valence quark and the direction of momentum of the outgoing hadron in analyses both of the hyperon polarization in unpolarized \(pA\) collisions and single-spin asymmetry\[34, 35, 36\]. Therefore, following this argument, in our previous paper\[40\] we have introduced the spin dependence in the quark-diquark cascade model. There we assumed that, when a leading baryon is produced, the valence diquark in the incident nucleon tends to combine with a spin-down sea quark and the spin-up valence quark in the projectile is chosen in preference to the spin-down valence quark by a sea diquark. We successfully analyzed the hyperon polarization, but could not explain the anti-hyperon polarization.

In this paper, we analyze the anti-hyperon polarization in baryon fragmentation regions by introducing the intrinsic diquark-antidiquark state in the incident baryon and by using the quark-diquark cascade model with spin. We investigate the soft hadronic interactions in the regions of \(p_T < 2\) GeV/c. We analyze hyperon and anti-hyperon polarizations in unpolarized \(pA\) and \(\Sigma A\) collisions. We find that the spin-\(\frac{3}{2}\) baryon contains an intrinsic diquark-antidiquark state with a probability of about 7%. In Sec. 2, we describe our model. We assume the existence of the intrinsic antidiquark state in the incident baryon and introduce spin dependence in the model. In Sec. 3, we analyze data on polarized hyperon and anti-hyperon productions. Conclusion and discussion are given.
Figure 1: Breaking up of incident baryon $A$ into two constituents illustrated by bold lines: (a) valence quark and valence diquark, (b) quark and antiquark, (c) intrinsic diquark and intrinsic antidiquark with a non-leading baryon $B$. $B_A^L$ denotes the leading baryon in the fragmentation region of $A$.

in Sec. 4.

2 Model

2.1 Structure of the incident baryon

We treat the incident baryon as to be the superposition of a valence quark-diquark and a valence quark-diquark with an intrinsic diquark-antidiquark state:

$$|B >_{in} = c_0 |(qq)_V q_V > + c_1 |(qq)_V q_V (qq) > .$$

(1)

The probabilities of the intrinsic diquark-antidiquark state in the incident baryon is denoted by $c_2^2 (1 - P_{PM})$. Here $P_{PM}$ denotes the probability for the Pomeron exchange process. It is assumed that the intrinsic diquark immediately combines with the valence quark and converts into a non-leading baryon, and the remaining intrinsic antiquark (antidiquark) behaves as a valence constituent. In order to explain the anti-hyperon polarization, the remaining intrinsic antidiquark is assumed to be in a spin-1 state. Let us consider the hyperon productions in the inclusive reaction $A + B \rightarrow C + X$ in the beam fragmentation region at $p_T < 2\text{GeV}/c$. When a collision occurs, the incident baryon breaks up into two constituents, as shown in Fig.1, (a) breaking into $(qq)_V$ and $q_V$ with probability $(1 - c_2^2)(1 - P_{PM})$, (b) emission of gluons converting into a quark-antiquark pair with probability $P_{PM}$, and (c) emission of a non-leading baryon and breaking into a valence diquark and an intrinsic antidiquark with probability $c_1^2 (1 - P_{PM})$.

2.2 Introduction of spin into the incident baryon and the cascade process

We extended the quark-diquark cascade model\[41\] to include the spin dependence by using SU(6) wave functions for hadrons and the quark-diquark representation for baryons as discussed in Ref.\[42\]. We then applied our model to hyperon polarization in $hA$ collisions.\[40\]
The wave function for the incident $p^\uparrow$ in the state represented by the first term of (1) is written as

$$|p^\uparrow> = \sqrt{2\over 9} \sin \theta (\sqrt{2}|{uu}\rangle_{11}d^+_V - |{uu}\rangle_{10}d^+_V - |{ud}\rangle_{11}u^+_V + |{ud}\rangle_{10}u^+_V + |{ud}\rangle_{00}u^+_V >$$

$$+ \cos \theta |{ud}\rangle_{00}u^+_V >,$$

where the parameter $\theta$ is the mixing angle. The incident spin-up proton ($p^\uparrow$) breaks up into a valence quark and a valence diquark:

$$d^+_V + \{uu\}^V_{11}, d^+_V + \{uu\}^V_{10}, u^+_V + \{ud\}^V_{11}, u^+_V + \{ud\}^V_{10}, u^+_V + |{ud}\rangle_{00},$$

with probabilities $(1 - c^2_1)(1 - P_{PM})$ times $4\over 9 \sin^2 \theta, 2\over 9 \sin^2 \theta, 2\over 9 \sin^2 \theta, 1\over 9 \sin^2 \theta$ and $\cos^2 \theta$, respectively and into a quark and an antiquark:

$$u^\uparrow + \bar{u}^\uparrow, \bar{u}^\uparrow + \bar{u}^\uparrow, d^\uparrow + \bar{d}^\uparrow, d^\uparrow + \bar{d}^\uparrow, s^\uparrow + \bar{s}^\uparrow, s^\uparrow + \bar{s}^\uparrow$$

with probabilities $P_{PM}/2$ times $P_{uu}, P_{u\bar{u}}, P_{dd}, P_{d\bar{d}}, P_{ss}$ and $P_{s\bar{s}}$, respectively. It also breaks up into a valence diquark, an intrinsic antidiquark and a non-leading baryon with probabilities $c^2_1(1 - P_{PM})$ times the corresponding diquark-antidiquark pair creation probabilities. The brackets $[ ]$ and $\{ \}$ for the diquark states denote flavor anti-symmetric and symmetric states, respectively, and subscripts denote the spin states.

Hadrons are produced by the cascade processes as follows;

(i) baryon productions

$$q^\uparrow \rightarrow B^{\frac{1}{2}+}(q[q'q'']) + \{q'q''\}_{00}, B^{\frac{1}{2}+}(q[q'q'']) + \{q'q''\}_{11},$$

$$B^{\frac{3}{2}+}(q[q'q'']) + \{q'q''\}_{1-1}, B^{\frac{3}{2}+}(q[q'q'']) + \{q'q''\}_{10},$$

$$B^{\frac{5}{2}+}(q[q'q'']) + \{q'q''\}_{11},$$

$$[q'q'']_{00} \rightarrow B^\uparrow(q[q'q'']) + \bar{q}^\uparrow, B^\uparrow(q[q'q'']) + \bar{q}^\uparrow,$$

$$\{q'q''\}_{11} \rightarrow B^{\frac{3}{2}+}(q[q'q'']) + \bar{q}^\uparrow, B^{\frac{3}{2}+}(q[q'q'']) + \bar{q}^\uparrow,$$

$$\ldots, (3)$$

(ii) meson productions

$$q^\uparrow \rightarrow M_{00}(q\bar{q}) + q^\uparrow, M_{10}(q\bar{q}) + q^\uparrow, M_{11}(q\bar{q}) + q^\uparrow,$$

$$M_{20}(q\bar{q}) + q^\uparrow, M_{21}(q\bar{q}) + q^\uparrow, (5)$$

$$[q'q'']_{00} \rightarrow M_{00}(q\bar{q}) + [q'q'']_{00}, M_{10}(q\bar{q}) + [q'q'']_{10},$$

$$M_{11}(q\bar{q}) + [q'q'']_{1-1},$$

$$\{q'q''\}_{11} \rightarrow M_{11}(q\bar{q}) + [q'q'']_{00}, M_{11}(q\bar{q}) + [q'q'']_{10},$$

$$M_{10}(q\bar{q}) + [q'q'']_{11}, M_{21}(q\bar{q}) + [q'q'']_{10},$$

$$\ldots, (6)$$
where $q$ denotes $u,d$ and $s$ and $[q'q'']$ does $[ud],[us]$ and $[ds]$ and so on. $\epsilon$ and $1-\eta$ denote probabilities of baryon production from a quark and a diquark, respectively. We consider only $j=3/2$ decuplet and $j=1/2$ octet baryons as produced baryons.

From the isospin invariance, the $q\bar{q}$ pair creation probabilities are $P_{u\bar{u}} = P_{d\bar{d}}$ and $P_{s\bar{s}} = 1-2P_{u\bar{u}}$. The probabilities of $[qq']$$[qq]^3$, $[qq']$$[qq'^3]$ and $[qq']$$[qq]$ pair creations from a quark are chosen as $\epsilon P_{qq}P_{qq'}$, $\epsilon P_{qq}P_{qq'^3}$ and $\epsilon P_{qq'^3}$, respectively. For example, baryons are produced from $[ud]_{00}$ and $\{uu\}_{11}$ as follows:

$$[ud]_{00} \rightarrow p^\dagger + \bar{u}^\dagger, p^\dagger + \bar{u}^\dagger, n^\dagger + \bar{d}^\dagger, n^\dagger + \bar{d}^\dagger, \Lambda^\dagger + \bar{s}^\dagger, \Lambda^\dagger + \bar{s}^\dagger,$$

with probabilities

$$N_1P_{u\bar{u}}/2, N_1P_{u\bar{u}}/2, N_1P_{d\bar{d}}/2, N_1P_{d\bar{d}}/2, N_1P_{s\bar{s}}/3, N_1P_{s\bar{s}}/3,$$

respectively, where $N_1 = (1-\eta)/(P_{u\bar{u}} + P_{d\bar{d}} + 2P_{s\bar{s}})$, and

$$\{uu\}_{11} \rightarrow p^\dagger + \bar{d}^\dagger, \Sigma^{\dagger} + \bar{s}^\dagger, \Delta_{u}^{\dagger} + \bar{u}^\dagger, \Delta_{u}^{\dagger} + \bar{u}^\dagger, \Delta_{s}^{\dagger} + \bar{d}^\dagger, \Sigma_{s}^{\dagger} + \bar{s}^\dagger, \Sigma_{s}^{\dagger} + \bar{s}^\dagger,$$

with probabilities

$$2N_2P_{d\bar{d}}/9, 2N_2P_{s\bar{s}}/9, N_2P_{u\bar{u}}, N_2P_{u\bar{u}}/3,$$

$$N_2P_{d\bar{d}}/3, N_2P_{d\bar{d}}/9, N_2P_{s\bar{s}}/3, N_2P_{s\bar{s}}/9,$$

respectively, where $N_2 = (1-\eta)/(4P_{u\bar{u}} + 2P_{d\bar{d}} + 2P_{s\bar{s}})$. Similarly, from $s^\dagger$, we have

$$s^\dagger \rightarrow \Lambda^\dagger + [ud]_{00}, \Sigma^{\dagger} + \{uu\}_{10}, \Sigma^{\dagger} + \{uu\}_{11},$$

$$\cdots,$$

$$\Xi^s_{u} + \{ds\}_{1-1}, \Xi^s_{u} + \{ds\}_{10}, \Xi^s_{u} + \{ds\}_{11},$$

$$\Omega^s_{d} + \{ss\}_{1-1}, \Omega^s_{d} + \{ss\}_{10}, \Omega^s_{d} + \{ss\}_{11},$$

with probabilities

$$\frac{1}{3}N_3P_{u\bar{u}}P_{d\bar{d}}, \frac{1}{9}N_3P_{u\bar{u}}^2, \frac{2}{9}N_3P_{u\bar{u}}^2,$$

$$\cdots,$$

$$\frac{2}{3}N_3P_{d\bar{d}}P_{s\bar{s}}, \frac{4}{9}N_3P_{d\bar{d}}P_{s\bar{s}}, \frac{2}{9}N_3P_{d\bar{d}}P_{s\bar{s}},$$

$$N_3P_{s\bar{s}}^2, \frac{2}{3}N_3P_{s\bar{s}}^2, \frac{1}{3}N_3P_{s\bar{s}}^2,$$

respectively. Here, $N_3 = \epsilon/(5(P_{u\bar{u}}^2 + P_{d\bar{d}}^2) + 4P_{u\bar{u}}P_{d\bar{d}} + 2(P_{u\bar{u}} + P_{d\bar{d}} + P_{s\bar{s}})P_{s\bar{s}})$. 

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In the final step of the cascade process, we assume that the constituents recombine into hadrons by the following processes:

\[ q^\uparrow + q'^\uparrow \rightarrow M_{11}(qq'), M_{21}(qq''), \]
\[ q^\uparrow + [q'q'']_00 \rightarrow B^\dagger(q[q'q'']_00), \]
\[ q^\uparrow + \{q'q''\}_{10} \rightarrow B^\dagger(q\{q'q''\}_{10}), B_{3\frac{1}{2}}(q\{q'q''\}_{10}), \]
\[ \{qq'\}_{10} + [\bar{q}q'q''']_{00} \rightarrow B^\dagger(q''\{q'q''\}) + \bar{B}^\dagger(\bar{q}''[\bar{q}q'q''']) \] (13)

and so on. For example, the constituents \( d^\uparrow \) and \( \{us\}_{11} \) recombine as

\[ d^\uparrow + \{us\}_{11} \rightarrow \Sigma_{\frac{1}{2}+}, \Sigma_{\frac{1}{2}+}, \Lambda_{\frac{1}{2}+} \] (14)

with probabilities \( \frac{1}{2}, \frac{1}{8} \) and \( \frac{3}{8} \), respectively. The momenta of the recombined hadrons are the sum of those of the final constituents. In order to put the recombined hadrons on the mass shell, we multiply the momenta of all produced hadrons by a common factor so that the summation of energies of the produced hadrons is equal to the center of mass energy \( \sqrt{s} \). Resonances directly produced by the above processes (3)-(6) and (13) decay into stable particles. Here, we note that we use SU(6) wave functions for calculating baryon production ratios, i.e., \( \cos^2 \theta = \frac{1}{2} \).

The normalized distribution functions of the constituents in the incident baryon, which are composed of \( q_V \) and \( (q'q'')^V \), are expressed in terms of the light-like fraction \( z \) as

\[ n_{qV/B}(z) = n_{(q'q'')^V/B}(1 - z) = \frac{z^{\beta_{qV} - 1}(1 - z)^{\beta_{(q'q'')^V} - 1}}{B(\beta_{qV}, \beta_{(q'q'')^V})}. \] (15)

The dynamical parameters \( \beta \)'s are related to the intercepts of the Regge trajectories as \( \beta_u = \beta_d = 1 - \alpha_{\rho - \omega}(0) \approx 0.5 \) and \( \beta_s = 1 - \alpha_{\phi}(0) \approx 1.0 \). We put \( \beta_{(q'q'')^V} = 1.5(\beta_q' + \beta_{q''}) \) and \( \beta_{(q'q'')^V} = 2.0(\beta_q' + \beta_{q''}) \) for anti-symmetric and symmetric valence diquarks, respectively. Similarly, the momentum sharing function of \( j \) for the cascade process \( i \rightarrow H(ij) + j \) is assumed as

\[ F_{ij}(z) = \frac{z^{\gamma \beta_j - 1}(1 - z)^{\beta_j + \beta_j - 1}}{B(\gamma \beta_i, \beta_i + \beta_j)}, \] (16)

where \( \gamma \) is chosen to be 1.75. The factors 1.5, 2.0 and 1.75 are extracted from the analysis of hadron spectra in \( p \) fragmentation region. The transverse momentum distribution of the hadron \( H \) in the cascade processes is given by the distribution function

\[ G(p_T^2) = \frac{\sqrt{m_H}}{\alpha \sqrt{p_T^2}} \exp(-\frac{\alpha}{\sqrt{m_H}}p_T^2) \] (17)

in \( p_T^2 \) space where \( m_H \) denotes the mass of \( H \). The parameter \( \alpha \) is fixed to \( \alpha = 1.8 \text{ GeV}^{-\frac{3}{2}} \) by using experimental data on \( p_T^2 \) distributions of pions in \( \pi p \) collisions. Details of energy-momentum distributions and sharing used in our model have been provided in Refs. [41, 45].
2.3 Quantization direction and spin asymmetry constraint

The quantization direction for the polarization of an observed particle $C$ is defined as the direction $\mathbf{n} = \mathbf{p}_{\text{inc}} \times \mathbf{p}_{\text{out}} / |\mathbf{p}_{\text{inc}} \times \mathbf{p}_{\text{out}}|$, where $\mathbf{p}_{\text{inc}}$ and $\mathbf{p}_{\text{out}}$ are the momenta of the projectile $A$ ($B$) and the produced hadron $C$ in $A$ ($B$) fragmentation region, respectively. The collision axis is chosen to be parallel to the $z$-axis and the azimuthal angle of $\mathbf{n}$ is denoted by $\varphi$. We use the sign convention in which a positive polarization is in the same direction as $\mathbf{n}$.

The baryon (anti-baryon) composed of a diquark (antidiquark), which is converted from the valence diquark (antidiquark) only through the cascade processes (6), is also treated as a leading baryon (anti-baryon). We assume that the quantization direction for the reaction is the normal of the production plane of one of the leading hadrons with non zero transverse momentum from $A$ and $B$. The leading hadron on the most massive cascade chain is selected to determine the spin quantization axis. When two leading hadrons are produced in the most massive cascade chain, the one with the larger energy is selected. The quantization direction of the selected hadron is chosen as the normal of the production plane of the selected leading hadron for the reaction is the normal of the production plane of $A$ ($B$) for the selected leading hadron in the fragmentation region, respectively.

The spin states of the produced hadrons with respect to the direction $\mathbf{n}_L$ determined from the occurrence probabilities of the processes (3)-(6) and (13). The observed polarization is the difference between the cross section of the baryon (anti-baryon) with an upward spin and that of the baryon with a downward spin with respect to the direction of its production plane. In our calculation, we first determine spin states with respect to $\mathbf{n}_L$ and then flip the spin of $C$ according to the difference between azimuthal angles $|\Delta \varphi| = |\varphi - \varphi_L|$, in order to obtain the spin state with respect to the direction $\mathbf{n}$.

The hyperon polarization in an unpolarized $pA$ collision is related to the single-spin asymmetry because of the correlation between the spin of the fragmenting valence quark and the direction of the momentum of the outgoing hadron. The positive value of the single-spin asymmetry of $\pi^+$ in $p^+p$ collisions implies that the valence quark tends to go left and the valence diquark ($udV$) tends to go right looking downstream, as shown in Fig.2(a), provided the transverse momentum is conserved during the breaking up of the projectile $p^+$. When the valence quark $u^+_V$ quark and a sea diquark ($qq'$) produce a leading baryon $B_L(u^+_V(qq'))$ in the direction of $u^+_V$, the valence quark tends to be in the spin-up state with respect to the direction $\hat{\mathbf{n}}_L = \mathbf{p}_{\text{inc}} \times \mathbf{p}_L / |\mathbf{p}_{\text{inc}} \times \mathbf{p}_L|$, i.e., the direction of the normal of the production plane of $B_L(u^+_V(qq'))$, as shown in Fig.2(a). Then, we assume that the spin-up valence quark in the incident hadron is chosen in preference to the spin-down valence quark by a sea diquark to form a leading baryon, with respect to the direction $\hat{\mathbf{n}}_L$. When we consider the exclusive process $p^+ \to \pi^+ + n^+$ and neglect the angular momentum effect, $\pi^+$ tends to go left and $n^+$ tends to go right looking downstream, as shown in Fig.2(b). According to this picture, we assume that the valence diquark in the incident proton tends to pick up a spin-down sea quark to form a leading baryon with
respect to the direction $\hat{n}_L$.

The probabilities of symmetric and anti-symmetric valence diquarks picking up a sea $s^\uparrow$ quark forming a leading baryon are given by $P_{\{1\}V} = (1 + C_\{1\}^s)/2$ and $P_{[1]\{1\}V} = (1 - C_\{1\}^s)/2$, respectively. The probabilities of symmetric and anti-symmetric valence diquarks picking up $u^\uparrow$ or $d^\uparrow$ are given by $P_{\{1\}V} = (1 + C_\{1\}^q)/2$ and $P_{[1]\{1\}V} = (1 - C_\{1\}^q)/2$, respectively. Hereafter, $q$ denotes $u$ or $d$ quark. For the cases of the valence diquarks $[ud]_{00}$ in (7) and $\{uu\}_{11}$ in (9) forming a leading baryon with a sea quark, the probabilities (8) and (10) are changed to

$$\frac{N_1}{2}P_{u\bar{u}}(1 + C_\{1\}^q), \frac{N_1}{2}P_{u\bar{u}}(1 - C_\{1\}^q), \frac{N_1}{2}P_{d\bar{d}}(1 + C_\{1\}^s), \frac{N_1}{2}P_{d\bar{d}}(1 - C_\{1\}^s),$$

and

$$\frac{2}{9}N_2'P_{u\bar{u}}(1 + C_\{1\}^q), \frac{2}{9}N_2'P_{u\bar{u}}(1 - C_\{1\}^q),$$
$$N_2'P_{u\bar{u}}(1 + 8C_\{1\}^q), \frac{1}{3}N_2'P_{u\bar{u}}(1 - C_\{1\}^q), \frac{1}{3}N_2'P_{d\bar{d}}(1 + C_\{1\}^s),$$
$$\frac{1}{9}N_2'P_{d\bar{d}}(1 - C_\{1\}^s), \frac{1}{3}N_2'P_{s\bar{s}}(1 + C_\{1\}^s), \frac{1}{9}N_2'P_{s\bar{s}}(1 - C_\{1\}^s),$$

respectively.

When the selected leading baryon is produced from the valence quark in the incident baryon and a sea diquark $(ij)$, the probabilities of the spin state of the valence quark being up and down are given by $P_{qV}^{(ij)} = (1 + C_{q\{ij\}})/2$ and $(1 - C_{q\{ij\}})/2$ for valence $u$ and $d$ quarks, and $P_{sV}^{(ij)} = (1 + C_{s\{ij\}})/2$ and $(1 - C_{s\{ij\}})/2$ for a valence $s$ quark, respectively. That is, the probabilities of the spin-up valence quark $q$ (s) going left and right are $P_{qV}^{(ij)} = (1 + C_{q\{ij\}})/2$ and $(1 - C_{q\{ij\}})/2$ ($P_{sV}^{(ij)} = (1 + C_{s\{ij\}})/2$ and $1 - P_{sV}^{(ij)}$), respectively. For simplicity, we assume the relations between $P_{qV}^{(ij)}$ and $P_{qV}^{(ij)\uparrow}$ and between $P_{sV}^{(ij)}$ and

Figure 2: Production planes of leading particles in the fragmentation region of $p^\uparrow$; (a) Production of the leading baryon $B_L(u_\uparrow V(q\bar{q}'))$ from the valence quark $u_\uparrow V$. The exclusive process $p^\uparrow p \rightarrow \pi^+ n^\uparrow p$. The valence diquark $[ud]_{00}$ picks up a spin-down sea quark $d_s$ with respect to the direction $\hat{n}_L$. 
Figure 3: The $x$ dependence of the hyperon polarizations in $pBe$ collisions at (a) 400 GeV/c and (b) 800 GeV/c for $0.96 \text{ GeV}/c < p_T$. Data are taken from Refs.4,7,8 and Refs.5,9.

$P_{V}^{\uparrow \downarrow (ij)}$ to be as follows:

$$ P_{q_{V}}^{(ij)} = 1 - P_{(ij)V}^{q_{V} \uparrow}, \quad P_{s_{V}}^{(ij)} = 1 - P_{(ij)V}^{s_{V} \uparrow}. \quad (20) $$

2.4 Hadron-nucleus collision

For a $hA$ collision, we assume that the projectile hadron successively interacts with nucleons inside the nucleus $A$. At each collision, the projectile hadron $h$ loses its momentum and the rate of the momentum loss of $h$ is set to be $P(z) = 0.25z^{0.25-1}$ from the data on the $A$-dependence of the spectra of $h$. The probability of the incident hadron colliding with $\nu$ nucleons, $P_{hA}(\nu)$, is calculated by using a Glauber-type multiple collision model.\[46\] The number $\nu$ is determined from the distribution of nucleons in the nucleus and the cross section of the incident hadron with a nucleon $\sigma_{hN}$. The nucleon number density of a nucleus with a mass number $A$ is assumed to be given by $\rho(r) = \rho_0/(1+\exp((r-r_A)/d))$, where $\rho_0$ is the normalization factor. We choose $r_A = 1.19A^{\frac{1}{3}} - 1.61A^{-\frac{1}{3}}\text{fm}$ and $d = 0.54\text{fm}$ as used in Ref.\[17\].

3 Comparison with the data

3.1 Setting of parameters in pBe collision

In the present analysis, we assume that there is an intrinsic diquark-antidiquark state in the incident baryon with probability $c_1^2$. The intrinsic diquark recombines with the valence quark and becomes a non-leading baryon, but instead the intrinsic antidiquark behaves as
a valence constituent. The intrinsic antidiquark is assumed to be in the spin-1 state. The probability of the (anti)diquark produced through (6) being in the spin-1 state is denoted by $P_{1D}$. Here, we assumed that the intrinsic valence antidiquark has a property identical to that of the valence diquark, i.e., it tends to combine with the spin-down sea antiquark. We consider only $u, d$, and $s$ flavors, and the probability of $s \bar{s}$ pair creation is chosen to be $P_{s \bar{s}} = 0.12$. For other parameters irrelevant to polarization, we use the values of those determined in the previous analyses: $P_{PM} = 0.15, \epsilon = 0.07$ and $\eta = 0.25$.\[11\]

From the data on hyperon polarizations in $pBe$ collisions at $p_L = 400$ GeV/c, we set the parameters as follows: Since $\Lambda$ has a common diquark $[ud]_0$ with the incident proton, the spin dependent parameter $C^s_{[ud]}$ in (18) is fixed from the data on $\Lambda$ polarization in $pBe$ collisions. Since the major part of $\Sigma^+$ production comes from the valence $\{uu\}_{11}$ diquark, the negative value of $C^s_{\{uu\}}$ leads to the positive polarization of $\Sigma^+$ in $pBe$ collisions. To explain the $\Sigma^+$ polarization, we have to choose a small value of $C^s_{\{uu\}}$. We set the asymmetry parameters as

$$\begin{align*}
C^s_{[ud]} &= C^q_{[ud]} = C^s_{[qs]} = -0.4, \\
C^q_{[qs]} &= -1.0, \\
C^s_{\{qq\}} &= C^q_{\{qq\}} = C^s_{\{qs\}} = C^q_{\{ss\}} = C^s_{\{ss\}} = -1.0, \\
C^q_{\{qs\}} &= -0.2, \end{align*}$$

where $q$ denotes $u$ and $d$ quarks. In order to explain the positive $\Sigma^-$ polarization in $pBe$ collisions, we have to choose a large value of $P^1_D$ and assume that the valence diquark in the incident octet baryon is mainly in the spin-0 state:

$$P^1_D = 0.95, \quad \cos^2 \theta = 0.9. \quad (23)$$

The main production of leading $\Sigma^-$, $\Xi^0$ and $\Xi^-$ comes from the converted spin-1 diquark and the polarizations of directly produced $\Sigma^-$, $\Xi^0$ and $\Xi^-$ are positive. Since the branching ratio of $\Sigma^* \rightarrow \Sigma \pi$ is 12%, the effect of $\Sigma^*$ decay on $\Sigma^-$ polarization is small. On the other hand, $\Xi^0$ and $\Xi^-$ polarizations are affected by the 100% decay of $\Xi^* \rightarrow \Xi \pi$, leading to negative $\Xi^0$ and $\Xi^-$ polarizations. Here we note that the converted diquark through (6) from a valence diquark behaves like a valence diquark and produce a leading baryon. From the data on $\Sigma^-$ polarization, we set the parameter for the probability of the intrinsic diquark-antidiquark state in the incident baryon as

$$c^2_{1} = 0.07. \quad (24)$$

The $x$ dependence of the $\Lambda$ and $\Sigma^\pm$ polarizations at $p_L = 400\,[4,7,8]$ and $800\,[5,9]$ GeV/c in $pBe$ collisions is shown in Fig[3]. The $p_T$ dependence of the $\Sigma^-$ polarization at $p_L = 800$ GeV/c in $pCu$ collisions is shown in Fig[11]. If $c^2_1 = 0$, the $\Sigma^-$ polarization is zero. Thus, the second term in (1) plays an important role on the polarization of the anti-hyperon in our model.
Figure 4: The $p_T$ dependence of the $\bar{\Sigma}^-$ polarization in $pBe$ collisions at $p_L = 800$ GeV/c for $0.47 < x < 0.53$. Data are taken from Ref.13.

Figure 5: The $x$ dependence of $\Xi$ polarizations in $pBe$ collisions at (a) 400 GeV/c and (b) 800 GeV/c. Data are taken from Refs.10,11 and Ref.12.

Figure 6: The $p_T$ dependence of anti-hyperon polarizations in $pBe$ collisions at $p_L = 400$ and 800 GeV/c. Data on $\bar{\Lambda}$ and $\bar{\Xi}^+$ are taken from Ref.6 and Ref.14.
Figure 7: The $x$ dependence of $\Lambda$ and $\Xi^-$ polarizations in $\Sigma^- C$ and $\Sigma^- Cu$ collisions at $p_L = 340$ and 610 GeV/c in the regions (a) $0 < p_T < 0.2$, (b) $0.2 < p_T < 0.4$, (c) $0.4 < p_T < 0.6$, (d) $0.6 < p_T < 0.8$, (e) $0.8 < p_T < 1.0$ and (f) $1.0 < p_T < 1.2$ GeV/c. Data are taken from Refs.48,49,50.
3.2 Model predictions on other processes

In this subsection, we present the results of our model for polarizations of other hyperons in unpolarized $pA$ and $\Sigma^-A$ collisions. In Fig.5, the $x$ dependence of $\Xi$ polarization in $pBe$ collisions is compared with the data at $p_L = 400[10,11]$ and $800[12]$ GeV/c. In Fig.6, the results of the polarizations of $\Lambda$ and $\bar{\Xi}^+$ in $pBe$ collisions are compared with experimental data at $p_L = 400[6]$ and $800[14]$ GeV/c, respectively. By choosing the weight of the intrinsic antidiquark to be $c_2^2 = 0.07$, we obtain good agreement with experimental data.

Fig.7 shows the $x$ dependence of $\Lambda$ and $\Xi^-$ polarizations in $\Sigma^-C$ and $\Sigma^-Cu$ collisions at $p_L = 340[18,49]$ and $610$ GeV/c[50]. Since the incident $\Sigma^-$ is mainly made out of $[ds]_0^V$ and $d_V$, the negative value of $C_{[qs]}^0$ in (22) leads to negative $\Lambda, \Sigma^0$ and $\Xi^-$ polarizations. The leading decuplet baryon production is much suppressed and the resonance effect of decuplet baryon on hyperon polarization is small. However, the leading $\Sigma^0$ production is three times larger than the leading $\Lambda$ production in $\Sigma^-$ projectile from SU(6) wave function. Taking into account the 100 % branching ratio for $\Sigma^0 \rightarrow \Lambda \gamma$ and the spin conservation, one expects positive $\Lambda$ polarization in the $\Sigma^-Cu$ collision. In the proton projectile, there is no leading $\Sigma^0$ production and the $\Lambda$ polarization remains negative. The calculated results for $\Xi^-$ polarization at large $p_T$ show negative values, in agreement with the experimental data[49].

The $p_T$ dependence of $\Sigma^+$ polarization in $\Sigma^-C$ and $\Sigma^-Cu$ collisions at $p_L = 330$ GeV/c is shown in Fig.8(a)[51]. Although the main part of the converted diquark through (6) is in the spin-1 state, the presence of spin-0 diquarks $[us]$ is inferred from the negative $\Sigma^+$ polarization. In Fig.8(b), the results for anti-hyperons in $\Sigma^-C$ and $\Sigma^-Cu$ collisions at $p_L = 330$ GeV/c are shown[51]. The polarization of $\bar{\Lambda}$ is small, similar to the case of the $pBe$ collision.
3.3 Results from analysis

We show the $x$ distribution functions $n(x)$ of constituents in the incident baryons ($p$ and $\Sigma^{-}$) in Fig.9 as results from this analysis. For comparison, we show the CTEQ3 input parton distribution functions at $Q_0 = 1.6\text{GeV}$ of a global QCD analysis for various hard scattering processes\[52\]. In our model, it is assumed that incident baryons are mainly made out of valence spin-0 diquark and valence quark. Consequently, the magnitude of valence quarks are small as compared with those of CTEQ3 distributions. Since main part of sea (anti-)quarks are produced in the cascade processes (3)-(6), the magnitude of sea (ant-)quarks in the incident baryons are much suppressed as shown in Fig.9(b). The $x$-shape behavior of CTEQ3 distribution functions of valence and sea quarks in hard interaction are different from our results in soft interaction.

4 Conclusion and discussion

In our model, it is assumed that (i) the quantization axis is characterized by the leading baryon of the most massive cascade chain, (ii) the incident valence diquark tends to pick up a spin-down sea quark (or conversely the spin-up incident valence quark tends to turn
to the left and combines with a sea diquark to form a leading baryon), and (iii) the incident baryon contains an intrinsic antidiquark that produces a leading anti-baryon. Our model with the parameters in subsection 3.1 explains the hyperon and anti-hyperon polarizations both in $pA$ and $\Sigma^- A$ collisions well. From our analysis, we expect that the incident spin-1/2 baryon is mainly composed of a spin-0 valence diquark and a valence quark, but contains about 10% of spin-1 valence diquarks. Further, it appears that there is an intrinsic antidiquark with a probability of about 7%.

The complex hyperon polarizations may be explained by considering the leading particle effects of valence constituents and by taking into account the contributions of the decay products from resonances. Polarizations of hyperons having a common diquark with the projectile, such as $\Sigma^+, \Sigma^0$ and $\Lambda$, in unpolarized $pA$ collisions hardly depend on the center-of-mass energy $\sqrt{s}$, and those of hyperons having only one common quark with the projectile, such as $\Sigma^-, \Xi^0$ and $\Xi^-$ in $pA$ collisions, depend on $\sqrt{s}$. The target mass number dependence of polarizations of hyperons is low. The energy dependence of hyperon polarization in $\Sigma^- A$ collisions is small due to the strangeness of the incident valence diquark.

Our approach is applicable to small $p_T$ regions ($p_T < 2\text{GeV/c}$), while the approaches based on QCD factorization are mainly applicable to large $p_T$ regions ($p_T > 2\text{GeV/c}$). Thus, there is no direct correspondence between these approaches. However, it is an important problem to research a relation of our model to QCD factorization model. We will investigate this problem as one of future works.

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