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Lambda polarization and single-spin left-right asymmetry in diffractive hadron-hadron collisions

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We discuss lambda polarization and single-spin left-right asymmetry in diffractive hadron-hadron scattering at high energies. We show that the physical picture proposed in a recent Letter is consistent with the experimental observation that Λ polarization in the diffractive process $pp \rightarrow \Lambda K^+ p$ is much higher than that in the inclusive reaction $pp \rightarrow \Lambda X$. We make predictions for the left-right asymmetry A_N and for the spin transfer D_{NN}^{Λ} in the single-spin process $p(\uparrow)p \rightarrow \Lambda K^+ p$ and suggest further experimental tests of the proposed picture.

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It has been known [1] for a long time that hyperons produced in hadron-hadron or hadron-nucleus collisions are polarized transversely to the production plane, although neither the projectile nor the target is polarized before the collision. Significant hyperon polarizations (up to 40%) in inclusive production processes have been observed [1] in the fragmentation regions for moderately large transverse momenta. The effect has been confirmed in past years by a large number of similar experiments at different energies and/or using different projectiles and/or targets and for the production of different hyperons. However, the physical origin of these striking polarizations is still a puzzle. The basic difficulty is that the helicity of the almost massless quarks is conserved in perturbative QCD (PQCD) in leading twist and at leading order [2], but the existence of large hyperon polarization requires a significant helicity flip at the hadron level. Different attempts have been made [3] to overcome this difficulty in the context of PQCD; other theoretical models have also been proposed [4–10]. It is clear that understanding this striking spin effect would also shed light on the spin structure of the hadron.

While most of the experimental data on hyperon polarization are in inclusive processes, the CERN R608 Collaboration has carried out an experiment [11] in the diffractive dissociation process $pp \rightarrow \Lambda K^+ p$. One of the obvious advantages of this exclusive experiment is that, here, one concentrates on a much simpler final state than in inclusive processes. In this way, one hopes to gain deeper insight into the mechanisms of lambda polarization. The results [11] of this experiment show that Λ produced in this process is also transversely polarized, and that the polarization has the same sign (negative) as that observed [1] in the inclusive process $pp \rightarrow \Lambda X$ but the magnitude is very large $(62\% \pm 4\%)$ — much larger than those observed in the inclusive process. Since the diffractive process $pp \rightarrow \Lambda K^+ p$ is the simplest channel for the inclusive process $pp \rightarrow \Lambda X$, the observation that Λ polarization P_Λ in this channel has a much larger value than that in $pp \rightarrow \Lambda X$, which is the average over all the different channels, suggests that this process plays indeed a special role.

In a recent Letter [10], we argued that there is a close relation between the above-mentioned hyperon polarization (P_H) observed [1] in inclusive production processes in unpolarized hadron-hadron collisions and the left-right asymmetry (A_N) observed [12] in inclusive hadron-hadron collisions using transversely polarized projectile or target. Theoretical arguments and experimental observations have been presented which strongly suggest that the two phenomena have the same origin and should be considered together. If this is indeed the case, it offers a new starting point to understand the origin of P_H.

In this Brief Report, we apply the picture to Λ production in diffractive hadron-hadron collisions to make further tests of the picture by comparing the obtained results with the available data. We show in particular that the much larger value of P_Λ in $pp \rightarrow \Lambda K^+ p$ should be considered as further strong evidence for the picture. We make suggestions for future experiments.

We now start by recollecting the key points of the picture proposed in [10]. The basic idea of the picture is that there is a close relation between P_H in unpolarized hadron-hadron collisions and A_N in single-spin hadron-hadron collisions. Hence, if we extract the essential points encoded in the A_N data, we should be able to understand P_H based on these points. The following two points, (a) and (b), have therefore been derived from the existing A_N data [12], and used as inputs to study P_H.

(a) *If a hadron is produced by an upwards polarized valence quark of the transversely polarized projectile, it has a large probability to have a transverse momentum pointing to the "left-hand side" looking downstream. This production mechanism gives rise to positive left-right asymmetry.* [12,13] Here, "left-hand side" is defined by the requirement that the scalar product $\mathcal{M} = \vec{S} \cdot (\vec{p}_B \times \vec{p})$ be positive, where $\vec{S}$ is the polarization vector of the transversely polarized beam, and $\vec{p}_B$ and $\vec{p}$ are the momenta of the beam and the produced hadron, respectively. Positive A_N measures the excess of hadrons produced to the left-hand side over those produced to the right-hand side. The above point has been derived directly from the data [12,13] on A_N in meson production.

We denote the difference of the probabilities for $\mathcal{M}$ to be positive and to be negative by C. C should lie in the region $0<C<1$.

(b) *If a hadron is produced by two valence quarks (valence diquark) of the projectile, the remaining valence quark produces an associated hadron. The left-right asymmetry due to this production mechanism is opposite to that of the associated hadron.* This is consistent with the data on A_N in Λ production [12,14]. It explains in particular the surprising experimental result [12,14] that Λ produced by a spin-zero (ud) diquark from the polarized projectile also exhibits left-right asymmetry [16]!

These two points are supplemented by the following two points, which are consistent with the recent ALEPH and OPAL data [17,18] on longitudinal polarization of Λ in $e^+e^- \to Z^0 \to q\overline{q} \to \Lambda + X$, in order to give a description of P_H in hadron-hadron collisions.

(1) Quark polarization is *not* destroyed in fragmentation.

(2) The SU(6) wave function can be used to describe the relation between the spin of the fragmenting quark and that of the hadron produced in the fragmentation process.

We recall that the SU(6) wave functions have been widely used in studying hyperon polarization in hadron-hadron collisions in the literature (see, e.g., [4], [5], and [7]); i.e., point (2) has been assumed to be true. From this point, we obtain immediately that Λ polarization is completely determined by its s valence quark. This result is quite different from that suggested by the recent polarized deep-inelastic lepton-nucleon scattering (DIS) data [19]. The recent DIS data suggest that, at large Q^2, the quarks and antiquarks carry only a small fraction of the nucleon spin. When applied to Λ, it suggests that [20] Λ spin is not completely determined by its s quark. This initiated the discussions (see, e.g., [20–25]) whether such a picture of the spin structure should also be used for describing the relation between the spins of the fragmenting quarks and the polarization of the hyperon produced in the fragmentation processes. It has been pointed out in [15] that measurements of the longitudinal polarization of Λ in $e^+e^- \to Z^0 \to \Lambda X$ can provide some hints to answer this question. The available data [17,18] are still far from accurate and enormous enough to provide a conclusive judgement. But these available data [17,18] seem to favor [15] the SU(6) description. [26]

We note that the four points (a), (b), (1), and (2) form the basis of the picture in [10]. They are consistent with the data now available [12–14,17,18]. Whether, if yes, how they can be derived from QCD are questions which have been discussed frequently in recent years in the literature. Many models have been proposed to understand in particular points (a) and (b) in terms of the quark-parton model in the framework of QCD. Since the purpose of [10] and that of the present paper are to discuss the close relationship between the left-right asymmetries observed in single-spin hadron-hadron collisions with hyperon polarization in unpolarized hadron-hadron collisions, we use these points as input. In this sense, the results obtained in the following and those in [10] are consequences of a phenomenological model which is consistent with the basic principles and the empirical facts from other experiments. Using this picture, we showed [10] that various data on hyperon polarization in inclusive production processes can be understood provided that the s and $\overline{s}$ taking part in the associated production of the Λ and K^+ have opposite transverse spins. We found in particular that, in this picture, Λ polarization comes mainly from the Λ's which contain two valence quarks of the proton projectile and are associated with a spin-zero meson such as K^+ which contains the remaining valence quark of the proton.

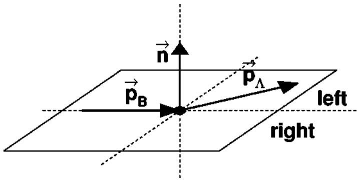

FIG. 1. Hyperon polarization is defined with respect to the unit vector $\vec{n} \equiv \vec{p}_B \times \vec{p}_\Lambda / |\vec{p}_B \times \vec{p}_\Lambda|$ which is perpendicular to the production plane. Here, $\vec{p}_B$ and $\vec{p}_\Lambda$ are momentum of the beam hadron and that of the produced Λ, respectively. From the figure, we see in particular that $\vec{n}$ is pointing upwards if $\vec{p}_\Lambda$ is pointing to the left.

We stress that, although the model is consistent with that proposed by DeGrand and Miettinen [5] on some points, it differs very much from the latter. In [5], polarization of hyperons originates from a semiclassical effect, Thomas precession, which leads to the ''slow-partons-spin-down-fast-partons-spin-up'' rule. This would in particular predict that hyperons produced in e^+e^- annihilations should also be transversely polarized, which contradicts the data [27,17]. The model in [10] relates hyperon polarization P_H in unpolarized collisions with left-right asymmetries A_N observed [12] in single-spin inclusive hadron production processes. Data on A_N suggest a correlation between the polarization of the valence quark and the transverse moving direction of the produced hadron [points (a) and (b) mentioned above]. The picture in [10] shows that the same correlations (a) and (b) lead also to hyperon polarization in unpolarized collisions.

We now come to the application of the picture to the diffractive process $pp \to \Lambda K^+ p$. We note that this is the simplest channel for the inclusive process $pp \to \Lambda X$ and it has the following peculiarities: First, unlike in $pp \to \Lambda X$, Λ has to contain two of the valence quarks from the colliding proton in this process. The associated spin-zero K^+ contains the other valence quark. This means that, in this channel, we have only Λ produced by mechanism (b) which, according to the picture in [10], provides the largest polarization. Second, there is no contribution from hyperon decay. This means that there is no contamination from such decay processes to the Λ polarization. In fact, this is the only channel where these conditions are completely satisfied. We therefore expect that Λ polarization should take its maximum in this process. This is consistent with the R608 observation [11] that P_Λ in this process is much larger than that in $pp \to \Lambda X$.

In order to estimate P_Λ in this process quantitatively, we recall that P_Λ is defined with respect to the production plane (see Fig. 1) and $P_\Lambda<0$ means that the Λ has a large probability to be polarized in the $-\vec{n}$ direction, where $\vec{n} \propto \vec{p}_B \times \vec{p}_\Lambda$ is the normal of the production plan. According to

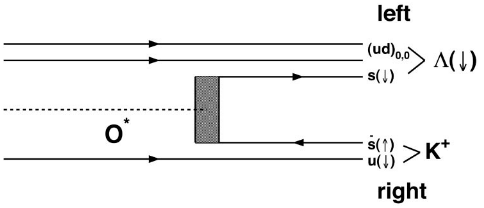

FIG. 2. Associated production of Λ containing two of the valence quarks of the projectile proton and K^+ containing the remaining u valence quark. Here, the three long straight solid lines represent the three valence quarks from the projectile proton; O^* represents some unknown object which carries the energy momentum needed to create the $s\bar{s}$ pair. From the figure, we see that polarization of Λ and that of the remaining u valence quark are the same provided that the s and $\bar{s}$ have opposite spins.

point (b), if $\vec{p}_\Lambda$ is in the direction as shown in the figure (denoted by ''left''), K^+ should be going right; thus $\vec{p}_B \times \vec{p}_{K^+}$ should be in the opposite direction as $\vec{n}$. According to point (a), the u valence quark should have a large probability to be polarized in the $-\vec{n}$ (downwards) direction. The difference of the probability for this u_v to be polarized in the $-\vec{n}$ and that to be polarized in the $\vec{n}$ direction is given by the constant C mentioned in point (a). Since K^+ is a spin-zero object, the $\bar{s}$ in K^+ should be polarized in the $\vec{n}$ direction if u_v is polarized in the $-\vec{n}$ direction. Hence, the s quark and thus the Λ should be polarized in the $-\vec{n}$ direction if s and $\bar{s}$ have opposite transverse spins (see Fig. 2). We see, in this case, that the polarization of Λ is the same as that for the remaining u valence quark which is contained in the associatively produced K^+. This implies that

$$P_\Lambda(pp \to \Lambda K^+ p) = -C. \tag{1}$$

Using the value $C=0.6$ determined (see, e.g., [16] and the references given therein) by fitting the A_N data, we obtain that $P_\Lambda(pp \to \Lambda K^+ p) = -0.6$ which is in good agreement with the R608 data [11], $P_\Lambda(pp \to \Lambda K^+ p) = -0.62 \pm 0.04$.

This result is rather encouraging. We therefore made a detailed analysis for the related spin effects in this processes. We found that the single-spin reaction $p(\uparrow)p \to \Lambda K^+ p$ with transversely polarized proton $p(\uparrow)$ is an ideal place to test the picture proposed in [10] and its applicability to diffractive processes. We obtained the following

(α) There should be a large left-right asymmetry A_N for Λ as well as for K^+ in $p(\uparrow)p \to \Lambda K^+ p$ in the fragmentation region of the transversely polarized proton $p(\uparrow)$, and

$$A_N^\Lambda[p(\uparrow)p \to \Lambda K^+ p] = -A_N^{K^+}[p(\uparrow)p \to \Lambda K^+ p] = -C. \tag{2}$$

This is because $|\Lambda^\uparrow\rangle = (ud)_{0,0}s^\uparrow$; thus only the configuration $(ud)_{0,0}u^\uparrow$ in the projectile proton $p(\uparrow)$ contributes to the process $p(\uparrow)p \to \Lambda K^+ p$. Hence, the u valence quark contained in K^+ is upwards polarized. According to the points (a) and (b) mentioned above, we obtain the results shown in Eq. (2).

TABLE I. Predictions of different spin parameters in the diffractive process $pp \to \Lambda K^+ p$ at high energies of the picture in [10]. The data for $P_\Lambda[pp \to \Lambda K^+ p]$ are taken from [11].

	Theory	Data
$P_\Lambda[pp \to \Lambda K^+ p]$	$-C(=-0.6)$	-0.62 ± 0.04
$A_N^\Lambda[p(\uparrow)p \to \Lambda K^+ p]$	$-C(=-0.6)$	
$A_N^{K^+}[p(\uparrow)p \to \Lambda K^+ p]$	$C(=0.6)$	
$D_{NN}^\Lambda[p(\uparrow)p \to \Lambda K^+ p]$	1	

(β) The ''spin transfer parameter'' D_{NN}^Λ for the produced Λ should be positive and large in $p(\uparrow)p \to \Lambda K^+ p$ in the fragmentation region of $p(\uparrow)$. We recall that D_{NN}^Λ is defined as the probability for the produced Λ to be polarized in the same transverse direction as the projectile. Although the ud diquark which comes from the projectile to form the produced Λ has to be in the spin-zero state and thus carries no information of polarization of the projectile, the remaining u valence quark completely determines the polarization of the projectile. They are polarized in the same direction. Hence, the $\bar{s}$ has to be polarized in the opposite direction as the projectile since K^+ has spin zero. The s quark, which has opposite transverse spin as the $\bar{s}$, and the Λ containing this s quark should be polarized in the same transverse direction of the projectile. Hence, we obtain

$$D_{NN}^\Lambda[p(\uparrow)p \to \Lambda K^+ p] = 1. \tag{3}$$

Both (α) and (β) are predictions which can be tested in future experiments. The predictions for the process $pp \to \Lambda K^+ p$ are summarized in Table I.

Here, it should be mentioned that Λ polarization has recently been measured [28] in another exclusive process $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ at incident momentum of 27.5 GeV/c. The results show the following: (i) The magnitude of P_Λ in this channel is much smaller than that in $pp \to p\Lambda K^+$. (ii) P_Λ is approximately the same for events where K^+ and Λ are produced in the same hemisphere and for those where they are in the opposite hemispheres. We show that both (i) and (ii) are consistent with the picture mentioned above. First, unlike that in $pp \to p\Lambda K^+$, Λ in this

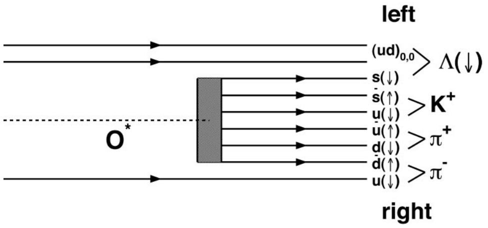

FIG. 3. Production Λ containing two of the valence quarks of the projectile proton associated with more than one pseudoscalar mesons with one of them containing the remaining u valence quark. We see here that the correlation between the polarization of Λ and that of the remaining u valence quark is not destroyed if more spin-zero mesons are associatively produced (cf. Fig. 2).

channel can be produced by two or one of the three valence quarks of the colliding proton. But according to the picture in [10], only the Λ's produced by two valence quarks are polarized; those produced by one are not. Second, while Λ in $pp \rightarrow \Lambda K^+ p$ is definitely associated with K^+, in $pp \rightarrow p \Lambda K^+ \pi^+ \pi^- \pi^+ \pi^-$, Λ can be associated with a vector meson such as K^{*0} which subsequently decays into $K^+ \pi^-$. As has been emphasized in [10], the correlation between the u valence quark in the associated meson and the s quark in the produced Λ will not be destroyed if more spin-zero mesons are associatively produced (see Fig. 3.), but it will be destroyed if one or more (spin-one) vector meson(s) are involved. Hence, we expect that point (i) is true. Furthermore, since P_Λ is not changed if more spin-zero mesons are produced in between (Fig. 3), it is therefore unimportant whether K^+ and Λ are produced in the same or in the opposite hemispheres. This implies that (ii) should also be true.

In summary, we have successfully applied the picture proposed in [10] to Λ production in diffractive processes. The obtained results are in agreement with the data now available. Predictions have been given which can be tested in future experiments.

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