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

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Abstract

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 $\Lambda$ 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, $D^\Lambda_{NN}$, in the single-spin process $p(\uparrow)p \rightarrow \Lambda K^+ p$ and suggest further experimental tests of the proposed picture.
It has been known\textsuperscript{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\textsuperscript{2} 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 helicity of the almost massless quarks is conserved in perturbative QCD (pQCD) in leading twist and at leading order\textsuperscript{3}, but the existence of large hyperon polarization requires significant helicity flip at the hadron level. Different attempts have been made\textsuperscript{4} to overcome this difficulty in the context of pQCD, other theoretical models have also been proposed\textsuperscript{4-10}. It is clear that understanding of this striking spin effect would also shed light on the spin structure of hadron.

While most of the experimental data on hyperon polarization are in inclusive processes, the CERN R608 Collaboration has carried out an experiment\textsuperscript{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\textsuperscript{11} of this experiment show that $\Lambda$ produced in this process is also transversely polarized, and that the polarization has the same sign (negative) as that observed\textsuperscript{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 $\Lambda$ polarization $P_\Lambda$ 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\textsuperscript{10}, we argued that there is a close relation between the above mentioned hyperon polarization ($P_H$) observed\textsuperscript{1} in inclusive production processes in unpolarized
hadron-hadron collisions and the left-right asymmetry ($A_N$) observed 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 note, we apply the picture to $\Lambda$ 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 $P_\Lambda$ in $pp \rightarrow \Lambda K^+ p$ should be considered as a 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, 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 down stream. This production mechanism gives rise to positive left-right asymmetry. 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, $\vec{p}_B$ 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 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 \( \Lambda \) production. It explains in particular the surprising experimental result that \( \Lambda \) produced by a spin zero \((ud)\)-diquark from the polarized projectile also exhibits left-right asymmetry.

These two points are supplemented by the following two points, which are consistent with the recent ALEPH and OPAL data on longitudinal polarization of \( \Lambda \) in \( e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow \Lambda + X \), 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 \( \Lambda \) 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. 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 \( \Lambda \), it suggests that \( \Lambda \) 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 \( \Lambda \) in \( e^+e^- \rightarrow Z^0 \rightarrow \Lambda X \) can provide some hints to answer this question. The available data are still far from accurate and enormous enough to provide a conclusive judgement. But these available data seem to favor the SU(6) description.

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. Whether, if yes, how they can be derived from QCD are questions which have been discussed frequently in recent years in literature. Many models have been proposed to understand in particular point (a) and (b).
in terms of 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 \( \bar{s} \) taking part in the associated production of the \( \Lambda \) and \( K^+ \) have opposite transverse spins. We found in particular that, in this picture, \( \Lambda \) polarization comes mainly from the \( \Lambda \)’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.

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 hyperon originates from a semi-classical 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 [7]. The model in [10] relates hyperon polarization \( P_H \) in unpolarized collisions with left-right asymmetries \( A_N \) observed 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 \( pp \to \Lambda X \), \( \Lambda \) 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 \( \Lambda \) 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 $\Lambda$ polarization. In fact, this is the only channel where these conditions are completely fulfilled. We therefore expect that $\Lambda$ polarization should take its maximum in this process. This is consistent with the R608 observation that $P_\Lambda$ in this process is much larger than that in $pp \rightarrow \Lambda X$.

In order to estimate $P_\Lambda$ in this process quantitatively, we recall that $P_\Lambda$ is defined with respect to the production plane (see Fig. 1) and $P_\Lambda < 0$ means that the $\Lambda$ 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 plane. According to 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 $-\vec{n}$ (downwards) direction. The difference of the probability for this $u_v$ to be polarized in $-\vec{n}$ and that to be polarized in $\vec{n}$ 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 $\vec{n}$ direction if $u_v$ is polarized in $-\vec{n}$ direction. Hence, the $s$ quark thus the $\Lambda$ should be polarized in $-\vec{n}$ direction if $s$ and $\bar{s}$ have opposite transverse spins. (See Fig.2). We see, in this case, the polarization of $\Lambda$ is the same as that for the remaining $u$-valence quark which is contained in the associatively produced $K^+$. This implies that,

$$P_\Lambda(pp \rightarrow \Lambda K^+ p) = -C. \quad (1)$$

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

This result is rather encouraging. We therefore made a detailed analysis for the related spin effects in this processes. We found that single-spin reaction $p(\uparrow)p \rightarrow \Lambda K^+ p$ 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 $\Lambda$ 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,

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

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).

(β) The “spin transfer parameter” $D_{NN}^\Lambda$ for the produced $\Lambda$ should be positive and large in $p(\uparrow)p \to \Lambda K^+p$ in the fragmentation region of $p(\uparrow)$. We recall that $D_{NN}^\Lambda$ is defined as the probability for the produced $\Lambda$ to be polarized in the same transverse direction as the projectile. Although the $ud$ diquark which comes from the projectile to form the produced $\Lambda$ has to be in the spin-zero state 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 $s$ 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 $\bar{s}$, thus the $\Lambda$ containing this $s$-quark should therefore be polarized in the same transverse direction of the projectile. Hence, we obtain,

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

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 $\Lambda$ polarization has recently been measured 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 $P_\Lambda$ in this channel is much smaller than that in $pp \to p\Lambda K^+$. (ii) $P_\Lambda$ is approximately the same for events where $K^+$ and $\Lambda$ 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
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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26. We note that this does not necessary mean that only constituent quarks are involved in the collisions. We recall that the SU(6) baryon wavefunction is a result of the following requirements: A baryon is a composite of three spin 1/2 objects (the quarks), and these three quarks form a color singlet (thus have a completely antisymmetric color wave function) so that their flavor and spin wave functions have to be completely symmetric. Hence, the validity of such wave function in describing the relationship between the spins of the fragmenting quarks and that of the produced baryon may imply that these quarks first evolve into constituent quarks then combine into the baryon. It can also imply that they first combine to form the $|qqq\rangle$ fock state of the baryon then evolve into the complete physical baryon, and so on. Both possibilities are consistent with the presently popular fragmentation models.
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TABLES

Table 1. Predictions on different spin parameters in the diffractive process $pp \rightarrow \Lambda K^+ p$ at high energies of the picture in [10]. The data for $P_{\Lambda}[pp \rightarrow \Lambda K^+ p]$ is taken from [11].

| Parameter | Theory | Data     |
|-----------|--------|----------|
| $P_{\Lambda}[pp \rightarrow \Lambda K^+ p]$ | $-C(= -0.6)$ | $-0.62 \pm 0.04$ |
| $A^L_N[p(\uparrow)p \rightarrow \Lambda K^+ p]$ | $-C(= -0.6)$ | |
| $A^K_N[p(\uparrow)p \rightarrow \Lambda K^+ p]$ | $C(= 0.6)$ | |
| $D^\Lambda_{NN}[p(\uparrow)p \rightarrow \Lambda K^+ p]$ | 1 | |
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 $\Lambda$, respectively. From the figure, we see in particular that $\vec{n}$ is pointing upwards if $\vec{p}_\Lambda$ is pointing to the left.
Fig. 2. Associated production of $\Lambda$ 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 $\Lambda$ and that of the remaining $u$ valence quark are the same provided that the $s$ and $\bar{s}$ have opposite spins.
Fig. 3. Production $\Lambda$ 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 $\Lambda$ and that of the remaining $u$ valence quark is not destroyed if more spin zero mesons are associatively produced. (C.f. Fig.2).