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Hyperon Polarization and Single Spin Left-Right Asymmetry
in Inclusive Production Processes at High Energies

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It is shown that the polarization of hyperons observed in high energy collisions using unpolarized hadron beams and unpolarized nucleon or nuclear targets is closely related to the left-right asymmetries observed in single spin inclusive hadron production processes. The relationship is most obvious for the production of the hyperons which have only one common valence quark with the projectile. Examples of this kind are given. Further implications of the existence of large polarization for a hyperon which has two valence quarks in common with the projectile and their consequences are discussed. A comparison with the available data is made. Further tests are suggested. \[S0031-9007(97)04459-1\]

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Since the discovery of the striking hyperon polarization ($P_H$) in inclusive production processes at high energies [1], there has been much interest in studying the origin of this effect, both experimentally [2] and theoretically [3]. It is now a well-known fact [1,2] that hyperons produced in high energy hadron-hadron collisions are polarized transversely to the production plane, although neither the projectiles nor the targets are polarized. Experimental results for different kinds of hyperons in different reactions at different energies show the following striking characteristics: (1) $P_H$ is significant in, and only in, the fragmentation regions of the colliding objects; (2) $P_H$ depends on the flavor quantum numbers of the produced hyperon; (3) $P_H$ in the projectile fragmentation region depends very much on the flavor quantum numbers of the projectile but little on those of the target.

More recently, striking left-right asymmetries ($A_N$) have been observed [4–7] in single-spin hadron-hadron collisions. The available data for inclusive production of different mesons and of the $\Lambda$ hyperon show very much the same characteristics as those for $P_H$: we can simply replace $P_H$ by $A_N$ in (1)–(3) above. Not only these striking similarities but also the following reasonings strongly suggest that these two phenomena should be closely related to each other. We note $A_N \neq 0$ implies that the direction of transverse motion of the produced hadron depends on the polarization of the projectile. For example, for $\pi^+$ in $p(\Sigma^+) + p \to \pi^+ + X$, $A_N > 0$ [5,6]; this means that the produced $\pi^+$ has a large probability to go left looking downstream if the projectile is upwards polarized. $P_H \neq 0$ means that there exists a correlation between the direction of transverse motion of the produced hyperon ($H$) and the polarization of this hyperon. We recall that $P_H$ is defined with respect to the production plane and, e.g., $P_\Lambda < 0$ in $p + p \to \Lambda + X$ means that the $\Lambda$’s which are going left (looking downstream) have a larger probability to be downwards polarized. We see that both phenomena show the existence of a correlation between transverse motion and transverse polarization. Hence, unless we insist on assuming that the polarization of the produced hyperons in the projectile fragmentation region is independent of that of the projectile—which would in particular contradict the empirical fact recently observed by E704 Collaboration [6] for $\Lambda$ production—we are practically forced to accept that $A_N$ and $P_H$ are closely related to each other.

The close relation between $A_N$ and $P_H$ is most obvious in the case in which the produced hyperon ($H$) has only one valence quark in common with the projectile. In this case, the beam fragmentation region is dominated by the hadronization product that contains this common valence quark. To see whether such hyperon is polarized and, if yes, how large $P_H$ is, we recall the following.

(I) The existence of $A_N$ in single-spin reactions shows that the polarization of the valence quark and the transverse moving direction of the produced hadron containing this valence quark are closely related to each other: the data [4–7] show that meson (e.g., $\pi$, $\eta$, or $K$) containing $q_v^p$ and a suitable anti-sea-quark $\bar{q}_v^s$ have a large probability to go left if $q_v^p$ is upwards polarized. (Here, $P$ or $T$ denotes projectile or target, $v$ or $s$ valence or sea.) Hence, if the produced meson is going left, the corresponding $q_v^p$ should have a large probability to be upwards polarized. We assume that this is also true for the produced baryon which contains such a $q_v^p$ and a sea diquark.

(II) Recent measurement [8] of $\Lambda$ polarization from $Z^0$ decay by ALEPH Collaboration shows that, in the longitudinally polarized case, quark polarization remains the same before and after the hadronization. We assume that this is true not only for $\Lambda$ production but also for other hyperons and also in the transversely polarized case.

We note that both (I) and (II) are direct extensions of the experimental observations. They can also be directly tested by performing further experiments, e.g., by
measuring $A_N$ in $p(1) + p \to H + X$ and $P_H$ in the current fragmentation region of $e^- + p(1) \to e^- + H + X$ for $H = \Sigma^-$ (or $\Xi^0$, or $\Xi^-$), respectively. [Here, $p(1)$ denotes a transversely polarized proton.] Theoretically, whether (II) is true depends on the detailed mechanism of hadronization, which is in general of soft nature and at present can only be described using phenomenological models. It can easily be seen that (II) is indeed true in the popular models such as the LUND model [9]. The validity of (I) has been a puzzle for a long time and a number of models have been proposed [10] recently, which can give rise to such $A_N$’s. Yet, which one is more appropriate is still in debate. Since the purpose of this paper is to discuss the relationship between $P_H$ and $A_N$, independent of these models, we will just take (I) and (II) as assumptions and show that $P_H$ in unpolarized $pp$ collisions can be determined uniquely using these two points. This is quite straightforward: Since $P_H$ is defined with respect to the production plane, we need only to consider, e.g., those hyperons which are going left and check whether they are upwards (or downwards) polarized. According to (I), if the hyperon is going left, $q_v^u$ should have a large probability to be upwards polarized. This means, by choosing those hyperons which are going left, we obtain a subsample of hyperons which are formed by $q_v^u$’s that are upwards polarized with suitable sea diquarks. According to (II), these valence quarks remain upwards polarized in the produced hyperons. This, together with the wave function of the hyperon, determines whether the hyperons are polarized and, if yes, how large the polarizations are. To demonstrate this explicitly, we consider $p + p \to \Sigma^- + X$. Here, the dominating contribution in the fragmentation region is the $\Sigma^-$ made out of the common valence quark $d_v^p$ and a sea diquark $(d_s,s_d)^T$, and the wave function of $\Sigma^-$ is $|\Sigma^-(1/2)\rangle = \frac{1}{\sqrt{3}}[3d^s \langle ds \rangle_{0,0} + d^d \langle ds \rangle_{1,0} - \sqrt{2}d^s \langle ds \rangle_{1,1}],$ where the subscripts of the diquarks are their total angular momenta and the third components. We see that if $d_v^p$ is upwards polarized, $\Sigma^-$ has a probability of $5/6$ (1/6) to be upwards (downwards) polarized. Hence, we obtain that the $\Sigma^-$ which contains the $d_v^p$ and a $(d_s,s_d)^T$ is positively polarized and the polarization is $(5/6)C$ [where $0 < C < 1$ is the difference [11,12] between the probability for $B$ made out of $q_v^u$ and $(q_s,q_d)^T$ to go left and that to go right if $q_v^u$ is upwards polarized]. Similar analysis can also be done for other hyperons. We obtain, e.g., that both $\Xi^-$ and $\Xi^0$ produced in $pp$ collisions are negatively polarized and the polarization is $-C/3$, which implies that their magnitudes are smaller than that of $P_{\Sigma^-}$. Since hyperons containing the $q_v^u$’s dominate only at large $x_F$ ($x_F \equiv 2p_T/\sqrt{s}$, where $p_T$ is the longitudinal momentum of the produced hyperon, $\sqrt{s}$ is the total c.m. energy of the colliding hadron system), we expect that the magnitudes of $P_H$ increase with increasing $x_F$ and the above mentioned results are their limits at $x_F \to 1$. All these are consistent with the data [1,2].

Without any other input, we obtained also many further direct associations, in particular the following: (A) $P_{\Lambda}$ in the beam fragmentation region of $K^- + p \to \Lambda + X$ is large and is, in contrast to that in $pp$ collisions, positive in sign. This is because, according to the wave function, $|\Lambda^1\rangle = s^1(ud)_{0,0}$, the polarization of $\Lambda$ is entirely determined by the $s$ quark. Here, the dominating contribution is the $\Lambda$ which contains the $s_v^u$ of $K^-$ and a suitable $(u_s,d_s)^T$, and $s_v^u$ should have large probability to be upwards polarized if $\Lambda$ goes left. (B) $P_{\Lambda}$ in the beam fragmentation region of $\pi^- + p \to \Lambda + X$ should be negative and the magnitude should be very small. This is because the dominating contribution here is the $\Lambda$ containing the $u_v^u$, $(d_v^p)$ of $\pi^-$ and a suitable $(d_s,s_d)^T$ [or a $(u_s,s_d)^T$]. Although the $u_v^u$, $(d_v^p)$ should have a large probability to be upwards polarized if $\Lambda$ goes left, $\Lambda$ itself remains unpolarized, since its polarization is determined solely by the $s$ quark. A small $P_{\Lambda}$ is expected only from the decay of $\Sigma^0$. (C) Not only hyperons but also the produced vector mesons are expected to be transversely polarized in the fragmentation region of hadron-hadron collisions. For example, $\rho^0, \phi, K^{*+}$ in the fragmentation regions of $pp$ collisions are expected to be positively polarized. This is because the dominating contribution here is the meson containing a $q_v^u$ and a $q_s^u$, and the $q_v^u$ should have a large probability to be upwards polarized if the meson is going left. (D) Neither the contribution from hadronization to $P_{\Lambda}$ nor that to $A_N$ can be large. The former is a direct implication of the results of measurements [8,13] in $e^+e^- \to \Lambda + X$, which show no significant transverse polarization $P_{\Lambda}$. The close relation between $A_N$ and $P_H$ implies that the latter should also be true. Presently, there are already data available for the processes mentioned in (A) and (B) [14,15], and both of them are in agreement with these associations. (D) is consistent with the results [16] of the recent measurements of jet handedness at SLAC, which show that the spin dependence of hadronization is very little. (C) can be checked by future experiments. Encouraged by these agreements, we continue to discuss the second case in which the produced hyperon has two valence quarks in common with the projectile and hence hyperons containing such common valence diquarks dominate the beam fragmentation region. The most well-known process of this type is $p + p \to \Lambda + X$. To see whether, and if yes how, we can also understand the existence of $P_{\Lambda}$ in this process, we start again from the single-spin process $p(1) + p \to \Lambda + X$. We recall that the recent E704 data [5,6] show that, also for $\Lambda$, there exists a significant $A_{\Lambda}$ in the beam fragmentation region. At first sight, this result seems rather surprising because $\Lambda$ in the beam fragmentation region comes predominantly from the hadronization of the spin-0 $(u_s,d_s)^T$ of the projectile. How can a spin-0 object transfer the information of polarization of the projectile to the produced $\Lambda$? This question has been discussed [12] and a solution has been suggested in which associated production plays an important role. It has been pointed out [12] that the production of the $\Lambda$ containing the spin-0 $(u_s,d_s)^T$ and a
$s^T_s$ is associated with the production of a Kaon containing the remaining $(u^p_s)^p$ of the projectile and the $s^T_i$ associated with the target. The information of polarization of the projectile is carried by the $(u^p_s)^p$ so that the produced $K$ has a large probability to go left if the projectile is upwards polarized. The $A$ has therefore a large probability to go right since the transverse momentum should be compensated. This explains why there should be also a significant $A_N$ for $A$, and the available data [5,6] have been reproduced successfully. According to this picture, if the produced $A$ is moving to the left in unpolarized $p\bar{p}$ collision, the associated $K$ should mainly move to the right. Hence, the $(u^p_s)^p$ contained in this $K$ should have a large probability to be downwards polarized. Since $K$ is a spin-0 object, the $\tilde{s}^T_i$ should be upwards polarized. Hence, to get a negative $P_A$, we need only to assume that the sea quark-antiquark pair $s_i\bar{s}_i$ from the nucleon has opposite transverse spins. Under this assumption, the polarization of the produced $A$ is completely determined [17] by that of the remaining $(u^p_s)^p$ which, together with a $\tilde{s}^T_i$, forms the associatively produced $K^+$. That the $s$ and $\tilde{s}$ of the sea $s_i\tilde{s}_i$-pair have opposite transverse spins should be considered as a further implication of the existence of $P_A$ in the above mentioned picture. Whether this is indeed the case can and should be checked experimentally. Theoretically, it is quite difficult to verify it since we are in the very small $x$ region (see, e.g., [12]); the production of such pairs is of soft nature in general and cannot be calculated using perturbative theory. It seems plausible since the sea quarks are products of the dissociation of one or more gluons and gluons are not transversely polarized. Here, we simply assume this is true and discuss the consequences to see whether they are consistent with the available data.

First, we made a similar analysis for the production of other hyperons, and obtained qualitative results for their $P_H$'s. They are all consistent with the available data [2].

Second, we made a quantitative estimation of $P_A$ in $p + p \rightarrow A + X$ as a function of $x_F$. To do this, we recall that $P_A(x_F \mid s)$ is defined as

$$P_A(x_F \mid s) = \frac{N^A(x_F \mid \uparrow \mid s) - N^A(x_F \mid \downarrow \mid s)}{N^A(x_F \mid \uparrow \mid s) + N^A(x_F \mid \downarrow \mid s)},$$

where $N^A(x_F, i \mid s)$ is the number density of $A$'s polarized in the same $(i = \uparrow)$ or opposite $(i = \downarrow)$ direction as the normal of the production plane, at a given $\sqrt{s}$. It is clear that the denominator is nothing else but the number density of $A$ without specifying the polarization. It contains all the $A$'s of different origins: those made out of $(u^p_s, d_s)^p$ and a $s^T_i$ [denoted by $D^A_i(x_F \mid s)$ in the following], those of $u^p_s$ and $(d_s, s)^T$ or $d^p_s$ and $(u_s, s)^T$ [denoted by $D^A_i(x_F \mid s)$], those from resonances decay, and those from pure sea-sea interactions (denoted by $N_0$). Since $u_s$ or $d_s$ does not carry any information of the spin of $A$, there is no contribution from $D^A_i(x_F \mid s)$ to the numerator, i.e., the difference $\Delta N^A(x_F \mid s)$. There is no contribution to $A_N$ from the $N_0$ part; hence we assume that it does not contribute to $P_H$ either [18]. We take the contribution from $\Sigma^0$ decay into account and obtain

$$\Delta N^A(x_F \mid s) = C[D^A_1(x_F \mid s) - \frac{1}{3} \sum_{i=1}^2 \Delta D^0_i(x_F \mid s)].$$

(2)

Here $\Delta D^H_i(x_F \mid s) \equiv D^H_i(x_F \mid \uparrow \mid s) - D^H_i(x_F \mid \downarrow \mid s) (H = \Lambda$ or $\Sigma^0$). From the wave functions of $\Lambda$, $\Sigma^0$, and that of proton, we obtain that $\Delta D^A_1(x_F \mid s) = -D^A_1(x_F \mid s)$, and $\Delta D^0_1(x_F \mid s) = (\frac{2}{3} \Delta D^0_2(x_F \mid s)$. The extra factor $-1/3$ for the $\Sigma^0$ decay terms comes from the relation [19] $P_\Lambda = -(1/3)P_{\Sigma^0}$ in this decay process. To calculate the different $D$'s and $N_0$, which are determined by the hadronization mechanisms, we simply used the direct fusion model in [12], which successfully reproduced not only the data of the cross section but also those of $A_N$. By taking the same value for the only free parameter $C$ as that determined in [11,12] by fitting the $A_N$ data [5,6], we obtained the result shown in Fig. 1.

Third, we derived a number of other consequences of the picture without any further input. The following are three examples which are closely related to the assumption that the $s$ and $\tilde{s}$ which take part in the associated production are opposite in transverse spins.

(i) The polarization of the projectile and that of $A$ in the fragmentation region of $p + p \rightarrow A + X$ should be closely related to each other. In other words, the spin transfer $D_{NN}$ (i.e., the probability for the produced $A$ to be upwards polarized in the case that the projectile proton is upwards polarized) is expected to be positive and large for large $x_F$. It is true that the $ud$ diquark which forms the $A$ is in a spin-zero state and thus carries no information of polarization. But, according to the mechanism of associated production, the polarization of the leftover $u^p_s$ determines the polarization of the projectile and that of the $s_i$ quark which combines with the $ud$ diquark to form the $A$. Hence, there should be a strong correlation between the polarization of the proton and that of the $A$. The result of a quantitative estimation is shown in Fig. 2.

(ii) $P_A$ in the beam fragmentation region of $\Sigma^- + A \rightarrow A + X$ should be negative and much less significant.
than that in \( p + p \rightarrow \Lambda + X \). Here, the dominating contributions are the \( \Lambda \)'s which consist of \( (u_s d_s)^p \) and \( u_s^0 \), \( d_s^0 \) and \( (u_s d_s)^T \), or \( s_s^0 \) and \( (u_s d_s)^T \). Exactly the same analysis as above for \( p + p \rightarrow \Lambda + X \) shows that the \( \Lambda \)'s of the first two kinds are unpolarized, and those of the third kind are positively polarized. Hence, if we exclude the contribution from \( \Sigma^0 \) and \( \Sigma^+ \) decay, \( P_\Lambda \) should be approximately zero for large \( x_F \) and should be small but positive in the middle \( x_F \) region. Taking \( \Sigma^0 \) and \( \Sigma^+ \) decay into account, we expect a small negative \( P_\Lambda \) for large \( x_F \).

(iii) Hyperon polarization in processes in which a vector meson is associatively produced should be very much different from that in processes in which a pseudoscalar meson is associatively produced. For example, \( P_\Lambda \) in the fragmentation region of \( p + p \rightarrow \Lambda + K^+ + X \) should be negative and its magnitude should be large, but \( P_\Lambda \) in the fragmentation region of \( p + p \rightarrow \Lambda + K^{*+} + X \) should be positive and its magnitude should be much smaller. This is because, in the latter case, using the same arguments as we used in the former case, we still obtain that \( (u_s d_s)^p \) (contained in \( K^{*+} \)) has a large probability to be downwards polarized if \( \Lambda \) is going left. But, in contrast to the former case, the \( s_s^0 \) here in the \( K^{*+} \) can be upwards or downwards polarized since \( K^{*+} \) is a spin-1 object. If \( s_s^0 \) is upwards polarized, the produced meson can be either a \( K^* \) or a \( K^0 \), and the corresponding \( \Lambda \) should be downwards polarized. But if \( s_s^0 \) is downwards polarized, the produced meson can only be a \( K^{*+} \) and the corresponding \( \Lambda \) should be upwards polarized, i.e., \( P_\Lambda > 0 \).

Presently, there are data available for the processes mentioned in (i) and (ii) [6,23], and both of them are in agreement with the above expectations. The prediction mentioned in (iii) is another characteristic feature of the model and can be used as a crisp test of the picture.

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[18] We note that this correlation remains unity even if more pseudoscalar mesons are created, but may be destroyed if vector mesons are associatively produced. Here, we consider only the former case. In this sense, what we obtain is the upper limit of the expectation from the picture. See in this connection also point (iii) later in this paper.
[19] This does not necessary mean that the sea quarks are absolutely unpolarized in a polarized nucleon. It may just mean that their relative polarization is negligibly small or they lose their information of polarization during the initial state interactions between the constituents of the two colliding hadrons.