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

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(Received 16 May 1997)

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]

PACS numbers: 13.88.+e, 12.39.Ki, 13.85.Ni

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 Λ 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 π^+ in $p(\uparrow) + p \to \pi^+ + X$, $A_N > 0$ [5,6]; this means that the produced π^+ 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 Λ'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 Λ 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., π, η, or K) containing q_v^P and a suitable anti-sea-quark $\bar{q}_s^T$ 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 Λ 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 Λ 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 $p(\uparrow) + p \to H + X$ and P_H in the current fragmentation region of $e^- + p(\uparrow) \to e^- + H + X$ for $H = \Sigma^-$ (or Ξ^0, or Ξ^-), respectively. [Here, $p(\uparrow)$ 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^P 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^P'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 Σ^- made out of the common valence quark d_v^P and a sea diquark $(d_s s_s)^T$, and the wave function of Σ^- is $|\Sigma^{-\uparrow}\rangle = \frac{1}{2\sqrt{3}}[3d^\uparrow(ds)_{0,0} + d^\uparrow(ds)_{1,0} - \sqrt{2}d^\downarrow(ds)_{1,1}]$, 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, Σ^- has a probability of $5/6$ $(1/6)$ to be upwards (downwards) polarized. Hence, we obtain that the Σ^- which contains the d_v^P and a $(d_s s_s)^T$ 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^P and $(q_s q_s)^T$ to go left and that to go right if q_v^P is upwards polarized]. Similar analysis can also be done for other hyperons. We obtain, e.g., that both Ξ^- and Ξ^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_{Σ^-}. Since hyperons containing the q_v^P's dominate only at large x_F ($x_F \equiv 2p_\parallel/\sqrt{s}$, where $p_\parallel$ 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_Λ 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, $|\Lambda^\uparrow\rangle = s^\uparrow(ud)_{0,0}$, the polarization of Λ is entirely determined by the s quark. Here, the dominating contribution is the Λ which contains the s_v^P of K^- and a suitable $(u_s d_s)^T$, and s_v^P should have large probability to be upwards polarized if Λ goes left. (B) *P_Λ in the beam fragmentation region of $\pi^\pm + p \to \Lambda + X$ should be negative and the magnitude should be very small.* This is because the dominating contribution here is the Λ containing the u_v^P (or d_v^P) of π^+ (or π^-) and a suitable $(d_s s_s)^T$ [or a $(u_s s_s)^T$]. Although the u_v^P (or d_v^P) should have a large probability to be upwards polarized if Λ goes left, Λ itself remains unpolarized, since its polarization is determined solely by the s quark. A small P_Λ is expected only from the decay of Σ^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, $\rho^\pm, \rho^0, K^{*+}$ 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^P and a $\bar{q}_s^T$, and the q_v^P should have a large probability to be upwards polarized if the meson is going left. (D) *Neither the contribution from hadronization to P_Λ 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_Λ. 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_Λ in this process, we start again from the single-spin process $p(\uparrow) + p \to \Lambda + X$. We recall that the recent E704 data [5,6] show that, also for Λ, there exists a significant A_N in the beam fragmentation region. At first sight, this result seems rather surprising because Λ in the beam fragmentation region comes predominately from the hadronization of the spin-0 $(u_v d_v)^P$ of the projectile. How can a spin-0 object transfer the information of polarization of the projectile to the produced Λ? 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 Λ containing the spin-0 $(u_v d_v)^P$ and a

s_s^T is associated with the production of a Kaon containing the remaining $(u_v^a)^P$ of the projectile and the $\bar{s}_s^T$ associated with the target. The information of polarization of the projectile is carried by the $(u_v^a)^P$ so that the produced K has a large probability to go left if the projectile is upwards polarized. The Λ 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 Λ, and the available data [5,6] have been reproduced successfully. According to this picture, if the produced Λ is moving to the left in unpolarized pp collision, the associated K should mainly move to the right. Hence, the $(u_v^a)^P$ contained in this K should have a large probability to be downwards polarized. Since K is a spin-0 object, the $\bar{s}_s^T$ should be upwards polarized. Hence, to get a negative P_Λ, we need only to assume that the sea quark-antiquark pair $s_s\bar{s}_s$ from the nucleon has opposite transverse spins. Under this assumption, the polarization of the produced Λ is completely determined [17] by that of the remaining $(u_v^a)^P$ which, together with a $\bar{s}_s^T$, forms the associatively produced K^+.

That the s and $\bar{s}$ of the sea $s_s\bar{s}_s$-pair have opposite transverse spins should be considered as a further implication of the existence of P_Λ 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_Λ in $p + p \to \Lambda + X$ as a function of x_F. To do this, we recall that $P_\Lambda(x_F \,|\, s)$ is defined as

$$P_\Lambda(x_F \,|\, s) \equiv \frac{N^\Lambda(x_F,\uparrow \,|\, s) - N^\Lambda(x_F,\downarrow \,|\, s)}{N^\Lambda(x_F,\uparrow \,|\, s) + N^\Lambda(x_F,\downarrow \,|\, s)}, \quad (1)$$

where $N^\Lambda(x_F, i \,|\, s)$ is the number density of Λ'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 Λ without specifying the polarization. It contains all the Λ's of different origins: those made out of $(u_v d_v)^P$ and a s_s^T [denoted by $D_2^\Lambda(x_F \,|\, s)$ in the following], those of u_v^P and $(d_s s_s)^T$ or d_v^P and $(u_s s_s)^T$ [denoted by $D_1^\Lambda(x_F \,|\, s)$], those from resonances decay, and those from pure sea-sea interactions (denoted by N_0). Since u_v or d_v does not carry any information of the spin of Λ, there is no contribution from $D_1^\Lambda(x_F \,|\, s)$ to the numerator, i.e., the difference $\Delta N^\Lambda(x_F \,|\, s)$. 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 Σ^0 decay into account and obtain

$$\Delta N^\Lambda(x_F \,|\, s) = C[\Delta D_2^\Lambda(x_F \,|\, s) - \frac{1}{3}\sum_{i=1}^{2} \Delta D_i^{\Sigma^0}(x_F \,|\, s)]. \quad (2)$$

Here $\Delta D_i^H(x_F \,|\, s) \equiv D_i^H(x_F,\uparrow \,|\, s) - D_i^H(x_F,\downarrow \,|\, s)$ ($H = \Lambda$ or Σ^0). From the wave functions of Λ, Σ^0, and that of proton, we obtain that $\Delta D_2^\Lambda(x_F \,|\, s) = -D_2^\Lambda(x_F \,|\, s)$, and $\Delta D_{1,2}^{\Sigma^0}(x_F \,|\, s) = (\frac{2}{3}, \frac{3}{5}) D_{1,2}^{\Sigma^0}(x_F \,|\, s)$. The extra factor $-1/3$ for the Σ^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 $\bar{s}$ which take part in the associated production are opposite in transverse spins.

(i) The polarization of the projectile and that of Λ in the fragmentation region of $p + p \to \Lambda + X$ should be closely related to each other. In other words, the spin transfer D_{NN} (i.e., the probability for the produced Λ 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 Λ 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_v^P determines the polarization of the projectile and that of the s_s quark which combines with the ud diquark to form the Λ. Hence, there should be a strong correlation between the polarization of the proton and that of the Λ. The result of a quantitative estimation is shown in Fig. 2.

(ii) P_Λ in the beam fragmentation region of $\Sigma^- + A \to \Lambda + X$ should be *negative* and much less significant

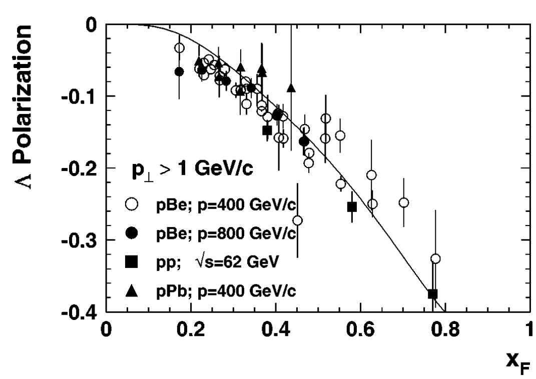

FIG. 1. Calculated results for the polarization of Λ, P_Λ, as a function of x_F. Data are taken from Refs. [20–22].

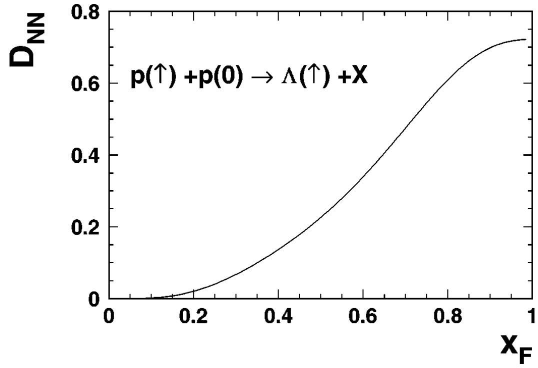

FIG. 2. D_{NN} as a function of x_F calculated using the proposed picture for the case that the correlation between the spin of the s_s^T [which forms together with the $(u_v d_v)_{0,0}^P$ the Λ] and the spin of the remaining u_v^P of the projectile (which forms together with the $\bar{s}_s^T$ the associated K^+) is maximal. In this sense, it stands for the upper limit of our expectation.

than that in $p + p \to \Lambda + X$. Here, the dominating contributions are the Λ's which consist of $(d_v s_v)^P$ and u_s^T, d_v^P and $(u_s s_s)^T$, or s_v^P and $(u_s d_s)^T$. Exactly the same analysis as above for $p + p \to \Lambda + X$ shows that the Λ's of the first two kinds are unpolarized, and those of the third kind are positively polarized. Hence, if we exclude the contribution from Σ^0 and Σ^{*0} decay, P_Λ should be approximately zero for large x_F and should be small but positive in the middle x_F region. Taking Σ^0 and Σ^* decay into account, we expect a small negative P_Λ 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_Λ in the fragmentation region of $p + p \to \Lambda + K^+ + X$ should be negative and its magnitude should be large, but P_Λ in the fragmentation region of $p + p \to \Lambda + K^{*+} + X$ 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 $(u_v^a)^P$ (contained in K^{*+}) has a large probability to be downwards polarized if Λ is going left. But, in contrast to the former case, the $\bar{s}_s^T$ here in the K^{*+} can be upwards or downwards polarized since K^{*+} is a spin-1 object. If $\bar{s}_s^T$ is upwards polarized, the produced meson can be either a K^* or a K, and the corresponding Λ should be downwards polarized. But if $\bar{s}_s^T$ is downwards polarized, the produced meson can only be a K^{*+} and the corresponding Λ 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.

We thank K. Heller, Meng Ta-chung, and R. Rittel for helpful discussions. This work was supported in part by Deutsche Forschungsgemeinschaft (DFG:Me 470/7-2).

[1] A. Lesnik *et al.*, Phys. Rev. Lett. **35**, 770 (1975); G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976).
[2] For a review of the data, see, e.g., K. Heller, in *Proceedings of the 12th International Symposium on Spin Physics, Amsterdam, 1996* (World Scientific, Singapore, 1997).
[3] B. Andersson, G. Gustafson, and G. Ingelman, Phys. Lett. **85B**, 417 (1979); T. A. DeGrand and H. I. Miettinen, Phys. Rev. D **24**, 2419 (1981); J. Szwed, Phys. Lett. **105B**, 403 (1981); L. G. Pondrom, Phys. Rep. **122**, 57 (1985); R. Barni, G. Preparata, and P. G. Ratcliffe, Phys. Lett. B **296**, 251 (1992); J. Soffer and N. Törnqvist, Phys. Rev. Lett. **68**, 907 (1992), and references therein.
[4] S. Saroff *et al.*, Phys. Rev. Lett. **64**, 995 (1990).
[5] D. Adams *et al.*, Phys. Lett. B **261**, 201 (1991); **264**, 462 (1991); **276**, 531 (1992); Z. Phys. C **56**, 181 (1992); A. Bravar *et al.*, Phys. Rev. Lett. **75**, 3073 (1995); **77**, 2626 (1996).
[6] A. Bravar, in *Proceedings of the Adriatico Research Conference: Trend in Collider Spin Physics, Trieste, 1995* (World Scientific, Singapore, 1997), p. 254.
[7] V. D. Apokin *et al.*, Phys. Lett. B **243**, 461 (1990).
[8] D. Buskulic *et al.*, Phys. Lett. B **374**, 319 (1996).
[9] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rep. **97**, 31 (1983).
[10] For a short summary of the main ideas in the different models and/or a list of references, see, e.g., C. Boros, Z. Liang, T. Meng, and R. Rittel, in *Proceedings of the 12th International Symposium on Spin Physics* (Ref. [2]), p. 419.
[11] Z. Liang and T. Meng, Z. Phys. A **344**, 171 (1992); Phys. Rev. D **49**, 3759 (1994); C. Boros, Z. Liang, and T. Meng, Phys. Rev. Lett. **70**, 1751 (1993); Phys. Rev. D **51**, 4867 (1995); **54**, 4680 (1996). Here, a model for A_N has been proposed, in which A_N is assumed to originate from the orbital motion of the valence quarks and the surface effect in single-spin hadron-hadron collisions.
[12] C. Boros and Z. Liang, Phys. Rev. D **53**, R2279 (1996).
[13] M. Althoff *et al.*, Z. Phys. C **27**, 27 (1985).
[14] S. A. Goulay *et al.*, Phys. Rev. Lett. **56**, 2244 (1986).
[15] J. Bensinger *et al.*, Phys. Rev. Lett. **50**, 313 (1983).
[16] K. Abe *et al.*, Phys. Rev. Lett. **74**, 1512 (1995).
[17] 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.
[18] 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.
[19] R. Gatto, Phys. Rev. **109**, 610 (1958).
[20] A. M. Smith *et al.*, Phys. Lett. B **185**, 209 (1987).
[21] B. Lundberg *et al.*, Phys. Rev. D **40**, 3557 (1989).
[22] E. J. Ramberg *et al.*, Phys. Lett. B **338**, 403 (1994).
[23] M. I. Adamovich *et al.*, Z. Phys. A **350**, 379 (1995).