

Hyperon production mechanisms and single-spin asymmetry in high energy hadron-hadron collisions

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It is shown that the existence of left-right asymmetry in single-spin inclusive Λ production, together with the characteristic features of the data, should be considered as another clear signature for the existence of orbiting valence quarks in polarized nucleons. Predictions for other hyperons are made. It is pointed out that measurements of such asymmetries are very helpful not only for probing the spin structure of the nucleons but also for studying the production mechanisms of the hyperons.

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Striking left-right asymmetries (A_N) have been observed in single-spin inclusive production processes at high energy (200 GeV/c) now not only for pions [1] but also for Λ [2] and η [3]. Comparing the new data [2,3] with those for pions [1] we see that, while the data [3] for η are essentially the same as that for π^0 , that for Λ as a function of $x_F (\equiv 2p_{\parallel}/\sqrt{s})$, where p_{\parallel} is the longitudinal momentum of the produced hadron with respect to the incident direction of the projectile, and s is the total center-of-mass energy squared of the colliding system) shows the following: (1) Similar to those for pions, $A_N(x_F, \Lambda|s)$ is significant in the large x_F region ($x_F \gtrsim 0.6$, say), but small in the central region; (2) $A_N(x_F, \Lambda|s)$ is negative in the large x_F region, and it behaves similarly as $-A_N(x_F, \pi^+|s)$ does in this region; (3) $A_N(x_F, \Lambda|s)$ begins to rise up later than $A_N(x_F, \pi^{\pm}|s)$ does. For x_F in the neighborhood of $x_F \sim 0.4-0.5$, it is even positive. In the region $0 < x_F \lesssim 0.5$, its behavior is similar to that of $A_N(x_F, \pi^0|s)$.

In recent publications [4,5], we pointed out that the existence of left-right asymmetry for pion production should be considered as a strong indication for the existence of orbiting valence quarks in polarized nucleons. Left-right asymmetries are expected to exist in inclusive single-spin processes when direct formations of particles (or particle systems) through fusions and/or annihilations of the orbiting valence quarks of the polarized projectile with suitable antiquarks associated with the target contribute significantly. Single-spin inclusive experiments are extremely useful in probing the orbital motion of the valence quarks in polarized hadrons. They provide also useful information for studying the production mechanisms of mesons in general and for distinguishing those mesons from direct formation processes from the others in particular. In connection with the new data [2,3] from E704 Collaboration we note the following: While that for η was expected in our earlier publications [4,5], no discussion has yet been made on hyperon production. We are therefore led to the following questions: Does the direct formation process play a significant role also for Λ and/or other hyperon production in the fragmentation regions? Can we also understand the left-right asymmetry for Λ production, especially the abovementioned characteristics of the data? What do we expect to see for other hyperons?

These are the questions we would like to discuss in this note. We show that the first two questions should be answered in the affirmative and that predictions for other hyperons can be made. In fact, as we will see in the following, just as mesons, for moderately large transverse momentum ($p_{\perp} \gtrsim 0.6$ GeV/c, say), a significant part of hyperons observed in the fragmentation regions are products of direct formation processes. The abovementioned differences and similarities between $A_N(x_F, \Lambda|s)$ and $A_N(x_F, \pi|s)$ directly reflect the interplay between the different kinds of direct formation processes and the non-direct-formation part. The existence of $A_N(x_F, \Lambda|s)$, together with its abovementioned characteristics, should be considered as another clear signature for the existence of orbiting valence quarks in polarized nucleon. Measurements of such left-right asymmetries are helpful not only in probing the spin structure of the nucleon but also in studying the production mechanisms of the hyperons.

We begin our discussions by briefly summarizing the key points of the proposed picture, which have been applied successfully to meson and lepton-pair productions in [4,5], as follows.

(i) Valence quarks in a nucleon are treated as Dirac particles in an effective confining potential. It is shown that orbital motion for these valence quarks is always involved even when they are in the ground states, and that the direction of the orbital motion is determined uniquely by the polarization of the valence quark.

(ii) Valence quarks in a polarized hadron are polarized either in the same or in the opposite direction as the hadron. This is determined by the wave function of the hadron. For protons, on the average, 5/3 of the u valence quarks are polarized in the same and 1/3 of them in the opposite direction as the proton. For d , they are 1/3 and 2/3, respectively.

(iii) A significant part of the particles (with moderately large transverse momenta) observed in the fragmentation regions in high-energy hadron-hadron collisions are products of the direct formation processes of the valence quarks of one of the colliding hadrons with suitable anti-sea quarks associated with the other.

(iv) There exists a significant surface effect in single-spin inclusive production processes. This implies that only those particles directly formed near the front surface of the polar-

ized hadron retain the information of the polarization. This leads to the conclusion that, for example, a meson which is formed through direct fusion of an upward polarized valence quark with an anti-sea quark should get an extra transverse momentum from the orbital motion of the valence quark to the left (looking down stream, as defined in the experiments [1–3]).

We note that points (i), (ii), and (iv) are independent of what kind of particles we look at. They are valid also when we study the single-spin inclusive hyperon production processes. We recall that (iii) is a well-known fact for lepton-pair production, and is consistent with the data analysis by Ochs [6], the theoretical calculations by Das and Hwa [7], and the recent calculations from us [8] for meson production. How is the situation for hyperon production? We recall that in proton we have two u and one d valence quarks, and that the flavor content of Λ is uds . Hence, there are the following three possibilities for direct formation for Λ production: (a) a $(u_v d_v)$ -valence diquark from the projectile P picks up a s_s -sea quark associated with the target T and forms a Λ : $(u_v d_v)^P + s_s^T \rightarrow \Lambda$; (b) a u_v -valence quark from the projectile P picks up a $(d_s s_s)$ -sea diquark associated with the target T and forms a Λ , $u_v^P + (d_s s_s)^T \rightarrow \Lambda$; (c) a d_v -valence quark from the projectile P picks up a $(u_s s_s)$ -sea diquark associated with the target T and forms a Λ : $d_v^P + (u_s s_s)^T \rightarrow \Lambda$.

We first consider their contributions to Λ production in unpolarized reaction $p(0) + p(0) \rightarrow \Lambda + X$ and compare them with data [9]. (Here, as well as in the following, we use the same notations as we used in [4,5]: The first particle on the left-hand side of a reaction denotes the projectile, the second is the target, (0) means unpolarized, and (\uparrow) means transversely polarized.) Just as for the meson [4,5], the number density for the Λ produced through these three direct formation processes can be expressed as

$$D_a(x_F, \Lambda|s) = \kappa_\Lambda^d f_D(x^P | u_v d_v) s_s(x^T), \quad (1)$$

$$D_b(x_F, \Lambda|s) = \kappa_\Lambda u_v(x^P) f_D(x^T | d_s s_s), \quad (2)$$

$$D_c(x_F, \Lambda|s) = \kappa_\Lambda d_v(x^P) f_D(x^T | u_s s_s), \quad (3)$$

respectively. Here $x^P \approx x_F$ and $x^T \approx m_\Lambda^2/(s x_F)$, followed from energy-momentum conservation in the direct formation processes. $q_i(x)$ is the quark distribution function, where q denotes the flavor of the quark and the subscript i denotes whether it is for valence or sea quarks. $f_D(x|q_i q_j)$ is the diquark distribution functions, where $q_i q_j$ denotes the flavor and whether they are valence or sea quarks. κ_Λ^d and κ_Λ are two constants. The number density for Λ produced in an unpolarized reaction $p(0) + p(0) \rightarrow \Lambda + X$ is given by

$$N(x_F, \Lambda|s) = N_0(x_F, \Lambda|s) + D(x_F, \Lambda|s), \quad (4)$$

where $D(x_F, \Lambda|s) = \sum_{i=a,b,c} D_i(x_F, \Lambda|s)$ is the total contribution from direct formation processes; and $N_0(x_F, \Lambda|s)$ is the contribution from the processes other than direct formation. Using the parametrizations of the quark and diquark distribution given in the literature [10,11] we calculated $D(x_F, \Lambda|s)$. The two constants κ_Λ and κ_Λ^d are fixed by fit-

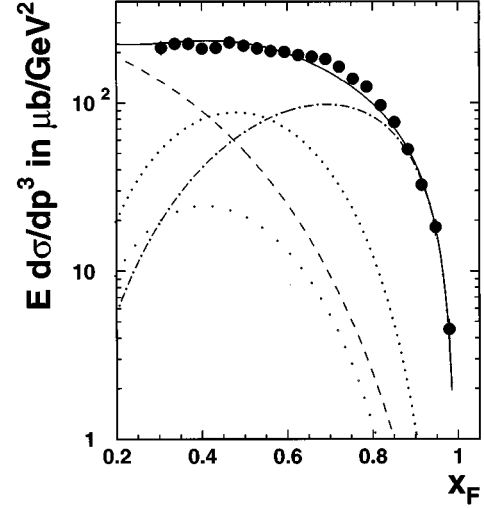


FIG. 1. The differential cross section $E d\sigma/dp^3$ for $p(0) + p(0) \rightarrow \Lambda + X$ as a function of x_F at $p_\perp = 0.65$ GeV/c and ISR energies as a sum of different contributions. The dash-dotted and the two dotted lines represent the contributions from the direct formation processes (a), (b), and (c) given in the text, respectively. The dashed line represents the non-direct-formation part, which is parametrized as $300(1-x_F)^2 e^{-3x_F}$. The solid line is the sum of all contributions. The data is taken from Ref. [9].

ting two data points in the large x_F region. The results are compared with the data [9] in Fig. 1. It is interesting to see that the data can indeed be fitted very well in the fragmentation region. In fact, the characteristic feature of the data [9], compared with those for pions [12], is that it is much broader than the latter, and this is just a direct consequence of the contribution from the valence diquarks through process (a) given above. We see also that the whole $0 < x_F < 1$ region can be divided into three parts: In the large x_F region (say, $x_F \geq 0.6$), direct process (a) plays the dominating role; and for small x_F values ($x_F \leq 0.3$, say), the non-direct-formation part $N_0(x_F, \Lambda|s)$ dominates, while in the middle (that is, in the neighborhood of $x_F \sim 0.4-0.5$), direct formation processes (b) and (c) provide the largest contributions.

Having seen that the unpolarized data [9] in the fragmentation region can indeed be described using the direct formation mechanism, we continue to discuss the left-right asymmetry in the corresponding processes with transversely polarized proton projectile. We note that according to points (i), (ii), and (iv), Λ produced through the direct formation process (b) should have large probabilities to go left and thus give positive contributions to A_N , while those from (c) contribute negatively to it. For the direct formation process (a) we note the following: This direct formation process (a) should be predominately associated with the production of a meson directly formed through fusion of the u valence quark of the projectile with a suitable anti-sea quark of the target. It follows from points (i), (ii), and (iv) (see also [4,5]) that this meson should have a large probability to obtain an extra transverse momentum to the left. Thus, according to momentum conservation, the Λ produced through (a) should have a large probability to obtain an extra transverse momentum to the right. This implies that (a) contributes negatively to A_N , opposite to that of the associatively produced meson

(π^+ or K^+ or other). As we have mentioned above, (a) plays the dominating role in the large x_F ($x_F \gtrsim 0.6$) region. We therefore expect that $A_N(x_F, \Lambda|s)$ is large in magnitude and negative in sign, and behaves in a similar way as $-A_N(x_F, \pi^+|s)$ does in this region. In the region $x_F \lesssim 0.5$, we have the interplay between the non-direct-formation part $N_0(x_F, \Lambda|s)$ and the contributions from the direct formation processes (b) and (c). The situation is very much similar to that for π^0 production. We expect therefore that, for $x_F \lesssim 0.5$, $A_N(x_F, \Lambda|s)$ is positive in sign, smaller than $A_N(x_F, \pi^+|s)$, and has the similar behavior as $A_N(x_F, \pi^0|s)$. It should change its sign somewhere and rises up later than $-A_N(x_F, \pi^+|s)$ does. All these qualitative features are consistent with the characteristics of the data [2] from the E704 Collaboration.

Encouraged by these good agreements between the qualitative results and the characteristics of the data, we now calculate $A_N(x_F, \Lambda|s)$ quantitatively. We recall that left-right asymmetry is defined as

$$A_N(x_F, \Lambda|s) \equiv \frac{N(x_F, \Lambda|s, \uparrow) - N(x_F, \Lambda|s, \downarrow)}{N(x_F, \Lambda|s, \uparrow) + N(x_F, \Lambda|s, \downarrow)}, \quad (5)$$

where

$$N(x_F, \Lambda|s, i) \equiv \frac{1}{\sigma_{\text{in}}} \int_R d^2 p_{\perp} \frac{d\sigma}{dx_F dp_{\perp}^2}(x_F, \vec{p}_{\perp}, \Lambda|s, i) \quad (6)$$

(with $i = \uparrow$ or \downarrow) is the normalized number density of the observed Λ in a given kinematical region R when the projectile is upward (\uparrow) or downward (\downarrow) polarized. σ_{in} is the total inelastic cross section. $x_F \equiv 2p_{\parallel}/\sqrt{s}$, p_{\parallel} and p_{\perp} are the longitudinal and transverse components of the momentum of the Λ . According to the proposed picture, $\Delta N(x_F, \Lambda|s) \equiv N(x_F, \Lambda|s, \uparrow) - N(x_F, \Lambda|s, \downarrow)$ comes predominately from the direct formation part of the Λ 's and is proportional to $\Delta D(x_F, \Lambda|s) \equiv D(x_F, \Lambda|s, +) - D(x_F, \Lambda|s, -)$ for cases (b) and (c). Here, $D(x_F, \Lambda|s, \pm)$ denotes the number density of

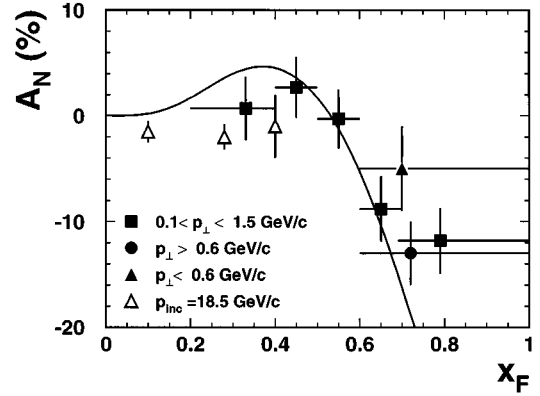


FIG. 2. Left-right asymmetry A_N for $p(\uparrow) + p(0) \rightarrow \Lambda + X$ at 200 GeV/c. The data are from Ref. [2] and the low energy data are from Ref. [13].

the Λ 's formed through direct fusion or combination of valence quarks [u_v in case (b) and d_v in case (c)] polarized in the same (+) or opposite (-) direction as the projectile with suitable sea diquarks associated with the target. The contribution from (a) is opposite in sign to that of the associatively produced meson and is proportional to $-r(x|u_v, \text{tr}) \equiv -\Delta u_v(x|\text{tr})/u_v(x)$, where x is the fractional momentum of the u_v valence quark. We have, therefore,

$$\Delta N(x_F, \Lambda|s) = C[-r(x|u_v, \text{tr})D_a(x_F, \Lambda|s) + \Delta D_b(x_F, \Lambda|s) + \Delta D_c(x_F, \Lambda|s)]. \quad (7)$$

The expressions for $D_{b,c}(x_F, \Lambda|s, \pm)$ are similar to those for $D_{b,c}(x_F, \Lambda|s)$ which are given by Eqs. (2) and (3) with $u_v(x^P)$ and $d_v(x^P)$ being replaced by $u_v^\pm(x^P|\text{tr})$ and $d_v^\pm(x^P|\text{tr})$. Here, $u_v^\pm(x^P|\text{tr})$ and $d_v^\pm(x^P|\text{tr})$ are the number densities of the valence quarks polarized in the same (+) or opposite (-) direction as the transversely polarized proton. We obtain therefore,

$$A_N(x_F, \Lambda|s) = C \frac{-\kappa_\Lambda^d r(x|u_v, \text{tr}) f_D(x^P|u_v d_v) s_s(x^T) + \kappa_\Lambda [\Delta u_v(x^P|\text{tr}) f_D(x^T|d_s s_s) + \Delta d_v(x^P|\text{tr}) f_D(x^T|u_s s_s)]}{N(x_F, \Lambda|s)}, \quad (8)$$

where $\Delta q_v(x|\text{tr}) \equiv q_v^+(x|\text{tr}) - q_v^-(x|\text{tr})$. For a rough estimation of $A_N(x_F, \Lambda|s)$, we use the ansatz for $q_v^\pm(x|\text{tr})$ used in [4,5], which is the simplest one that satisfies the condition mentioned in point (ii). In this case $r(x|u_v, \text{tr}) = 2/3$ is a constant. The results of this calculation are compared with the data [2] in Fig. 2. We see that all the qualitative features of the data [2] are well reproduced.

Similar analysis can be made for other hyperons in a straightforward way. For example, for Σ^+ , which has a flavor content uus , we have following two possibilities for direct formation: $(u_v u_v)^P + s_s^T \rightarrow \Sigma^+$ and $u_v^P + (u_s s_s)^T \rightarrow \Sigma^+$. The first process contributes to A_N opposite to that

from the associatively produced meson through fusion of d_v with a suitable anti-sea quark, and is thus opposite to $A_N(x_F, \pi^-|s)$ or similar to $A_N(x_F, \pi^+|s)$. The contribution from the second one is determined by the u_v valence quark and is also similar to $A_N(x_F, \pi^+|s)$. We therefore expect that $A_N(x_F, \Sigma^+|s)$ has the similar behavior as $A_N(x_F, \pi^+|s)$ in the whole x_F region $0 < x_F < 1$. For Σ^- , whose flavor content is dds , we have only one possibility for direction formation, i.e., $d_v^P + (ds)_s^T \rightarrow \Sigma^-$. We expect therefore $A_N(x_F, \Sigma^-|s)$ to have the same behavior as $A_N(x_F, \pi^-|s)$. Although Σ^0 has the same flavor content as Λ , there is the following difference: While the ud -valence diquark in Λ is in the state with

TABLE I. Sign for the left-right asymmetry A_N for hyperon production in $p(\uparrow)+p(0)\rightarrow$ hyperon + X in the large x_F region.

Hyperons	Λ	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
$A_N(x_F \gtrsim 0.6)$	-	+	+	-	+	-

the sum of their total angular momenta $j_{ud}=0$, the ud -valence diquark in Σ^0 is in a $j_{ud}=1$ state. We note that the proton wave function [5] can be written in the following way [14]:

$$|p(\uparrow)\rangle = \frac{1}{2\sqrt{3}} \left\{ 3u(\uparrow) \frac{1}{\sqrt{2}} [u(\uparrow)d(\downarrow) - u(\downarrow)d(\uparrow)] \right. \\ \left. + u(\uparrow) \frac{1}{\sqrt{2}} [u(\uparrow)d(\downarrow) + u(\downarrow)d(\uparrow)] \right. \\ \left. - \sqrt{2}u(\downarrow)u(\uparrow)d(\uparrow) \right\}, \quad (9)$$

where (\uparrow) and (\downarrow) denote that the z component of the total angular momentum of the corresponding valence quark is either $j_z = +1/2$ or $j_z = -1/2$, respectively. We see clearly that, if the ud diquark is in a $j_{ud}=1$ -state, the other u -valence quark is either polarized upward or downward, with relative probabilities 1:2. So if Σ^0 is produced through the same kind of direct formation process as shown in (a), the associatively produced meson should have a large probability to go right. Hence, we expect that $A_N(x_F, \Sigma^0|s)$ behaves differently from $A_N(x_F, \Lambda|s)$ does in the large x_F region ($x_F \gtrsim 0.6$, say). In contrast to $A_N(x_F, \Lambda|s)$, $A_N(x_F, \Sigma^0|s)$ is positive in sign in this region. But, they have the similar behavior in the $x_F \lesssim 0.5$ region. This implies also that there is no change of sign in $A_N(x_F, \Sigma^0|s)$ as a function

of x_F . Similarly, we expect that $A_N(x_F, \Xi^0|s)$ behaves similar to $A_N(x_F, \pi^+|s)$; while $A_N(x_F, \Xi^-|s)$ likes $A_N(x_F, \pi^-|s)$. In Table [I] we summarize the sign of these A_N 's in the large x_F region for different hyperons.

It should be emphasized that, although the left-right asymmetries are in general different for different hyperons, they have the following in common: All of them are significant mainly in the fragmentation region of the polarized colliding object, and are approximately independent of the unpolarized one. No asymmetry is expected for hyperons in the fragmentation region of the unpolarized colliding object. All these can be tested by future experiments. It is also interesting to see that the polarization of hyperons observed [15] in reactions with unpolarized projectile and unpolarized target are also significant mainly for sufficiently large p_\perp and/or in the fragmentation region. It can be imagined that such hyperon polarizations and the left-right asymmetries in single-spin processes are closely related to each other. Such a study is under way, the results will be published elsewhere [16].

In summary, we have shown that the striking left-right asymmetry for inclusive Λ production in single-spin hadron-hadron collisions [4] is a direct consequence of the existence of orbiting valence quarks in polarized nucleons. Direct formation of particles through fusions of valence quarks (diquarks) with suitable sea antiquarks (sea quarks) plays a significant role not only for the production of mesons but also for hyperons with moderately large p_\perp in the fragmentation region. This implies that left-right asymmetry exists not only for Λ but also for other hyperons in single-spin inclusive production processes. Measurements of such asymmetries provide extremely useful information not only for the spin structure of nucleon but also for the production mechanisms of hyperons.

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small, the momentum and the corresponding left-right asymmetry of Σ^0 will be mainly transferred to Λ . The results remain approximately the same, as if the Λ were directly formed.

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