Production mechanisms and single-spin asymmetry for kaons in high energy hadron-hadron collisions

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Abstract

Direct consequences on kaon production of the picture proposed in a recent Letter and subsequent publications are discussed. Further evidence supporting the proposed picture is obtained. Comparison with the data for the inclusive cross sections in unpolarized reactions is made. Quantitative results for the left-right asymmetry in single-spin processes are presented.
Single-spin asymmetry ($A_N$) study has recently received much attentions, both experimentally [1-7] and theoretically [8]. Striking experimental results have been obtained by FNAL E704 Collaboration [3-7] at high energy (200 GeV/c) for mesons as well as for Lambda hyperon. Large left-right asymmetries have been observed in the fragmentation region of the polarized beam particles. The data shows that the asymmetry is not only different for reactions using different polarized beams but also different for the production of different kinds of hadrons.

In a recent Letter [10] and the subsequent publications [9-13], we suggested that these observed asymmetries are due to the orbital motion of the valence quarks of the polarized projectiles. Theoretical arguments and experimental indications supporting the proposed picture have been given; and the characteristic features of the proposed picture have been discussed. It has been pointed out in particular that measurements of such single-spin asymmetries are not only extremely useful in studying the spin structure of the nucleon but also very helpful in studying the production mechanisms of hadrons in high energy hadron-hadron collisions. It has been shown, in this connection, that only part of the observed hadrons are direct formation (fusion) products of orbiting valence quarks of the projectile and anti-sea-quarks associated with the target. The observed left-right asymmetry in particular its $x_F$-dependence reflects the interplay between the contribution of the direct formation mechanism and the non-direct-formation part. (Here, $x_F \equiv 2p_\|/\sqrt{s}$, $p_\|$ is the longitudinal momentum of the produced hadron, and $s$ is the center of mass energy squared for the colliding hadron system.) Single-spin asymmetry measurements can in particular differentiate these two kinds of contributions since only the former depends on the polarization of the projectile. Direct consequences of such a picture for the production of pions and $\Lambda$ have been studied in detail in single-spin, as well as in unpolarized, hadron-hadron collision processes. Good agreements between experiments [2-7] and theory [9-13] have been found. It is then natural to ask: What do we expect to see for the production of other kinds of mesons such as kaons? How are they compared with experiments? A qualitative
discussion on the left-right asymmetry for $K$ production has already been made in [12]. The purpose of this brief report is to present the detailed study of the direct consequences of this picture on the production of kaons and anti-kaons in unpolarized reactions and to present the quantitative calculations for the left-right asymmetry in single-spin processes. This is of particular interest for the following reasons: First, preliminary data for the left-right asymmetry for $K_s^0$ is now available from FNAL E704 Collaboration [7]. They are consistent with our qualitative predictions in [12]. Second, for kaons, direct fusion of the valence quarks of the proton-projectile with suitable anti-sea-quarks of the targets does not contribute to the production of $K^-$ and $\bar{K}^0$. This means, for such kaons, we have only the contributions from the non-direct-formation parts. Hence, the non-direct-formation part for kaon production can be determined unambiguously even in experiments using unpolarized projectiles and unpolarized targets. Comparison of the results obtained from the proposed picture with the data from both unpolarized and polarized experiments provides further quantitative tests of the picture.

We begin our discussions by recollecting some of the formulae which are particularly useful here. We recall that the left-right asymmetry $A_N(x_F, h|s)$ for hadron production in single-spin process $p(\uparrow) + p(0) \rightarrow h + X$ is defined [1-7] as the ratio of the difference and the sum of $N(x_F, h|s, \uparrow)$ and $N(x_F, h|s, \downarrow)$. Here, $h$ stands for a hadron which can be a pion, a kaon or a hyperon; and $N(x_F, h|s, \uparrow)$ is the number-density of $h$ observed in a given kinematic region $R$ (for example, with transverse momentum $p_\perp \geq 0.7\text{GeV}/c$ and in a given acceptance solid angle on the left-hand-side looking down stream in the above-mentioned experiments [2-7]) in $p(\uparrow) + p(0) \rightarrow h + X$ at total c.m.s.-energy $\sqrt{s}$ using upwards transversely polarized proton projectile $p(\uparrow)$ and unpolarized proton target $p(0)$. $N(x_F, h|s, \downarrow)$ is the corresponding density function for such hadrons observed in $p(\downarrow) + p(0) \rightarrow h + X$. We consider now the cases where $h = M$ is a meson $M$ and denote by $D(x_F, M, +|s, \uparrow)$ the number-density for those mesons $M$ which are directly formed by the valence quarks polarized in the same direction as the transversely polarized projectile proton, and $D(x_F, M, -|s, \uparrow)$ the corresponding number.
density for mesons formed by the valence quarks polarized in the opposite direction as the projectile proton. We recall that these $D$’s can be expressed [10] as the following integrals,

$$D(x_F, M, \pm | s, tr) = \sum_{q_v, \bar{q}_s} \int dx_P dx_T q_v^\pm(x_P | s, tr) \bar{q}_s(x_T | s) K(x_P, q_v; x_T, \bar{q}_s | x_F, M, s).$$

(1)

Here $q_v^\pm(x|s, tr)$ is the distribution of the valence quarks polarized in the same or in the opposite direction of the transversely polarized proton, and $\bar{q}_s(x|s)$ is the spin-averaged sea-quark distribution; $K(x_P, q_v; x_T, \bar{q}_s | x_F, M, s)$ is the probability density for a valence quark of flavor $q_v$ with fractional momentum fraction $x_P$ to combine directly with an anti-sea-quark of flavor $\bar{q}_s$ with fractional momentum $x_T$ to form a meson $M$ of fractional momentum $x_F$.

We recall also whether, if yes how much, the $K$-function depends on the dynamical details of this direct formation process is something we do not know a priori. But, what we do know is that this function has to guarantee the validity of all the relevant conservation laws. Hence, it contains, in practice, as factors a product of Kronecker delta’s and Dirac $\delta$-functions, where every one is associated with a given quantum number. This implies, in particular, that the simplest choice of the corresponding $K$-function for $K^+ = (u\bar{s})$ or $K^0 = (d\bar{s})$ production is the following:

$$K(x_P, q_v; x_T, \bar{q}_s | x_F, K^+, s) = \kappa_K \delta_{q_v, u} \delta_{\bar{q}_s, \bar{s}} \delta(x_P - x_F) \delta(x^T - x_0/x_F),$$

(2)

$$K(x_P, q_v; x_T, \bar{q}_s | x_F, K^0, s) = \kappa_K \delta_{q_v, d} \delta_{\bar{q}_s, \bar{s}} \delta(x_P - x_F) \delta(x^T - x_0/x_F).$$

(3)

where $\kappa_K$ is a constant; the two Dirac-$\delta$-functions come from the energy and momentum conservation which requires $x_P \approx x_F$ and $x^T \approx x_0/x_F$ where $x_0 = m^2/s$ ($m$ is the mass of the produced meson). We thus obtain,

$$D(x_F, K^+, \pm | s, tr) = \kappa_K u_v^\pm(x_F | s, tr) \bar{s}_s(x_0/x_F | s),$$

(4)

$$D(x_F, K^0, \pm | s, tr) = \kappa_K d_v^\pm(x_F | s, tr) \bar{s}_s(x_0/x_F | s).$$

(5)

According to the proposed picture [9,10], the difference $\Delta N(x_F, M|s, tr) \equiv N(x_F, M|s, \uparrow) - N(x_F, M|s, \downarrow)$ comes only from those mesons that are directly formed
through the fusion of the orbiting valence quarks of the polarized projectile with suitable
anti-sea-quark associated with the target, i.e., \( \Delta N(x_F, M|s, tr) = C \Delta D(x_F, M|s, tr) \). [Here
0 < C < 1 is a constant, and \( \Delta D(x_F, M|s, tr) \equiv D(x_F, M,+|s, tr) - D(x_F, M,-|s, tr) \).] The
sum of them is nothing else but two times the corresponding number density \( N(x_F, M|s) \) in
reactions using unpolarized projectiles and unpolarized targets,

\[
N(x_F, M|s) = N_0(x_F, M|s) + D(x_F, M|s),
\]

where \( D(x_F, M|s) \equiv [D(x_F, M,+|tr,s) + D(x_F, M,-|tr,s)]/2 \). We have therefore,

\[
A_N(x_F, M|s) = \frac{C \Delta D(x_F, M|s, tr)}{2[N_0(x_F, M|s) + D(x_F, M|s)]},
\]

It can easily be seen that \( N_0(x_F, M|s) \) — especially the interplay between this quantity
and the corresponding \( D(x_F, M|s) \) — plays a key role in understanding the \( x_F \)-dependence
of \( A_N(x_F, M|s) \).

The direct consequences of these equations for pion production have been discussed in
detail in [9-11] and they are in good agreement with experiments. Now let us consider \( K \)-
production and see what they tell us. First, in unpolarized collision processes \( p(0) + p(0) \rightarrow
K + X \), since there is no contribution from the direct fusion of the valence quarks of the
projectile with suitable anti-sea-quarks of the target to \( K^- = (\bar{u}s) \) and \( \bar{K}^0 = (\bar{d}s) \), we obtain
from Eq.(6) that,

\[
N(x_F, K^+|s) = N_0(x_F, K^+|s) + D(x_F, K^+|s),
\]

\[
N(x_F, K^0|s) = N_0(x_F, K^0|s) + D(x_F, K^0|s),
\]

\[
N(x_F, K^-|s) = N_0(x_F, K^-|s),
\]

\[
N(x_F, \bar{K}^0|s) = N_0(x_F, \bar{K}^0|s),
\]

where

\[
D(x_F, K^+|s) = \kappa_K u_v(x_F|s) \bar{s}_s(x_0/x_F|s)/2, \text{ and } D(x_F, K^0|s) = \kappa_K d_v(x_F|s) \bar{s}_s(x_0/x_F|s)/2. \]

\( N_0 \)
comes from the interactions of the sea (the sea quarks, the sea antiquarks and the gluons) of
the projectile with that of the target and is therefore expected to be isospin invariant and to
be the same for particle and anti-particle. This implies, in particular for $K$-production, that,
\[ N_0(x_F, K^+|s) = N_0(x_F, K^0|s) = N_0(x_F, K^-|s) = N_0(x_F, \bar{K}^0|s) \equiv N_0(x_F, K|s). \]
Hence, we obtain the following relations between the number densities (or the corresponding differential
cross sections) for $K$ produced in $p(0) + p(0) \rightarrow K + X$:
\[ N(x_F, K^-|s) = N(x_F, K^0|s) = N_0(x_F, K|s), \tag{12} \]
\[ N(x_F, K^+|s) = N(x_F, K^-|s) + \kappa_K u_v(x_F|s)\bar{s}_s(x_0/x_F|s)/2, \tag{13} \]
\[ N(x_F, K^0|s) = N(x_F, K^-|s) + \kappa_K d_v(x_F|s)\bar{s}_s(x_0/x_F|s)/2, \tag{14} \]
Recall that $K^0_S \approx (K^0 + \bar{K}^0)/\sqrt{2}$ and $K^0_L \approx (K^0 - \bar{K}^0)/\sqrt{2}$, we have
\[ N(x_F, K^0_S|s) = N(x_F, K^0_L|s) = N(x_F, K^-|s) + \kappa_K d_v(x_F|s)\bar{s}_s(x_0/x_F|s)/4. \tag{15} \]
These are direct consequences of the proposed picture which can be tested by unpolarized
experiments. For example, Eq.(13) implies that $N(x_F, K^+|s)$ is determined completely by
$N(x_F, K^-|s)$ and the spin averaged quark distribution functions. The only parameter is the
constant $\kappa_K$ which can be determined by fitting one data point. In Fig. 1, we compare such
results with data [15,16] and we see that the agreement is indeed very good.

Next, we consider the single-spin process $p(\uparrow) + p(0) \rightarrow K + X$. It follows from
Eqs.(4),(5),(7) and (13-14) that,
\[ A_N(x_F, K^+|s) = \frac{C\kappa_K \Delta u_v(x_F|s, tr)\bar{s}_s(x_0/x_F|s)}{2N(x_F, K^-|s) + \kappa_K u_v(x_F|s)\bar{s}_s(x_0/x_F|s)}, \tag{16} \]
\[ A_N(x_F, K^0|s) = \frac{C\kappa_K \Delta d_v(x_F|s, tr)\bar{s}_s(x_0/x_F|s)}{2N(x_F, K^-|s) + \kappa_K d_v(x_F|s)\bar{s}_s(x_0/x_F|s)}, \tag{17} \]
and $A_N(x_F, K^-|s) = A_N(x_F, \bar{K}^0|s) = 0$. These are the same results as those in [12] [see
Eqs. (22) and (23) there] with $N_0(x_F, K|s)$ replaced by $N(x_F, K^-|s)$. From them, we
expected that $A_N(x_F, K^+|s)$ is similar to $A_N(x_F, \pi^+|s)$, and that $A_N(x_F, K^0|s)$ is similar to $A_N(x_F, \pi^-|s)$. Since both the $K^0_S$ and $K^0_L$ are linear combinations of $K^0$ and $\bar{K}^0$, the left-right asymmetry is the same for them, and it is given by

$$A_N(x_F, K^0_S|s) = \frac{C \kappa_K \Delta d_v(x_F|s, tr) s_s(x_0/x_F|s)}{4N(x_F, K^-|s) + \kappa_K d_v(x_F|s) s_s(x_0/x_F|s)},$$

(18)

Hence $A_N(x_F, K^0_S|s)$ should have the same sign as $A_N(x_F, \pi^-|s)$. This is confirmed by the preliminary data of E704 Collaboration [7]. Now we can use the parameterization of $N(x_F, K^-|s)$ and those for the quark distribution functions to calculate these $A_N$ quantitatively. The results are given in Fig.2.

In this connection, it may be particularly interesting to note the following. If we use, instead of transversely polarized proton beam, transversely polarized anti-proton beam, we have,

$$A_{\bar{N}}^{\bar{p}(\uparrow)p}(x_F, K^-|s) = \frac{C \kappa_K \Delta \bar{u}^p(x_F|s, tr) s_s(x_0/x_F|s)}{2N(x_F, K^-|s) + \kappa_K \bar{u}^p(x_F|s) s_s(x_0/x_F|s)},$$

(19)

$$A_{\bar{N}}^{\bar{p}(\uparrow)p}(x_F, K^0_S|s) = \frac{C \kappa_K \Delta \bar{d}^p(x_F|s, tr) s_s(x_0/x_F|s)}{4N(x_F, K^-|s) + \kappa_K \bar{d}^p(x_F|s) s_s(x_0/x_F|s)},$$

(20)

and $A_{\bar{N}}^{\bar{p}(\uparrow)p}(x_F, K^+|s) = 0$. Using $\Delta \bar{q}^p(x|s, tr) = \Delta q_v(x|s, tr)$ and $\bar{q}^p(x|s) = q_v(x|s)$, we obtain that

$$A_{\bar{N}}^{\bar{p}(\uparrow)p}(x_F, K^-|s) = A_N(x_F, K^+|s),$$

(21)

$$A_{\bar{N}}^{\bar{p}(\uparrow)p}(x_F, K^0_S|s) = A_N(x_F, K^0_S|s).$$

(22)

Eq.(21) is the same as what we obtained in [12]. Eq.(22) is a direct consequence of what we had in [12] for $K^0$ and $\bar{K}^0$. The latter is also confirmed by the preliminary data of E704 Collaboration [7].

In summary, direct consequence on $K$ production of the picture proposed in a recent Letter [10] and subsequent publications [9-13] are discussed. Further evidences supporting the proposed picture are obtained in unpolarized, as well as in single-spin, processes.
Quantitative predictions have been made for the left-right asymmetry for kaon production in single spin proton-proton or anti-proton-proton collision processes. The results are in agreement with the preliminary data of FNAL E704 Collaboration [7] and can be further tested by experiments in the future.

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Figure captions

Fig. 1. Inclusive invariant cross section $Ed^3\sigma/d^3p$ for $p(0) + p(0) \rightarrow K^+ + X$ as a function of $x_F$ at $p_\perp = 0.75$ GeV/c and the ISR energies is shown as the sum of the following two parts: (1) the isospin-independent non-direct-formation part which is taken as the same as $Ed^3\sigma/d^3p$ for $p(0) + p(0) \rightarrow K^- + X$ [parameterized as $N(1 - x_F)^3 exp(-10x_F^3)$, shown by the dashed curve], (2) the corresponding flavor-dependent direct formation part $\kappa_K u_v(x_F)\bar{s}_s(x_0/x_F)x_F/2$ (shown by the dashed-dotted curve). Data are taken from [15] and [16]. Those at larger $x_F$ are from [15] and they are for $p_\perp = 0.75$ GeV/c. Those at lower $x_F$ are from [16] and they are for $p_\perp = 0.8$ GeV/c.

Fig. 2. Left-right asymmetry $A_N$ for $p(\uparrow)+p(0) \rightarrow K^+ + X$ and that for $p(\uparrow)+p(0) \rightarrow K^0_S + X$ as functions of $x_F$ at 200 GeV/c. The data points are the preliminary results from FNAL E704 Collaboration[7].
\[ p(\uparrow) + p(0) \rightarrow K^+ + X \]
$p+p \rightarrow K + X$

$E \frac{d\sigma}{dp^3}$ (mb/GeV$^2$)

$X_F$

$K^+$

$K^-$