Quark Spin Distribution and Quark-Antiquark Annihilation in Single-Spin Hadron-Hadron Collisions

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We show that quark-antiquark annihilation processes in single-spin inclusive production experiments can yield useful information on hadron spin structure in general, and provide crucial tests for the existence of orbiting valence quarks in particular. There are several experimental indications and theoretical arguments for the existence of such orbital motion inside polarized protons or antiprotons. Simple relations between quark-spin distributions and left-right asymmetries in such production processes can be given, and quantitative predictions can be made.

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It has been pointed out some time ago that the left-right asymmetry observed in single-spin elastic proton-proton scattering experiments [1] can be understood in terms of a semiclassical model [2]. The model is based on Chou and Yang's geometrical picture [3] in which the constituents of a polarized hadron are assumed to perform orbital motion about the polarization axis. Prompted by the recent striking results obtained in high-energy single-spin inclusive meson production experiments [4], it seems natural to ask whether the left-right asymmetry observed in these experiments [4] can also be attributed to the existence of orbiting constituents inside polarized hadrons.

The purpose of this paper is to show that this question should be answered in the affirmative: Such asymmetries are expected to exist when annihilation of orbiting valence quarks takes place. This means in particular that, in single-spin hadron-hadron experiments using polarized proton or antiproton beams, not only mesons but also lepton pairs should show left-right asymmetry. The arguments are the following.

(i) Valence quarks as relativistic Dirac particles in an effective confining potential (caused by the presence of other constituents of the hadron) always generate color and flavor currents in a polarized hadron. Only the total, but not the orbital angular momentum, can be used to characterize the states of such quarks, because the latter is not a good quantum number. This implies in particular that *orbital motion is always involved—also when such particles are in their ground states* [3,5]. The effective orbital motion is counterclockwise to the polarization axis.

(ii) Relativistic baryon wave functions consistent with (i) can be obtained by replacing, in the static quark model [6], the Pauli spinors of the valence quark of a given flavor f and spin projection m ($\equiv s_x$, say) by the ground state wave functions $\psi_{\epsilon jmP}(\mathbf{r}|f)$ for $\epsilon=\epsilon_0$, $j=\frac{1}{2}$, $m\equiv j_x=\pm\frac{1}{2}$, and $P=+$. (Here j is the total angular momentum and P is the parity.) Using these wave functions, the magnetic moment of the proton and those of the other baryons can be readily calculated [5,7]. Expressed in terms of the magnetic moments μ_q ($q=u,d,s$) of the valence quarks, baryons' magnetic moments (μ_B's) obtained in such a relativistic model have *exactly the same form* as those in the static model, and this form is independent of the confining potential. Since μ_q for $q=u$, d, and s are parameters in the static quark model [6], and "the good agreement between experiment and model" merely means it gives a good fit to the data [6], the obtained result is as good (or as bad) as that in the static model. *The same proton wave function can also be used to determine the polarization of the valence quarks in a polarized proton*: Among the two u valence quarks inside a polarized proton, on the average, $\frac{5}{3}$ is polarized in the same, and $\frac{1}{3}$ in the opposite direction of the proton. For the d valence quark, the result is $\frac{1}{3}$ and $\frac{2}{3}$, respectively. Hence, *there is asymmetry in valence-quark polarization, and such asymmetry is flavor dependent.* The sea-quark pairs are not polarized. They (at least on the average) do not perform orbital motion about the polarization axis of the hadron.

(iii) Since quark-antiquark annihilation [8–10] may significantly contribute to hadronic production processes, especially in the fragmentation regions, it is expected that mesons and lepton pairs may be directly formed in these regions—also when the projectile (or the target) hadron is polarized. In the case of transverse polarization, the linear momentum of an orbiting valence quark may have a nonzero component perpendicular to the beam direction (which we hereafter call the z axis) and perpendicular to the polarization axis (which we call the x axis). Hence *the meson or the lepton pair directly formed by the annihilation of such an orbiting valence quark is expected to have a nonzero component along the y axis.*

(iv) Consistent with the fact that hadrons are spatially extended objects within the range of which the constituents (quarks and gluons) interact with one another through color forces—and only color singlet can leave color fields—a significant "surface effect" is assumed to exist in such production processes. It implies in particular that, when one of the colliding hadrons is transversely polarized (up or down), *only color-singlet $q\bar{q}$ systems* *directly formed near the front surface can acquire extra momenta due to the orbital motion of the valence quarks.* This is because *only such valence quarks do not have enough time to become randomly distributed before they meet a suitable antiquark.* As a consequence, they either go left or go right, depending on the (transverse) polarization of their parent valence quarks.

We note that the essence of (i.e., the fundamental hypotheses contained in) (i), (ii), and (iii) is the following: The valence quarks in a hadron are confined; they are spin $\frac{1}{2}$ objects with (compared to the hadron) relatively small masses. The baryon wave functions are completely antisymmetric in color and thus (according to Pauli's principle) symmetric in flavor, spin, and space. Annihilation of valence quarks can take place when they encounter suitable (sea or valence) antiquarks, and such annihilation may significantly contribute to production processes in the fragmentation regions. We also note that these hypotheses are in excellent agreement with (well-known) experimental facts [11], and that they have already been discussed and developed by many authors [12]. In this paper, we combine these hypotheses with an additional assumption stated in (iv), and formulate a simple calculable model to demonstrate that a picture based on these hypotheses not only describes the observed asymmetry in inclusive meson production, but also predicts a significant asymmetry in lepton-pair production.

A number of direct consequences can be readily deduced from the proposed picture, and they can be tested experimentally: (A) In the projectile-fragmentation region of inclusive meson production processes $p(\uparrow)+p(0)\rightarrow\pi^+(\pi^-,\pi^0$ or $\eta)+X$ in which the valence quarks of the upwards polarized projectile proton contribute, the produced π^+,π^0 *and* η *go left,* while π^- *go right.* (B) By using transversely polarized *antiproton* instead of proton beams, one should see that while π^0 *and* η *behave in the same way as that in the proton-beam case,* π^+ *and* π^- *behave differently.* (Their roles interchange.) (C) In the corresponding production processes using *pseudoscalar meson* beams—irrespective of what kind of target is used and whether the target is polarized—there should be *no left-right asymmetry in the projectile-fragmentation region.* (D) The asymmetry of the produced mesons is expected to be *more significant for large* x_F in the fragmentation region of the transversely polarized projectile. (E) Not only mesons but also lepton pairs in such experiments are expected to exhibit left-right asymmetry.

Encouraged by the good agreement between the experimental findings [4] and the qualitative features mentioned in A–D (the associations B and C have been predicted [5] before the corresponding data were known), an attempt has been made to describe the data *quantitatively.* The results are summarized here: We first consider $p(\uparrow)+p(0)\rightarrow(q\bar{q})+X$ at a given c.m.-system energy $\sqrt{s}$, where $(q\bar{q})$ stands for a color-singlet quark-antiquark system which appears either as a meson or as a lepton pair of invariant mass Q. We recall that the left-right asymmetry $A_N\equiv A_N(x_F,Q|s)$ at x_F is defined as [4]

$$A_N=\frac{N(x_F,Q|s,\uparrow)-N(x_F,Q|s,\downarrow)}{N(x_F,Q|s,\uparrow)+N(x_F,Q|s,\downarrow)}\,, \tag{1}$$

where $N(x_F,Q|s,i)$, $(i=\uparrow,\downarrow)$ is the normalized number density of the $q\bar{q}$ system observed in a given kinematical region D (an acceptance solid angle on the left-hand side looking downstream). It is the integral of the single-particle inclusive cross section, $d\sigma/dx_Fd\mathbf{p}_\perp(x_F,\mathbf{p}_\perp;Q|s,i)$ in this reaction with upwards/downwards polarized proton beams integrated over $\mathbf{p}_\perp$ in D divided by the total inelastic cross section $\sigma_{\text{in}}(s)$.

The denominator on the right-hand side of Eq. (1) is nothing else but $2N(x_F,Q|s)$, 2 times the spin-averaged number density of the $q\bar{q}$ system with invariant mass Q observed at x_F in the corresponding reaction with *unpolarized* beams. The numerator ΔN is proportional to $D(x_F,Q,+|s,\text{tr})-D(x_F,Q,-|s,\text{tr})$ (hereafter denoted by ΔD) where $D(x_F,Q,\pm|s,\text{tr})$ is the number density for the $q\bar{q}$ systems formed by annihilations of the valence quarks of the projectile and sea antiquarks of the target, where the polarization of the former is parallel/antiparallel to that of the transversely polarized projectile proton. That is,

$$D(x_F,Q,\pm|s,\text{tr})=\sum_{q_v,\bar{q}_s}\int dx^P dx^T q_v^{\pm}(x^P|s,\text{tr})\bar{q}_s(x^T|s)\times K(x^P,q_v;x^T,\bar{q}_s|x_F,Q,s)\,, \tag{2}$$

where $q_v^{\pm}(x|s,\text{tr})$ is the distribution of the valence quarks polarized in the same/opposite direction of the transversely polarized proton, and $\bar{q}_s(x|s)$ is the spin-averaged sea-quark distribution. Note that the quark polarization indicated by $\pm$ in $q_v^{\pm}$ refers to the projection of the total angular momentum $j_x=\pm\frac{1}{2}$ instead of that of the spin $s_x=\pm\frac{1}{2}$ (which is the case in the quark-parton model [13] where the interaction and the transverse motion are completely neglected). But, in the large x region, where the magnitude of the longitudinal momentum is much larger than that of its counterparts in the transverse directions, the influence on the longitudinal momentum distributions caused by the above-mentioned difference can be neglected. Hence, except for small x values, the usual spin-dependent valence-quark distributions $u_v^{\pm}(x;Q^2|\text{tr}),d_v^{\pm}(x;Q^2|\text{tr})$ obtained from deep inelastic scattering data (where Q^2 simulates the s dependence) are expected to be useful approximations for $q_v^{\pm}(x|s,\text{tr})$. It follows from point (ii) that for the protons the integrals over x of $u_v^{\pm}(x|s,\text{tr})$ and $d_v^{\pm}(x|s,\text{tr})$ between 0 and 1 should be $\frac{5}{3}$, $\frac{1}{3}$, $\frac{1}{3}$, and $\frac{2}{3}$, respectively. This implies that the corresponding integrals of their differences $\Delta u_v(x|s,\text{tr})$ and $\Delta d_v(x|s,\text{tr})$ should be $\frac{4}{3}$ and $-\frac{1}{3}$, respectively. The function K in Eq. (2) is the probability density for such a valence quark and a suitable sea antiquark to annihilate each other and form the observed $q\bar{q}$ system. It is this function which guarantees the validity of all the relevant conservation laws. In practice, it contains as factors a product of Kronecker deltas and Dirac δ functions, where every one is associated with a given quantum number. In this connection we first consider the case in which $q\bar{q}$ appears as a lepton pair $l\bar{l}$—the well-known Drell-Yan process [8]. In this case, we have

$$A_N^{l\bar{l}}(x_F,Q|s)=\frac{C\sum_q e_q^2\Delta q_v(x^P,Q^2|\mathrm{tr})\bar{q}_s(x^T,Q^2)}{\sum_q e_q^2\{[q_v(x^P,Q^2)+q_s(x^P,Q^2)]\bar{q}_s(x^T,Q^2)+(P\leftrightarrow T)\}}, \tag{3}$$

where $x^{P,T}\equiv[\pm x_F+(x_F^2+4Q^2/s)^{1/2}]/2$. C is the proportionality constant between ΔN and ΔD. Because of the "surface effect" and the fluctuations of the transverse momenta of the quarks, C—the only unknown constant—is expected to have a value between 0 and 1.

In the case in which the $q\bar{q}$ system is a pion, it is useful to note the empirical facts pointed out by Ochs [9] and the theoretical calculations performed by Hwa and coworkers [10] for reactions with unpolarized projectiles and targets. Here, we take into account the similarities and the differences between lepton-pair and meson production processes on the one hand, and those between the unpolarized and polarized protons on the other. This implies in particular that energy and momentum conservation requires $x^P\approx x_F$ and $x^T\approx x_0/x_F$ where $x_0=m^2/s$ (m is the pion mass), and that the simplest choice of the corresponding K function contains, besides the two δ functions which relate x^P and x^T to x_F and x_0, only the following Kronecker deltas: $\kappa_\pi\delta_{q_v,u}\delta_{\bar{q}_s,\bar{d}}$, $\kappa_\pi\delta_{q_v,d}\delta_{\bar{q}_s,\bar{u}}$, or $\frac{1}{2}\kappa_\pi(\delta_{q_v,u}\delta_{\bar{q}_s,\bar{u}}+\delta_{q_v,d}\delta_{\bar{q}_s,\bar{d}})$, respectively, where κ_π is a constant which can, e.g., be determined by comparing the cross sections for reactions without polarization. Hence,

$$A_N^{\pi^+}=C\kappa_\pi\bar{q}_s(x^T,Q^2)\frac{\Delta u_v(x^P,Q^2|\mathrm{tr})}{2N(x_F,\pi^+|s)}, \tag{4a}$$

$$A_N^{\pi^-}=C\kappa_\pi\bar{q}_s(x^T,Q^2)\frac{\Delta d_v(x^P,Q^2|\mathrm{tr})}{2N(x_F,\pi^-|s)}, \tag{4b}$$

$$A_N^{\pi^0}=C\kappa_\pi\bar{q}_s(x^T,Q^2)\frac{\Delta u_v(x^P,Q^2|\mathrm{tr})+\Delta d_v(x^P,Q^2|\mathrm{tr})}{2[N(x_F,\pi^+|s)+N(x_F,\pi^-|s)]}. \tag{4c}$$

Here, $A_N^{\pi^{+,-,0}}$ stands for $A_N^{\pi}(x_F,\pi^{+,-,0}|s)$, respectively; $\Delta u_v(x^P,Q^2|\mathrm{tr})$ and $\Delta d_v(x^P,Q^2|\mathrm{tr})$ are the differences of the quark distribution functions of the transversely polarized u and d valence quarks, $\bar{q}_s(x^T,Q^2)$ stands for $\bar{d}_s(x^T,Q^2)=\bar{u}_s(x^T,Q^2)$ is the distribution of the sea quarks. Note that a considerable part of $N(x_F,\pi^\pm|s)$ is due to gluons and/or sea-quark pairs which are independent of the polarization of the proton, and such contributions cancel out in the numerator on the right-hand side of Eq. (1). It follows from Eqs. (4a)-(4c),

$$\frac{\Delta d_v}{\Delta u_v}=-\frac{A_N^{\pi^-}}{A_N^{\pi^+}}\frac{A_N^{\pi^0}-A_N^{\pi^+}}{A_N^{\pi^0}-A_N^{\pi^-}}, \tag{5}$$

which implies that $\Delta d_c/\Delta u_v\equiv\Delta d_v(x,Q^2|\mathrm{tr})/\Delta u_v(x,Q^2|\mathrm{tr})$ can be determined directly by asymmetry measurements in single-spin inclusive π^+, π^-, and π^0 production. Furthermore, for not too small x values [cf. related discussions below Eq. (2)] where the conventional quark-parton model [13] is expected to be a useful approximation, the sum of the spin-dependent structure functions $g_1(x)$ and $g_2(x)$ is

$$g_1(x)+g_2(x)=\tfrac{2}{9}\Delta u_v(x|\mathrm{tr})+\tfrac{1}{18}\Delta d_v(x|\mathrm{tr}) \tag{6}$$

when only valence quarks contribute. Here, $\Delta u_v(x|\mathrm{tr})$ stands for $\Delta u_v(x,Q^2|\mathrm{tr})$ for large Q^2 at constant x, and similarly for $\Delta d_v(x|\mathrm{tr})$. This means, by using Eqs. (5) and (6), $\Delta u_v(x|\mathrm{tr})$ and $\Delta d_v(x|\mathrm{tr})$ can be determined if $g_1(x)+g_2(x)$ and the asymmetries $A_N^{\pi}(x|\pi^{\pm,0})$ are known and vice versa.

What can we do, before empirically determined Δu_v and Δd_v are available? Since, on the average, the probability of finding a u-valence quark with the same polarization as the polarized proton is $\frac{5}{6}$, while that of finding such a d-valence quark is $\frac{1}{3}$, the simplest possibility to satisfy these conditions is the following ansatz: $u_v^{\pm}(x,Q^2|\mathrm{tr})$ are $(\frac{5}{6},\frac{1}{6})$ of $u_v(x,Q^2)$, and $d_v^{\pm}(x,Q^2|\mathrm{tr})$ are $(\frac{1}{3},\frac{2}{3})$ of $d_v(x,Q^2)$, respectively, where $u_v(x,Q^2)$ and $d_v(x,Q^2)$ are the corresponding spin-averaged valence-

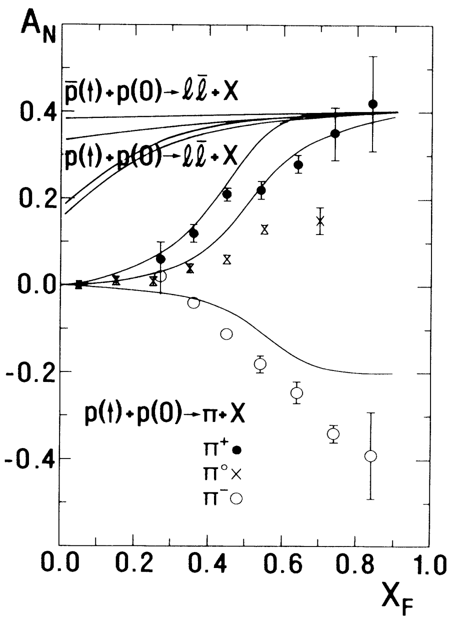

FIG. 1. Left-right asymmetry as a function of x_F. The spin-averaged quark distributions are from Ref. [15]. The data for pions are from Ref. [4]. For lepton pairs, the upper and lower curves are for $Q=9$ and 4 GeV, respectively, which is the same Q range as in Ref. [18].

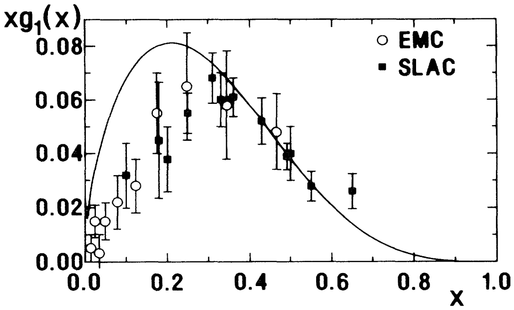

FIG. 2. The spin-dependent proton structure function $g_1(x)$. The data are from Ref. [16]. The spin-averaged quark distributions are from Ref. [15].

quark distribution functions. By inserting this ansatz into Eq. (4) and by noting that $N(x,\pi^{\pm}|s)$ and $u_v(x,Q^2)$, $d_v(x,Q^2)$ and $\bar{q}_s(x,Q^2)$ are empirically known [14,15], A_N^{π} for π^+, π^-, and π^0 can be evaluated. The results are shown in Fig. 1, where the only unknown constant C is determined by comparing with one point in the data [4]. Furthermore, it follows from Eq. (6) that this ansatz gives $g_1(x)+g_2(x)$ which is simply $u_v(x,Q^2)/27 - d_v(x,Q^2)/54$. The result is given in Fig. 2. It shows that $g_1(x)$ agrees with the data [16] for $x > 0.3$ when $g_2(x)$ is neglected as usual [17]. In addition to the discussions below Eqs. (2) and (6), the following should be mentioned: In the small x region, the influence of the confining forces and that of transverse motion are significant. Hence, the spin-dependent structure functions (for transverse as well as longitudinal polarization) have to be evaluated by the interactions and the transverse momenta into account. This implies in particular that Eq. (6) is not valid in the small x region, because in this region, there is *a priori* no reason to believe that the obtained results should be the same as those in the quark-parton model. Keeping in mind that the data analysis performed by the European Muon Collaboration (EMC) [16] is based on the quark-parton model, the crisis [17] of the quark-parton model caused by the EMC data [16] *does not* imply that "valence quarks cannot contribute to proton's spin" in the present model.

Encouraged by these results, we also calculated $A_N^{l\bar{l}}$ for $p(\uparrow)+p(0)\to l\bar{l}+X$ and $\bar{p}(\uparrow)+p(0)\to l\bar{l}+X$ (for different values of Q, see, e.g., Ref. [18]) by inserting the now known constant C (=0.6) and the same ansatz into Eq. (3). It is interesting to see (cf. Fig. 1) that the results are qualitatively different from those in pion production and from each other. The qualitative feature of such an experiment—*the existence or the nonexistence of left-right asymmetry*—should be a crucial test of the present model.

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