Transverse momentum in semi-inclusive polarized deep inelastic scattering and the spin-flavor structure of the proton

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The nonvalence spin-flavor structure of the proton extracted from semi-inclusive measurements of polarized deep inelastic scattering depends strongly on the transverse momentum of the detected hadrons which are used to determine the individual polarized sea distributions. This physics may explain the recent HERMES observation of a positively polarized strange sea through semi-inclusive scattering, in contrast with the negative strange sea polarization deduced from inclusive polarized deep inelastic scattering.

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Understanding the internal spin structure of the proton is one of the most challenging problems facing subatomic physics: How is the spin of the proton built up out from the intrinsic spin and orbital angular momentum of its quark and gluonic constituents? A key issue is the contribution of polarized sea quarks (up, down, and strange) in building up the spin of the proton. Fully inclusive polarized deep inelastic scattering experiments suggest that the sea carries significant *negative* polarization (polarized in the opposite direction to the spin of the proton) [1]. In contrast, new semi-inclusive measurements performed by the HERMES [2,3] and Spin Muon Collaboration (SMC) [4] experiments with final state particle identification suggest that the light-flavored (up and down) sea contributes close to zero to the proton's spin, and that the strange sea is *positively* polarized.

Here we argue that the transverse momentum of the detected final-state hadrons in semi-inclusive scattering may be essential to understanding these results. The first moment of the g_1 spin structure function for polarized photon-gluon fusion ($\gamma^* g \rightarrow q\bar{q}$) receives a positive contribution proportional to the mass squared of the struck quark or antiquark which originates from low values of quark transverse momentum k_t with respect to the photon-gluon direction. It also receives a negative contribution from $k_t^2 \sim Q^2$, where Q^2 is the virtuality of the hard photon—see Eqs. (3)–(6) below. Thus, the spin-flavor structure of the sea extracted from semi-inclusive measurements depends strongly on the k_t distribution of the detected hadrons. Understanding this physics is essential to ensure that the theory and experimental acceptance are correctly matched when extracting new information from present and future experiments. We first give a brief overview of the experimental situation and then explain the importance of transverse momentum, including calculations in the kinematics of the HERMES and SMC experiments.

Following pioneering experiments at SLAC [5], recent experiments in fully inclusive polarized deep inelastic scattering have extended measurements of the nucleon's g_1 spin dependent structure function to lower values of Bjorken x where the nucleon's sea becomes important [1]. From the first moment of g_1, these experiments have revealed a small value for the flavor-singlet axial-charge:

$$g_A^{(0)}|_{\rm pDIS} = \Delta u + \Delta d + \Delta s = 0.2 - 0.35. \qquad (1)$$

This result is particularly interesting [6] because $g_A^{(0)}$ is interpreted in the parton model as the fraction of the proton's spin which is carried by the intrinsic spin of its quark and antiquark constituents. The value (1) is about half the prediction of relativistic constituent quark models ($\sim 60\%$). It corresponds to a negative strange-quark polarization $\Delta s = -0.10 \pm 0.04$.

The small value of $g_A^{(0)}$ measured in polarized deep inelastic scattering has inspired vast experimental and theoretical activity to understand the spin structure of the proton. New experiments are underway or being planned to map out the proton's spin-flavor structure and to measure the amount of spin carried by polarized gluons in the polarized proton. These include semi-inclusive polarized deep inelastic scattering [3], polarized proton-proton collisions at the BNL Relativistic Heavy Ion Collider (RHIC) [7], and polarized *ep* collider studies [8].

Here we focus on semi-inclusive measurements of fast pions and kaons in the current fragmentation region. These measurements are being used by the HERMES experiment [2,3] (following earlier work by SMC [4]) to reconstruct the individual up, down, and strange quark contributions to the proton's spin. In contrast to inclusive polarized deep inelastic scattering where the g_1 structure function is deduced by detecting only the scattered lepton [9], the detected particles in the semi-inclusive experiments are high-energy (greater than 20% of the energy of the incident photon) charged pions and kaons in coincidence with the scattered lepton. For large energy fraction $z = E_h / E_\gamma \rightarrow 1$ the most probable occurrence is that the detected $\pi^\pm$ and $K^\pm$ contain the struck quark or antiquark in their valence Fock state. They therefore act as a tag of the flavor of the struck quark [9]. In leading order (LO) QCD the double-spin asymmetry for the production of hadrons h in semi-inclusive polarized γ^*-polarized proton collisions is

$$A_{1p}^h(x,Q^2) \simeq \frac{\sum_{q,h} e_q^2 \Delta q(x,Q^2) \int_{z_{\rm min}}^1 D_q^h(z,Q^2)}{\sum_{q,h} e_q^2 q(x,Q^2) \int_{z_{\rm min}}^1 D_q^h(z,Q^2)}, \qquad (2)$$

where $z_{\min}\sim 0.2$. Here $D_q^h(z,Q^2)=\int dk_t^2 D_q^h(z,k_t^2,Q^2)$ is the fragmentation function for the struck quark or antiquark to produce a hadron $h(=\pi^\pm,K^\pm)$ carrying energy fraction $z=E_h/E_\gamma$ in the target rest frame, $\Delta q(x,Q^2)$ is the quark (or antiquark) polarized parton distribution, and e_q is the quark charge. Note the integration over the transverse momentum k_t of the final-state hadrons [10]. (In practice this integration over k_t is determined by the acceptance of the experiment.) Since pions and kaons have spin zero, the fragmentation functions are the same for both polarized and unpolarized leptoproduction. NLO corrections to Eq. (2) are discussed in Ref. [11].

The semi-inclusive data reported by HERMES and SMC suggest that the (measured) light-flavored (up and down quark) sea contributes close to zero to the spin of the proton [2–4] and that the (measured) strange sea polarization is *positive* [3], in contrast with the result ($\Delta s=-0.10\pm0.04$) deduced from inclusive scattering. The mean Q^2 for these experiments is 2.5 GeV^2 (HERMES) and 10 GeV^2 (SMC). For HERMES the average transverse momentum of the detected fast hadrons is less than about 0.5 GeV [12], whereas for SMC the k_t of the detected fast pions was less than about 1 GeV [13]. Further semi-inclusive measurements are planned with the COMPASS experiment at CERN and the proposed future Electron-Ion Collider (EIC), extending the kinematic range to smaller Bjorken x.

Transverse momentum is essential to understanding polarized semi-inclusive data. Consider the polarized photon-gluon fusion process $\gamma^* g\to q\bar{q}$. We evaluate the g_1 spin structure function for this process as a function of the transverse momentum squared of the struck quark k_t^2 with respect to the photon-gluon direction. We use q and p to denote the photon and gluon momenta and use the cutoff $k_t^2\geqslant\lambda^2$ to separate the total phase space into "hard" ($k_t^2\geqslant\lambda^2$) and "soft" ($k_t^2<\lambda^2$) contributions. One finds [14,15]

$$g_1^{(\gamma^* g)}|_{\rm hard}=-\frac{\alpha_s}{2\pi}\frac{\sqrt{1-4(m^2+\lambda^2)/s}}{1-(4x^2P^2/Q^2)}\Bigg[(2x-1)\left(1-\frac{2xP^2}{Q^2}\right)\times\Bigg\{1-\frac{1}{\sqrt{1-[4(m^2+\lambda^2)/s]}\sqrt{1-[4x^2P^2/Q^2]}}\ln\left(\frac{1+\sqrt{1-(4x^2P^2/Q^2)}\sqrt{1-4(m^2+\lambda^2)/s}}{1-\sqrt{1-(4x^2P^2/Q^2)}\sqrt{1-4(m^2+\lambda^2)/s}}\right)\Bigg\}+\left(x-1+\frac{xP^2}{Q^2}\right)\frac{(2m^2(1-4x^2P^2/Q^2)-P^2x(2x-1)(1-2xP^2/Q^2))}{(m^2+\lambda^2)(1-4x^2P^2/Q^2)-P^2x(x-1+xP^2/Q^2)}\Bigg] \quad (3)$$

for each flavor of quark liberated into the final state. Here m is the quark mass, $Q^2=-q^2$ is the virtuality of the hard photon, $P^2=-p^2$ is the virtuality of the gluon target, x is the Bjorken variable ($x=Q^2/2pq$) and s is the center of mass energy squared $s=(p+q)^2=Q^2(1-x/x)-P^2$, for the photon-gluon collision. When $Q^2\to\infty$ the expression for $g_1^{(\gamma^* g)}|_{\rm hard}$ simplifies to the leading twist ($=2$) contribution

$$g_1^{(\gamma^* g)}|_{\rm hard}=\frac{\alpha_s}{2\pi}\Bigg[(2x-1)\Bigg\{\ln\frac{Q^2}{\lambda^2}+\ln\frac{1-x}{x}-1+\ln\frac{\lambda^2}{x(1-x)P^2+(m^2+\lambda^2)}\Bigg\}+(1-x)\frac{2m^2-P^2x(2x-1)}{m^2+\lambda^2-P^2x(x-1)}\Bigg]. \quad (4)$$

Here we take λ to be independent of x. Note that for finite quark masses, phase space limits Bjorken x to $x_{\max}=Q^2/[Q^2+P^2+4(m^2+\lambda^2)]$ and protects $g_1^{(\gamma^* g)}|_{\rm hard}$ from reaching the $\ln(1-x)$ singularity in Eq. (4). For this photon-gluon fusion process, the first moment of the "hard" contribution is [14]

$$\int_0^1 dx g_1^{(\gamma^* g)}\Big|_{\rm hard}=-\frac{\alpha_s}{2\pi}\Bigg[1+\frac{2m^2}{P^2}\frac{1}{\sqrt{1+4(m^2+\lambda^2)/P^2}}\times\ln\left(\frac{\sqrt{1+4(m^2+\lambda^2)/P^2}-1}{\sqrt{1+4(m^2+\lambda^2)/P^2}+1}\right)\Bigg]. \quad (5)$$

The "soft" contribution to the first moment of g_1 is then obtained by subtracting Eq. (5) from the inclusive first moment (obtained by setting $\lambda=0$):

$$\int_0^1 dx g_1^{(\gamma^* g)}\Big|_{\rm soft}=\frac{\alpha_s}{2\pi}\frac{2m^2}{P^2}\Bigg[\frac{1}{\sqrt{1+4(m^2+\lambda^2)/P^2}}\times\ln\left(\frac{\sqrt{1+4(m^2+\lambda^2)/P^2}-1}{\sqrt{1+4(m^2+\lambda^2)/P^2}+1}\right)-\frac{1}{\sqrt{1+4m^2/P^2}}\ln\left(\frac{\sqrt{1+4m^2/P^2}-1}{\sqrt{1+4m^2/P^2}+1}\right)\Bigg]. \quad (6)$$

Equation (6) measures the contribution to the polarized sea from k_t less than the cutoff λ in the limit $Q^2\to\infty$.

For fixed gluon virtuality P^2 the photon-gluon fusion process induces two distinct contributions to the first moment of g_1. Consider the leading twist contribution, Eq. (7). The first term $-\alpha_s/2\pi$ in Eq. (5) is mass independent and comes from the region of phase space where the struck quark carries large transverse momentum squared $k_t^2 \sim Q^2$. It measures a contact photon-gluon interaction and is associated [16,17] with the axial anomaly [18]. The second mass-dependent term comes from the region of phase-space where the struck quark carries transverse momentum $k_t^2 \sim m^2, P^2$. This *positive* mass-dependent term is proportional to the mass squared of the struck quark. The mass-dependent term in Eqs. (5) and (6) can safely be neglected for light-quark flavor (up and down) production. It is very important for strangeness (and charm [19,20]) production. For vanishing cutoff ($\lambda^2 = 0$) this term vanishes in the limit $m^2 \ll P^2$ and tends to $+\alpha_s/2\pi$ when $m^2 \gg P^2$ (so that the first moment of $g_1^{(\gamma^* g)}$ vanishes in this limit) [21].

Equation (5) leads to the well known formula [16,17,22]

$$g_A^{(0)}|_{\rm pDIS} = \left(\sum_q \Delta q - 3\frac{\alpha_s}{2\pi}\Delta g \right)_{\rm partons}, \qquad (7)$$

where Δg is the amount of spin carried by polarized gluon partons in the polarized proton and $\Delta q_{\rm partons}$ measures the spin carried by quarks and antiquarks carrying "soft" transverse momentum $k_t^2 \sim m^2, P^2$, with P^2 a typical gluon virtuality in the proton wave function. Since $\Delta g \sim 1/\alpha_s$ under QCD evolution [22], the two terms in Eq. (7) both scale as $Q^2 \to \infty$.

We now evaluate the effect of the strange quark mass on the k_t distribution of the final-state hadrons produced in photon-gluon fusion. In Figs. 1 and 2 we show the first moment of $g_1^{(\gamma^* g)}|_{\rm soft}$ for the strange and light (up and down) flavors, respectively, as a function of the transverse momentum cutoff (acceptance) $k_t^2 < \lambda^2$. Here we set $Q^2 = 2.5$ GeV^2 (corresponding to the HERMES experiment) and 10 GeV^2 (SMC) and integrate the full expression in Eq. (3). Following Ref. [16], we take $P^2 \sim \Lambda_{\rm qcd}^2$ and set $P^2 = 0.1$ GeV^2. We take the strange quark mass $m = 0.2$ GeV. Observe the small value for the light-quark sea polarization at low transverse momentum and the positive value for the integrated strange sea polarization at low $k_t^2 : k_t < 1.5$ GeV at the HERMES $Q^2 = 2.5$ GeV^2. When we relax the cutoff, increasing the acceptance of the experiment, the measured strange sea polarization changes sign and becomes negative (the result implied by fully inclusive deep inelastic measurements).

For $P^2 = 0.1$ GeV^2 the fully inclusive first moment of $g_1^{(\gamma^* g)}$ for strange quark production is 0.26 times $-\alpha_s/2\pi$ at $Q^2 = 2.5$ GeV^2, and 0.28 times $-\alpha_s/2\pi$ at $Q^2 = 10$ GeV^2 (and also in the scaling limit $Q^2 \to \infty$ indicating only a small higher-twist contribution). In practice a full calculation of the k_t dependence of the polarized sea would involve integrating over the distribution of gluon virtualities in the proton wave function [19]. While this distribution is strongly peaked at small P^2, it is interesting to investigate the effect of increasing the value of P^2. For $Q^2 = 2.5$ (10) GeV^2 the contribution to the total polarized strangeness from $k_t < \lambda$ changes sign and becomes negative at $\lambda = 0.7$ (1.4) GeV for a gluon with $P^2 = 0.5$ GeV^2 and $\lambda = 0.5$ (1.0) GeV for a highly virtual

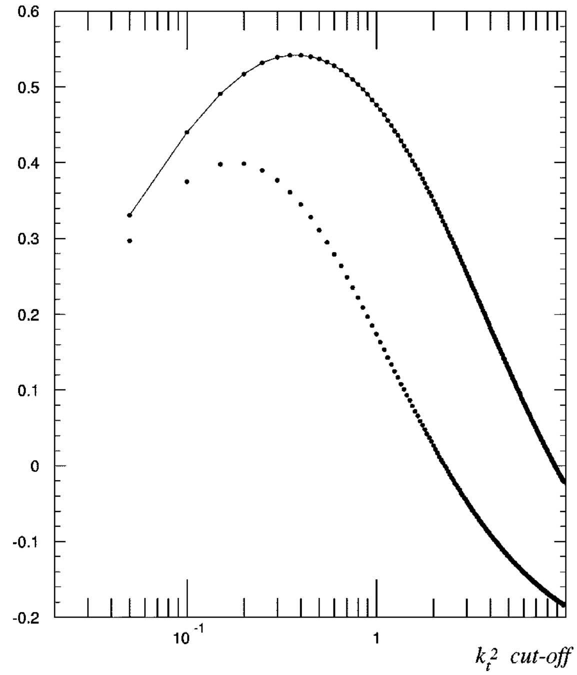

FIG. 1. $\int_0^1 dx g_1^{(\gamma^* g)}|_{\rm soft}$ for polarized strangeness production with $k_t^2 < \lambda^2$ in units of $\alpha_s/2\pi$. Here $Q^2 = 2.5$ GeV^2 (dotted line) and 10 GeV^2 (solid line).

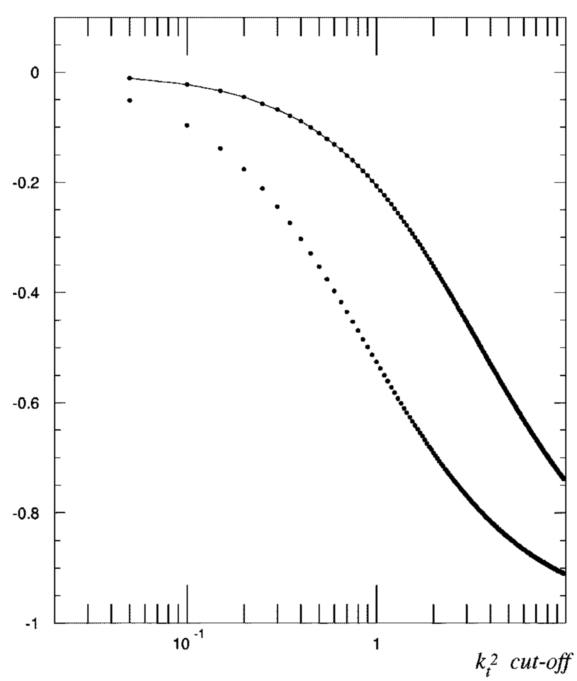

FIG. 2. $\int_0^1 dx g_1^{(\gamma^* g)}|_{\rm soft}$ for light-flavor (u or d) production with $k_t^2 < \lambda^2$ in units of $\alpha_s/2\pi$. Here $Q^2 = 2.5$ GeV^2 (dotted line) and 10 GeV^2 (solid line).

gluon with $P^2=1.0$ GeV^2. For $Q^2=2.5$ (10) GeV^2 the total, inclusive, polarized strangeness $\int_0^1 dx g_1^{(\gamma^* g)}$ induced by photon-gluon fusion increases to 0.52 (0.61) times $-\alpha_s/2\pi$ for $P^2=0.5$ GeV^2 and 0.54 (0.71) times $-\alpha_s/2\pi$ for $P^2=1.0$ GeV^2.

We summarize our results. The small value for the light-quark sea polarization and the positive strange sea polarization observed in semi-inclusive measurements of polarized deep inelastic scattering may have a simple interpretation in terms of the transverse momentum dependence of polarized photon-gluon fusion. It would be very interesting to extend the present measurements to include final-state hadrons with the highest values of transverse momentum k_t to look for the growth in the (negative) polarization of the light-(up and down) flavor sea and the sign change for the polarized strangeness that are expected at large k_t [23]. Finally, we note that an independent measurement of the strange quark axial-charge Δs could be obtained from a precision measurement of elastic νp scattering [24]. (The elastic νp process is independent of assumptions about the behavior of spin structure functions at $x \sim 0$.) Semi-inclusive and inclusive polarized deep inelastic scattering together with elastic νp scattering provide complementary information about the transverse momentum and Bjorken x distributions of strange quark polarization in the nucleon.

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