QUARK HELICITY FLIP AND THE TRANSVERSE SPIN DEPENDENCE OF INCLUSIVE DIS

A. AFANASEV\textsuperscript{1,2}, M. STRIKMAN\textsuperscript{3}, C. WEISS\textsuperscript{2}
\textsuperscript{1}Department of Physics, Hampton University, Hampton, VA 23668, USA
\textsuperscript{2} Theory Center, Jefferson Lab, Newport News, VA 23606, USA
\textsuperscript{3} Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA

Inclusive DIS with unpolarized beam exhibits a subtle dependence on the transverse target spin, arising from the interference of one–photon and two–photon exchange amplitudes in the cross section. We argue that this observable probes mainly the quark helicity–flip amplitudes induced by the non-perturbative vacuum structure of QCD (spontaneous chiral symmetry breaking). This conjecture is based on (a) the absence of significant Sudakov suppression of the helicity–flip process if soft gluon emission in the quark subprocess is limited by the chiral symmetry–breaking scale $\mu_{\text{chiral}}^2 \gg \Lambda_{\text{QCD}}^2$; (b) the expectation that the quark helicity–conserving twist–3 contribution is small. The normal target spin asymmetry is estimated to be of the order $10^{-4}$ in the kinematics of the planned Jefferson Lab Hall A experiment.

A fundamental property of QCD is that the quark helicity is conserved in perturbative interactions, because of chiral invariance in the light–quark sector. It is known, however, that non-perturbative interactions at distances of the order $1/\mu_{\text{chiral}} \sim 0.3\text{fm}$ cause the dynamical breaking of chiral symmetry and lead to the appearance of non-zero quark helicity–flip amplitudes. This effect essentially determines the structure and interaction of hadrons at large distances. An interesting question is what the presence of quark helicity–flip amplitudes implies for hard electromagnetic processes (invariant momentum transfer $Q^2 \gg 1\text{GeV}^2$). Such processes couple directly to the quark degrees of freedom and in certain cases can be described by factorization of the cross section/amplitude into “hard” and “soft” con-

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Fig. 1. QED processes contributing to the transverse target spin dependence of the inclusive $eN$ cross section at $O(\alpha^3)$. (a) Interference of one–photon and two–photon exchange. (b) Real photon emission (bremsstrahlung).

tributions. Quark helicity flip has been discussed e.g. in relation to the high–$Q^2$ behavior of the proton form factor ratio $QF_2/F_1$ and wide–angle Compton scattering.\textsuperscript{1,2} We have recently pointed out\textsuperscript{3} that quark helicity flip in hard processes can be probed in the transverse target spin dependence of inclusive deep–inelastic scattering (DIS) with unpolarized beam, $eN \rightarrow e'X$. In these proceedings we summarize the arguments relating this observable to quark helicity flip and discuss our estimate of the magnitude of the expected asymmetry (for details, see Ref. 3).

The differential cross section of inclusive $eN$ scattering with unpolarized beam depends on the target spin $S$ as

$$d\sigma = d\sigma_U + \frac{(S \cdot l \times l')}{|l \times l'|} d\sigma_N$$

(1)

($l, l'$ are the initial/final electron momenta in the lab frame), and the normal spin asymmetry is defined as

$$A_N \equiv \frac{d\sigma_N}{d\sigma_U}.$$  (2)

The spin–dependent term is zero in the one–photon exchange approximation to DIS, by the combination of $P$ and $T$ invariance and the hermiticity of the electromagnetic current operator (Christ–Lee theorem). A non-zero spin dependence appears only in higher orders of the QED coupling constant, from the interference of one–photon and absorptive two–photon exchange amplitudes in the cross section (Fig. 1a), as well as from real photon emission (bremsstrahlung, Fig. 1b). It is important that the two contributions to the spin–dependent cross section are individually free of QED infrared (IR) divergences and thus can be considered as distinct physical effects; this follows from the general factorization properties and the spin–independence of IR photon exchange in QED.\textsuperscript{3} The two–photon exchange amplitude is also free of QED collinear divergences (vanishing photon virtuality at non-zero momentum); this is a general consequence of electromagnetic gauge invariance.\textsuperscript{3,4} The spin–dependent two–photon exchange cross section, Fig. 1a,
Fig. 2. Transverse spin dependence of the DIS cross section in QCD. (a) Dominance of two-photon exchange with the same quark. (b) Quark helicity-conserving process involving interactions with the target remnants. (c) Quark helicity flip due to interaction with non-perturbative vacuum fields.

thus represents a well-defined observable in QED, which can be used as a new probe of hadron structure.

In DIS kinematics we expect the spin-dependent two-photon exchange cross section to arise predominantly from the amplitudes in which the two-photon exchange couples to a single quark, namely the same quark which is hit in the interfering one-photon exchange amplitude, see Fig. 2a. This expectation is based on the absence of “anomalous” (IR or collinear-enhanced) contributions in the two-photon exchange amplitude, and on general considerations of scattering from a hadronic system with momentum transfer $Q^2 \gg R_{\text{hadron}}^{-2}$. However, one can easily see that no transverse spin dependence can arise in the parton model approximation in which the electron scatters from an on-shell massless quark, as the transverse spin-dependent cross section for scattering from an on-shell quark requires quark helicity flip and is explicitly proportional to the quark mass. A spin dependence of the hadronic cross section thus can come only from the two mechanisms indicated in Figs. 2b and c.

In the process of Fig. 2b the quark helicity is conserved in the electron-quark subprocess, and the helicity flip between the interfering hadronic amplitudes happens at the level of the quark distribution in the nucleon. This process requires non-zero virtuality (off-shellness) of the active quark, and, at the same time, explicit interaction of the active quark with the spectator
system. The two effects are linked by electromagnetic gauge invariance; only
the sum of the two maintains transversality of the amplitude and avoids
the appearance of unphysical collinear divergences. (An attempt to calcu-
late the transverse spin asymmetry including finite virtuality of the active
quark but neglecting explicit interactions has produced a divergent result.5)
In the process of Fig. 2c the quark helicity is flipped in the electron–quark
subprocess. This process requires interaction of the active quark with the
non-perturbative vacuum fields which cause the spontaneous breaking of
chiral symmetry. It does not require interactions with the spectator system
and exists already for on–shell quarks. Perturbative QCD interactions do
not “mix” the contributions of Figs. 2b and c. An interesting question is
whether in typical DIS kinematics one of the two mechanisms dominates
or both make comparable contributions to the transverse spin dependence.

Following Ref. 3, we suggest here that the quark helicity–flip contribu-
tion, Fig. 2c, may be sizable and could well be the dominant mechanism in
the transverse target spin dependence. This perhaps somewhat surprising
assertion rests on the following two observations.

(1) *Insignificant Sudakov suppression of helicity–flip process.* The
helicity–flip process in QCD requires propagation through quark configu-
rations with virtualities \( \lesssim \mu^2_{\text{chiral}} \), which experience significant interactions
with the chiral symmetry breaking vacuum fields. This leads to Sudakov
suppression of the cross section compared to the case of unrestricted virtual-
ities. A similar suppression takes place in the usual DIS cross section (where
the restriction to small virtualities results from the condition of producing
real particles in the final state); however, there it is compensated by real
gluon emissions. In the case of the transverse spin asymmetry this compen-
sation is likely to be incomplete, and some residual Sudakov suppression of
the interference cross section should remain. Numerical estimates based on
the on–shell Sudakov formfactor of QCD show that this suppression should
be marginal for \( Q^2 \sim \text{few GeV}^2 \), if the IR cutoff governing soft gluon emis-
sion in the Sudakov formfactor is of the order of \( \mu^2_{\text{chiral}} \gg \Lambda^2_{\text{QCD}} \). While
we cannot presently prove that this magnitude of the IR cutoff is dictated
by chiral symmetry breaking in QCD, it certainly appears natural in the
light of dynamical models such as the instanton vacuum, which suppose
that gluons of wavelength \( < \mu^{-1}_{\text{chiral}} \) are “contained” in the non-perturbative
field configurations which break chiral symmetry.

(2) *Non-partonic character of helicity–conserving process.* The quark
helicity–conserving process, Fig. 2b, explicitly involves non-zero virtuality
of the initial quark and its interaction with the spectator system, and is
thus of essentially “non-partonic” character. The calculation of this process within the collinear QCD expansion starts from the “handbag diagram” with the twist–3 quark helicity–conserving distribution $g_T(x)$, which also appears in the calculation of the spin structure function $g_1 + g_2$ measured with polarized beam and transversely polarized target. However, retaining only the contribution from the “handbag diagram” would not be a consistent approximation for the spin–dependent two–photon exchange cross section, as this would violate electromagnetic gauge invariance and lead to the appearance of QED collinear divergences. The interaction of the active quark with the gluon field in the target needs to be included in order to restore electromagnetic gauge invariance. An interesting question is whether this “restoration” of gauge invariance will altogether eliminate the contribution from the dynamical twist–2 operators originally present in $g_T$, or whether some part of it survives in the final result. In the former case the helicity–conserving contribution to the asymmetry would be governed by the same mechanism as the twist–3 (“non–Wandzura–Wilczek”) part of $g_2$, which has been shown to be very small compared to $g_1$ by the SLAC\textsuperscript{6} and Jefferson Lab Hall A\textsuperscript{7} experiments. In the latter case, one could estimate the relative order–of–magnitude of the contributions from Figs. 2b and c by comparing\textsuperscript{3}

$$\frac{\langle k_T^2 \rangle}{M} g_{T,f}(x) \rightarrow M_q h_f(x),$$

where on the left–hand side $\langle k_T^2 \rangle$ is the typical quark intrinsic transverse momentum, $M$ the nucleon mass, and $g_{T,f}(x)$ is given in terms of the twist–2 quark helicity distribution, $g_f(x)$, by the Wandzura–Wilczek relation, and on the right–hand side $M_q \approx 0.3$–0.4 GeV is a typical constituent quark mass, determining the strength of the helicity–flip amplitude for low–virtuality quarks, and $h_f$ the quark transversity distribution ($f = u, d$ denotes the quark flavor). The numerical estimate of Fig. 3 shows that even under these assumptions the quark helicity–conserving process is unlikely to dominate over the quark helicity–flip one.

To summarize, we have argued that a sizable, perhaps dominant, contribution to the transverse spin–dependent cross section comes from the quark helicity–flip process governed by the quark transversity distribution in the nucleon. To validate this conjecture, a more detailed investigation of the effects of electromagnetic gauge invariance on the quark helicity–conserving contribution is needed. We note that this problem bears some similarity to that of gauge invariance in the QCD light–cone expansion of deeply–virtual Compton scattering (DVCS), where it was found that the twist–2
Fig. 3. Comparison of the proton’s twist–3 helicity–conserving quark distribution $g_T(x)$ [calculated in terms of the twist–2 quark helicity distribution $g(x)$ using the Wandzura–Wilczek relation] with the twist–2 helicity–flip (transversity) distribution $h(x)$ [estimated assuming that $h(x) = g(x)$, i.e., transversity = helicity distribution]. Shown are the results for both $u$ and $d$ quarks.

contribution to the amplitude alone is not transverse, and that transversality is restored by including certain “kinematical” twist–3 contributions. If the smallness of the helicity–conserving contribution of Figs. 2b could indeed be confirmed by explicit calculation, the normal spin asymmetry in inclusive DIS, Eq. (2), would be a very interesting observable for testing the mechanism of non-perturbative quark helicity flip in QCD.

A numerical estimate of the normal spin asymmetry in DIS kinematics was made in Ref. 3 using a light–front constituent quark model, in which DIS is described as elastic scattering from pointlike constituent quarks, and quark helicity–flip amplitudes are generated by the constituent quark mass. In order to have a self–consistent picture, this model was treated in the “composite nucleon” approximation, where we suppose that the quark transverse momenta, which are of the order of the inverse nucleon size, are parametrically small compared to the constituent quark mass,

$$\langle k_T^2 \rangle \sim R_N^{-2} \ll M_q^2. \quad (4)$$

Physically, this corresponds to a picture of the nucleon as an assembly of weakly interacting, massive quarks. In this picture the quark helicity–flip contribution to the transverse spin asymmetry (which is proportional to $M_q$) dominates over the quark helicity–conserving one (proportional to $\langle k_T^2 \rangle$) and can be calculated in a relativistic impulse approximation with
Fig. 4. The normal target spin asymmetry $A_N$ obtained from the light–front constituent quark model with the the composite nucleon approximation, Eq. (4), with different assumptions about the spin–flavor wave function: (a) $SU(6)$ symmetry, (b) transversity = helicity distributions, $h(x) = g(x)$. The kinematics corresponds approximately to the planned Jefferson Lab Hall A experiment ($s = 2E_{\text{beam}}M + M^2$ is the squared electron–nucleon center–of–mass energy).

The normal spin asymmetry in electron–neutron DIS is to be measured in a dedicated Jefferson Lab Hall A experiment with a polarized $^3$He target ($E_{\text{beam}} = 6 \text{ GeV}, x = 0.1 - 0.45, Q^2 = 1 - 3.5 \text{ GeV}^2$), with a projected absolute statistical error of $\delta A_N = 2 - 4 \times 10^{-4}$ in each of the four $Q^2$ bins. This measurement will improve the sensitivity of the only previous measurement at SLAC by two orders of magnitude (in the SLAC experiment the asymmetry was found to be compatible with zero at the level of $\sim 3.5\%$). The statistical error of the planned JLab measurement is of the same order as the value of the asymmetry predicted by the compos-
ite nucleon approximation Eq. (4), see Fig. 4. However, as already stated, this approximation was made for technical reasons and can provide only a rough estimate of the expected asymmetry. More realistic dynamical model calculations of this observable are certainly needed. Work on this problem is in progress.

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