

SINGLE-SPIN ASYMMETRIES AND QIU-STERMAN EFFECT(S) *

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I discuss the relation between the Qiu-Sterman effects on one hand and the Collins, Sivers and Boer-Mulders effects on the other hand. It was suggested before that some of these effects are in fact the same, thus providing interesting connections between transverse-momentum dependent twist-2 functions and collinear twist-3 functions. Here I propose an alternative way to reach similar conclusions.

1. Introduction

Single-spin asymmetries have been observed in semi-inclusive deep inelastic scattering and proton-proton collisions.^{1,2} Seemingly different mechanisms have been advocated to explain these effects. Qiu and Sterman proposed three possibilities, which I shall call chiral-even distribution, chiral-odd distribution and chiral-odd fragmentation Qiu-Sterman effects.³ Earlier work in the same direction was carried out by Efremov and Teryaev.⁴ On the other hand, the Sivers⁵, Boer-Mulders⁶ and Collins⁷ effects can give rise to the same asymmetries. It was argued by Boer, Mulders and Pijlman⁸, that these mechanisms are related, as all of them involve gluonic-pole matrix elements. This conclusion is apparently surprising, since the Sivers, Boer-Mulders and Collins effects can be described by *T-odd*, twist-2 distribution or fragmentation functions depending on intrinsic transverse momentum, while the effects discussed by Qiu-Sterman are T-odd, twist-3, and collinear. In my talk, I shall present an alternative derivation of the

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connection between the Sivers function and the Qiu-Sterman chiral-even distribution functions. A similar relation should hold also between the Boer-Mulders function and the Qiu-Sterman chiral-odd distribution function. On the other hand, I shall argue that the Collins function has a different origin compared to the Qiu-Sterman chiral-odd fragmentation function.

2. Semi-inclusive deep inelastic scattering

Single-spin asymmetries in deep inelastic scattering have been discussed in a large number of papers. I will now focus on the single-spin asymmetry that can be observed in the process $lp^\uparrow \rightarrow l\pi X$ when the target is transversely polarized and the transverse momentum of the final hadron is integrated over.^a This particular asymmetry has been studied in a few references^{9,6,10} in terms of T-odd distribution or fragmentation functions, while it has been studied in by Koike¹¹ in terms of Qiu-Sterman effects. No experimental measurement has been attempted so far, but it should be feasible at HERMES and COMPASS.

The general formula for the asymmetry up to subleading twist is⁶

$$A_{UT} = \frac{|\vec{S}_T|}{d\sigma_{UU}} \sum_q \frac{2\alpha^2 e_q^2}{sxy^2} V(y) \sin \phi_S \frac{M}{Q} \left[x f_T^q D_1^q - \frac{M_h}{M} h_1^q \frac{\tilde{H}^q}{z} \right], \quad (1)$$

where $V(y) = 2(2-y)\sqrt{1-y}$.

The function f_T is a twist-3 distribution function and can be split in two parts, an interaction-dependent part, which can be related via equation of motions to quark-gluon-quark correlations, and a Wandzura-Wilczek part, which is related to a twist-2 distribution function, in this case the Sivers function:¹²

$$x f_T = x \tilde{f}_T^q - f_{1T}^{\perp(1)q}. \quad (2)$$

Eq. (1) becomes

$$A_{UT} = \frac{|\vec{S}_T|}{d\sigma_{UU}} \sum_q \frac{2\alpha^2 e_q^2}{sxy^2} V(y) \sin \phi_S \frac{M}{Q} \left[(x \tilde{f}_T^q - f_{1T}^{\perp(1)q}) D_1^q - \frac{M_h}{M} h_1^q \frac{\tilde{H}^q}{z} \right], \quad (3)$$

Eq. (3) contains two different kinds of twist-3 contributions. As mentioned before, the terms with a tilde are related to quark-gluon-quark correlations. They don't vanish even if transverse momentum is naively neglected. They can be called *dynamical* twist-3 terms and should be related

^aA similar case is when the final-state lepton is integrated over, but the transverse momentum of the hadron is detected.

to the Qiu-Sterman contributions studied by Koike¹¹ (specifically to the chiral-even distribution G and chiral-odd fragmentation \hat{E} described in his work). The term $f_{1T}^{\perp(1)}$ denotes the first moment (in transverse momentum space) of the Sivers function. This term would vanish if a collinear approximation was adopted from the beginning. Dynamically, it is a twist-2 term coming from the gauge-link contribution to quark-quark correlations, but it appears at twist 3 due to the fact that in this particular asymmetry (and in general whenever the transverse momentum of the outgoing hadron is not observed) off-collinear effects are kinematically suppressed. It can be therefore called a *kinematical* twist-3 term and it has been studied by Anselmino *et al.*¹⁰ Note that in this asymmetry there is no contribution involving the Collins function due to off-collinear effects.

I come now to the main point of my talk. The A_{UT} asymmetry of Eq. (3) can be calculated also for totally inclusive deep-inelastic scattering (by replacing $D_1(z) \rightarrow \delta(1-z)$, $\tilde{H} \rightarrow 0$) and reduces to

$$A_{UT} = \frac{|\vec{S}_T|}{d\sigma_{UU}} \sum_q \frac{2\alpha^2 e_q^2}{sxy^2} V(y) \sin\phi_S \frac{M}{Q} (x \tilde{f}_T^q - f_{1T}^{\perp(1)q}), \quad (4)$$

However, in totally inclusive deep-inelastic scattering time-reversal invariance forbids the presence of such an asymmetry.^{13,14} A relation is implied by this observation, namely

$$x \tilde{f}_T^q(x) - f_{1T}^{\perp(1)q}(x) = 0, \quad (5)$$

In principle, the relation holds only for the sum over all quark flavors, but repeating the above argument for a hypothetical photon that couples selectively to different flavors, one obtains the above relation.

Eq. (5) is the main result presented in this talk and provides a complementary way to state that there is a relation between the chiral-even Qiu-Sterman distribution function and the first moment of the Sivers function. Note that the vanishing of the function f_T , which is equivalent to Eq. (5), was already discussed by Goeke, Metz and Schlegel.¹⁵

An appropriate treatment of the T-odd distribution functions up to twist-3 should lead to the same result from a more formal point of view, making clear that $x \tilde{f}_T$ and $f_{1T}^{\perp(1)}$ are indeed the same object and both originate from gluonic-pole matrix elements.⁸

Note that the asymmetry in Eq. (3) – once the first term is dropped – turns out to be a good way to measure transversity, in particular in experiments which are sensitive to higher twist observables.¹⁶ The function \tilde{H} was introduced for the first time by Jaffe and Ji,⁹ who called it \hat{e}_T^- . The

absence of the Collins function in Eq. (3) suggests that it is intrinsically different from \tilde{H} . In fact, in the literature it was already observed that the Collins function is not related to gluonic poles.^{17,18}

3. Drell-Yan

In analogy to semi-inclusive DIS, we can consider A_T asymmetries in Drell-Yan processes, $pp^\dagger \rightarrow l\bar{l}X$, integrated over the transverse momentum of the lepton pair. This asymmetry has been discussed by Boer, Mulders and Teryaev,¹² but the conclusions reached by those authors are incomplete due to the fact that at that time the gauge link was not taken into account as a source of T-odd effects. The only contributions to the A_T asymmetry should be (assuming proton A to be transversely polarized)

$$A_T \propto \frac{|\vec{S}_T|}{d\sigma_{UU}} \sum_q e_q^2 \sin \phi_S \frac{M}{Q} \left[x_A \left((1-c) f_T^q + c \tilde{f}_T^q \right) f_1^{\bar{q}} - h_1^q x_B \left(c h^{\bar{q}} + (1-c) \tilde{h}^{\bar{q}} \right) \right], \quad (6)$$

where the factor c depends on the frame of reference that is used to define the azimuthal angle ϕ_S and can assume values between 0 and 1.¹²

The first term of the asymmetry vanishes due to Eq. (5). Through a formal treatment of twist-3 distribution functions, it should be possible to prove that also the function h vanishes,¹⁵ implying a relation between the Boer-Mulders function⁶ and the Qiu-Sterman chiral-odd distribution function¹⁹ similar to Eq. (5). The asymmetry reduces then to

$$A_T \propto \frac{|\vec{S}_T|}{d\sigma_{UU}} \sum_q e_q^2 \sin \phi_S \frac{M}{Q} \left[c x_A \tilde{f}_T^q(x_A) f_1^{\bar{q}}(x_B) - (1-c) h_1^q(x_A) x_B \tilde{h}^{\bar{q}}(x_B) \right]. \quad (7)$$

Note that, when defined in the frame of reference where $c = 0$, this asymmetry gives the opportunity to measure the transversity distribution function in singly-polarized Drell-Yan, while in the frame where $c = 1$ gives an opportunity to study the Sivers function.

4. Proton-proton collisions

I now turn the attention to the A_N asymmetry in the process $pp^\dagger \rightarrow \pi X$. The situation here is more involved than in deep inelastic scattering, due to the fact that partonic kinematics cannot be reconstructed completely, in

particular in the transverse plane. Off-collinear kinematics at the partonic level has been analyzed in great detail by Anselmino *et al.*²⁰ It turns out that several T-odd distribution and fragmentation functions can contribute to the A_N asymmetry. These are again kinematical twist-3 contributions, in the sense that they involve twist-2 functions with a kinematical suppression due to off-collinear kinematics. Dynamical twist-3 effects in collinear kinematics are precisely those studied by Qiu and Sterman.²¹

As mentioned before, for distribution functions the two effects are identical and related to gluonic poles. The partonic cross sections to be used in both cases should not be normal partonic cross sections, but rather *gluonic-pole cross sections*. An example of the use of gluonic-pole cross sections with the Sivers and Boer-Mulders functions has been given for the process $pp^\uparrow \rightarrow \pi\pi X$.²² Gluonic-pole cross sections are essentially equal to the standard partonic cross sections multiplied by overall color factors. Where do they come from and why they are not used in DIS and Drell-Yan? In fact, they are already used in DIS and Drell-Yan, but they go somewhat unnoticed! We know that T-odd functions arise from gluonic poles present in the gauge link. In deep inelastic scattering, the partonic process is $lq \rightarrow lq$. The gluons of the gauge link can attach *only* to the *outgoing* quark. The resulting gluonic-pole cross section, $l\hat{g}q \rightarrow lq$, in this simple case corresponds to the normal partonic cross section. In Drell-Yan, the partonic process is $\bar{q}q \rightarrow l\bar{l}$, the gluon can attach *only* to the *incoming* antiquark and the resulting gluonic-pole cross section, $\bar{q}\hat{g}q \rightarrow l\bar{l}$ is equal to *minus* the standard $\bar{q}q \rightarrow l\bar{l}$ cross section.

In the partonic processes involved in $pp \rightarrow \pi X$, colored partons are present both in the initial and the final state. The resulting gluonic-pole cross sections are then equal to the standard partonic cross section multiplied by nontrivial overall color factors, to be computed for each individual process (and each individual channel of the process). Note that gluonic-pole cross sections have been studied only for the exchange of a single gluon. It is not clear what happens when multiple gluon interactions are taken into account.

For fragmentation functions the situation is different. Since the Collins function is not related to gluonic poles, standard partonic cross sections can be used with it, as done by Anselmino *et al.*²³ On the contrary, gluonic-pole cross sections should be used with the chiral-odd fragmentation function \tilde{H} .

5. Conclusions

I discussed the Qiu-Sterman effects on one hand and the Sivers, Boer-Mulders and Collins functions on the other hand. I proposed a relation between the chiral-even Qiu-Sterman distribution function and the first moment of the Sivers function. A similar relation probably holds also between the Boer-Mulders function and the chiral-odd Qiu-Sterman distribution function. On the contrary, I argued that the Qiu-Sterman chiral-odd fragmentation function has a different origin compared to the Collins function.

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