Probing the Nucleon's Transversity and the Photon's Distribution Amplitude in Lepton Pair Photoproduction

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We describe a new way to access the chiral-odd transversity parton distribution in the proton through the photoproduction of lepton pairs. The basic ingredient is the interference of the usual Bethe-Heitler or Drell-Yan amplitudes with the amplitude of a process, where the photon couples to quarks through its chiral-odd distribution amplitude, which is normalized to the magnetic susceptibility of the QCD vacuum. A promising phenomenology of single and double spin observables emerges from the unusual features of this amplitude.

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Transversity quark distributions remain the most unknown leading twist hadronic observables. This is mostly due to their chiral-odd character which enforces their decoupling in most hard amplitudes. After the pioneering works [1], much work [2] has been devoted to the exploration of many channels, but experimental difficulties have challenged the most promising ones. In particular, the measurement of double spin asymmetries in the Drell-Yan process will have to wait for a polarized antiproton facility [3]. Access to the related transversity generalized parton distributions has also been discussed [4]. Recent measurements in single inclusive deep inelastic scattering [5] have been performed which enable us to have a first glance at the magnitudes of the transversity distribution of u and d quarks [6]; these attempts are based on an extension of the collinear partonic picture which uses the concept of transverse momentum dependent parton distributions [7].

In the framework of the traditional collinear parton approach, we show here that the chiral-odd nature of the real photon distribution amplitude [8] allows us to define measurable spin asymmetries which are linear in the quark transversity distribution in the nucleon. The selection of these observables follows from a series of trivial steps: (i) the twist-2 transversity quark distribution is chiral odd, (ii) the real photon chiral-odd distribution amplitude has twist 2, (iii) lepton pair production comes from different eventually interfering processes, (iv) the interference of selected amplitudes may be singled out through the lepton azimuthal distribution or through a lepton-antilepton charge asymmetry.

We are thus lead to consider the following process (s_T is the transverse polarization vector of the nucleon):

$$\gamma(k, \epsilon)N(r, s_T) \longrightarrow l^-(p)l^+(p')X, \qquad (1)$$

with $q = p + p'$ in the kinematical region where $Q^2 = q^2$ is large, and the transverse component $|\vec{Q}_\perp|$ of q is of the same order as Q. This last requirement comes from the fact that hard amplitudes with two very different large scales suffer from the appearance of large logarithms of their ratio, which in turn require a resummation of such large logs. Our study does not require such a special kinematical regime.

Such a process occurs either through a Bethe-Heitler amplitude [Fig. 1(a)], where the initial photon couples to a final lepton, or through Drell-Yan–type amplitudes [Fig. 1(b)], where the final leptons originate from a virtual photon. Among these Drell-Yan processes, one must distinguish the cases where the real photon couples directly (through the QED coupling) to quarks or through its quark content, i.e., the photon structure function. Gluon radiation at any order in the strong coupling α_s does not, however, introduce any chiral-odd quantity if one neglects quark masses. Thus, in the domain of light quark physics, it seems that transversity effects do not show off. We are thus led to consider the contributions where the photon couples to the strong interacting particles through its twist-2 distribution amplitude [Fig. 1(c) and 1(d)]. One can easily see by inspection that this is the only way to get at the level of twist 2 (and with vanishing quark masses) a contribution to nucleon transversity dependent observables. We will call this amplitude $\mathcal{A}_\phi$. This is reminiscent of the successful Berger-Brodsky [9] strategy to unravel the pion distribution amplitude in the study of Drell-Yan

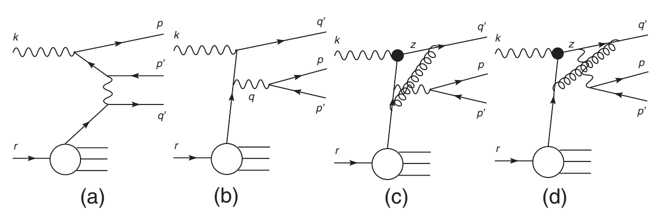

FIG. 1. Some amplitudes contributing to lepton pair photoproduction. (a) The Bethe-Heitler process. (b) The Drell-Yan process with the photon pointlike coupling. (c),(d) The Drell-Yan process with the photon distribution amplitude.

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pairs in a chosen kinematical regime. A related instance, namely, the ρ meson photoproduction at large momentum transfer or dijet photoproduction at large transverse momentum, where the photon couples to a hard process through its distribution amplitude, has been studied previously [10].

Reaction (1) thus opens a natural access to the transversity quark distribution, provided the amplitude $\mathcal{A}_\phi$ interferes with the Bethe-Heitler or a usual Drell-Yan process. Moreover, if this amplitude has an absorptive part, one may expect *single spin* effects. We will show below that this is indeed the case for the process (1). Similar absorptive parts also appear in studies of other processes like in deep inelastic scattering on polarized hadrons but at the twist-3 level [11], polarized and unpolarized meson induced Drell-Yan production [12], or in studies of T-odd Sivers distribution [13].

Kinematics.—We consider the γN center of mass reference frame, with the nucleon 3-momentum along the positive z axis. The quark entering the subprocess carries a fraction x of light-cone momentum. The leading order subprocess is

$$\gamma(k)u(xr) \to l^-(p)l^+(p')u(q'), \tag{2}$$

where u denotes a quark of any flavor. Scattering on an antiquark is easily deduced with straightforward changes. We define $s = (k + r)^2$, $u = (k - q')^2$; the Bjorken variable is $\tau = \frac{Q^2}{s}$, $\vec{v}_\perp$ denotes the component of any 3-vector transverse to the z direction. We describe 4-vectors through a Sudakov decomposition along k and r as

$$q = \alpha k + \frac{Q^2 + \vec{Q}_\perp^2}{\alpha s} r + Q_\perp, \tag{3}$$

$$p = \gamma\alpha k + \frac{(\gamma\vec{Q}_\perp + \vec{l}_\perp)^2}{\gamma\alpha s} r + \gamma Q_\perp + l_\perp, \tag{4}$$

$$p' = \bar{\gamma}\alpha k + \frac{(\bar{\gamma}\vec{Q}_\perp - \vec{l}_\perp)^2}{\bar{\gamma}\alpha s} r + \bar{\gamma} Q_\perp - l_\perp, \tag{5}$$

$$q' = \bar{\alpha} k + \frac{\vec{Q}_\perp^2}{\bar{\alpha} s} r - Q_\perp. \tag{6}$$

In the laboratory frame of a fixed target experiment, α measures the fraction of energy that the lepton pair carries with respect to the photon energy, and γ ($\bar{\gamma} = 1 - \gamma$) the fraction of energy carried by the lepton (antilepton) with respect to the dilepton energy. As usual, $\bar{\alpha}$ denotes $1 - \alpha$. Momentum conservation yields

$$x = \frac{\bar{\alpha}Q^2 + \vec{Q}_\perp^2}{\alpha\bar{\alpha}s}, \qquad Q^2 = \frac{\vec{l}_\perp^2}{\gamma\bar{\gamma}}. \tag{7}$$

If one measures the energies of the final leptons and the transverse momentum of the dilepton, one thus fixes x, α, γ.

Definitions.—The transversity distribution function is defined as (p is along the $+$ direction)

$$h_1^q(x) = \int \frac{dz^-}{4\pi} e^{ixp^+z^-} \langle p s_T | \bar{q}(0) i\sigma^{+s_T}\gamma_5 q(0, z^-, 0_T) | p s_T \rangle,$$

while the chiral-odd photon distribution amplitude $\phi_\gamma(u)$ reads [8]

$$\langle 0|\bar{q}(0)\sigma_{\alpha\beta}q(x)|\gamma^{(\lambda)}(k)\rangle = ie_q\chi\langle\bar{q}q\rangle(\epsilon_\alpha^{(\lambda)}k_\beta - \epsilon_\beta^{(\lambda)}k_\alpha) \times \int_0^1 dz e^{-iz(kx)}\phi_\gamma(z), \tag{8}$$

where the normalization is chosen as $\int dz\phi_\gamma(z) = 1$, and z stands for the momentum fraction carried by the quark. The product of the quark condensate and of the magnetic susceptibility of the QCD vacuum $\chi\langle\bar{q}q\rangle$ has been estimated [14] with the help of the QCD sum rules techniques to be of the order of 50 MeV [15] and a lattice estimate has recently been performed [16]. The distribution amplitude $\phi_\gamma(z)$ has a QCD evolution which drives it to an asymptotic form $\phi_\gamma^{\rm as}(z) = 6z(1 - z)$. Its z dependence at non-asymptotic scales is very model dependent [17].

Amplitudes.—While the Bethe-Heitler [Fig. 1(a)] and Drell-Yan amplitudes, both with a pointlike photon [Fig. 1(b)] and a photon content expressed through its quark distribution, have been much discussed [18], the amplitude where the photon interacts through its distribution amplitude has, to our knowledge, never been scrutinized. There are two diagrams contributing at lowest order, shown in Figs. 1(c) and 1(d). In Feynman gauge their sum is readily calculated as

$$\mathcal{A}_\phi(\gamma q \to l\bar{l}q) = 2i\frac{C_F}{4N_c}e_q^2 e4\pi\alpha_s\chi\langle\bar{q}q\rangle\frac{1}{Q^2} \times \int dz\phi_\gamma(z)\bar{u}(q')\left[\frac{A_1}{x\bar{z}s(t_1 + i\epsilon)} + \frac{A_2}{zu(t_2 + i\epsilon)}\right]u(r)\bar{u}(p)\gamma^\mu v(p'), \tag{9}$$

with $t_1 = (zk - q)^2$ and $t_2 = (\bar{z}k - q)^2$, and

$$A_1 = x\hat{r}\,\hat{\epsilon}\,\hat{k}\,\gamma^\mu + \gamma^\mu\hat{k}\,\hat{\epsilon}\,\hat{q}, \qquad A_2 = \hat{\epsilon}\,\hat{q}\,\gamma^\mu\hat{k} + \hat{k}\gamma^\mu\hat{q}\,\hat{\epsilon}, \tag{10}$$

which do not depend on the light-cone fraction z. Most interesting is the analytic structure of this amplitude since the quark propagators may be on shell so that the amplitude $\mathcal{A}_\phi$ develops an absorptive part proportional to

$$\int dz\phi_\gamma(z)\bar{u}(q')\left[\frac{A_1}{x\bar{z}s}\delta(t_1) + \frac{A_2}{zu}\delta(t_2)\right]u(r)\bar{u}(p)\gamma^\mu v(p').$$

This allows us to perform the z integration, the result of which, after using the $z - \bar{z}$ symmetry of the distribution amplitude, yields an absorptive part of the amplitude $\mathcal{A}_\phi$ proportional to $\phi_\gamma(\frac{\alpha Q^2}{Q^2 + \vec{Q}_\perp^2})$. This absorptive part, which may be measured in single spin asymmetries, as discussed below, thus scans the photon chiral-odd distribution amplitude.

Cross sections.—The cross section for reaction (1) can be read as

$$\frac{d\sigma}{d^4Qd\Omega} = \frac{d\sigma_{\rm BH}}{d^4Qd\Omega} + \frac{d\sigma_{\rm DY}}{d^4Qd\Omega} + \frac{d\sigma_\phi}{d^4Qd\Omega} + \frac{\Sigma d\sigma_{\rm int}}{d^4Qd\Omega},$$

where $\Sigma d\sigma_{\rm int}$ contains various interferences, while the transversity dependent differential cross section [we denote $\Delta_T\sigma = \sigma(s_T) - \sigma(-s_T)$] reads

$$\frac{d\Delta_T\sigma}{d^4Qd\Omega} = \frac{d\sigma_{\phi\rm int}}{d^4Qd\Omega}, \tag{11}$$

where $d\sigma_{\phi\rm int}$ contains only interferences between the amplitude $\mathcal{A}_\phi$ and the other amplitudes. Moreover, one may use the distinct charge conjugation property (with respect to the lepton part) of the Bethe-Heitler amplitude to select the interference between $\mathcal{A}_\phi$ and the Bethe-Heitler amplitude:

$$\frac{d\Delta_T\sigma(l^-) - d\Delta_T\sigma(l^+)}{d^4Qd\Omega} = \frac{d\sigma_{\phi\rm BH}}{d^4Qd\Omega}. \tag{12}$$

Conversely, one may use this charge asymmetry to cancel out the interference of $\mathcal{A}_\phi$ with the Bethe-Heitler amplitude

$$\frac{d\Delta_T\sigma(l^-) + d\Delta_T\sigma(l^+)}{d^4Qd\Omega} \propto \frac{d\sigma_{\phi\rm DY}}{d^4Qd\Omega}. \tag{13}$$

We cannot develop here the rich phenomenology of this new way to access transversity. Different possibilities are discussed at the end of this Letter. Instead, we now compute the simplest observable which contains all appealing features of our proposal and yet is not orders of magnitude too small to be measurable. This is the interference of $\mathcal{A}_\phi$ and the Bethe-Heitler amplitudes, see Eq. (12), in the unpolarized photon case. The polarization average of $d\sigma_{\phi\rm BH}$ reads:

$$\frac{1}{2}\sum_\lambda d\sigma_{\phi\rm BH}(\gamma(\lambda)p \to l^-l^+X) = \frac{(4\pi\alpha_{em})^3}{4s}\frac{C_F 4\pi\alpha_s}{2N_c}\frac{\chi\langle\bar{q}q\rangle}{\vec{Q}_\perp^2}\int dx\sum_q Q_l^3 Q_q^3 h_1^q(x) 2\,{\rm Re}(\mathcal{I}_{\phi\rm BH})d{\rm LIPS}, \tag{14}$$

with the usual phase space factor:

$$d{\rm LIPS} = (2\pi)^4\delta^4(P_{\rm in} - P_{\rm out})\Pi\frac{d^3p_i}{2E_i(2\pi)^3} \qquad (p_i = p, p', q')$$

$$\text{and}\quad 2\,{\rm Re}(\mathcal{I}_{\phi\rm BH}) = \phi_\gamma\left[\frac{\alpha Q^2}{Q^2+\vec{Q}_\perp^2}\right]\frac{32\pi\alpha^2\bar{\alpha}}{xs(\bar{\alpha}Q^2+\vec{Q}_\perp^2)^2}(Q^2+\vec{Q}_\perp^2)[\epsilon^{rks_TQ_\perp}A_1 + \epsilon^{rks_Tl_\perp}A_2], \tag{15}$$

where

$$A_1 = \frac{2}{\alpha^2Q^2}[-2\vec{l}_\perp\cdot\vec{Q}_\perp + \bar{\alpha}(\gamma-\bar{\gamma})Q^2] + \frac{Q^2[2\vec{l}_\perp\cdot\vec{Q}_\perp + (\gamma-\bar{\gamma})\vec{Q}_\perp^2]}{(\gamma Q^2 - 2\vec{l}_\perp\cdot\vec{Q}_\perp + \bar{\gamma}\vec{Q}_\perp^2)(\bar{\gamma}Q^2 + 2\vec{l}_\perp\cdot\vec{Q}_\perp + \gamma\vec{Q}_\perp^2)}, \tag{16}$$

and

$$A_2 = \frac{2}{\alpha^2Q^2}[\bar{\alpha}^2Q^2 + \vec{Q}_\perp^2] - \frac{\vec{Q}_\perp^2[Q^2+\vec{Q}_\perp^2]}{(\gamma Q^2 - 2\vec{l}_\perp\cdot\vec{Q}_\perp + \bar{\gamma}\vec{Q}_\perp^2)(\bar{\gamma}Q^2 + 2\vec{l}_\perp\cdot\vec{Q}_\perp + \gamma\vec{Q}_\perp^2)}. \tag{17}$$

Equations (14)–(17) thus demonstrate at the level of a highly differential cross section the existence of a nonvanishing observable proportional to the transversity nucleon distribution $h_1(x = \frac{Q^2}{\alpha s} + \frac{\vec{Q}_\perp^2}{\alpha\bar{\alpha}s})$ and the photon distribution amplitude $\Phi_\gamma(z = \frac{\alpha Q^2}{Q^2+\vec{Q}_\perp^2})$.

Phenomenological perspectives.—A natural concern at this point is about the observability of the effect that we propose to measure. The first obvious feature is that lepton pair photoproduction cross sections are of order α_{em}^3. This is by no means a signal of unmeasurability, as demonstrated by quite ancient measurements in slightly different kinematics [19] or recent exclusive experiments at JLab and HERA which measured the Bethe-Heitler process, the deeply virtual Compton scattering process and their interference [20]. Moreover, the timelike Compton process [21] (the exclusive analog of Drell-Yan photoproduction) and its interference with the Bethe-Heitler process is in the analysis process [22]. The unpolarized Drell-Yan cross section is estimated of the order a few picobarns for Q^2 values of a few GeV^2 in [18,23].

The order of magnitude of the fully differential cross section Eq. (14) is obviously not large enough to be directly measurable, and one thus needs to carry a detailed numerical analysis of all the kinematical domains in order to perform a judicious partial phase space integration and define less differential observables.

Moreover, our specific example, a single spin observable, is not necessarily the most easily accessible. A detailed phenomenological analysis should discuss both single spin and double spin observables. They are complementary: the photon polarization asymmetry is sensitive to the nonabsorptive (real) part of the amplitude $\mathcal{A}_\phi$ which does not contribute to the single spin observable of Eq. (14). The double spin observable is experimentally accessible since photons originating from polarized lepton beams are naturally circularly polarized.

We thus anticipate that a careful phenomenological study will allow us to define partially integrated observables which should be measurable, provided high luminosity photon beam, a dense and long enough polarized target, and high quality detectors are used. Recent progress in photon beams and the effort toward a dedicated photon beam at the future JLab 12 GeV facility [24] supports our optimism.

Conclusions.—We have outlined a new way to access the nucleon's transversity $h_1(x)$, through the chiral-odd coupling of a the real photon with quarks, which is proportional to the magnetic susceptibility of the QCD vacuum and the photon distribution amplitude $\Phi_\gamma(z)$. The basic tool is to select observables which selects the interference of the amplitude $\mathcal{A}_\phi$, where the photon couples to quark through its chiral-odd distribution amplitude with a better-known amplitude such as the Bethe-Heitler or the leading Drell-Yan amplitude. The result is that the differential transverse spin cross section difference—in the exemplary case we have studied—is proportional to $\chi\phi_\gamma(\frac{\alpha Q^2}{Q^2+\vec{Q}_\perp^2})h_1^q(\frac{Q^2}{\alpha s}+\frac{\vec{Q}_\perp^2}{\alpha\bar{\alpha}s})$, which allows us to scan both the photon distribution amplitude and the transversity nucleon distribution.

Experimental prospects cover mostly the future JLab 12 GeV upgrade and, in particular, its Hall D real photon program. Experiments at higher energy such as the Compass muon beam at CERN may open another kinematical domain. Both setups will have polarized quasireal photon beams and transversely polarized nuclear targets. A complete phenomenological study is needed to check that the foreseen photon luminosity and a good lepton pair reconstruction will give access to the interference of the chiral-odd amplitude driven by the magnetic susceptibility of the QCD vacuum and either the Bethe-Heitler or the usual Drell-Yan amplitudes.

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[1] J. P. Ralston and D. E. Soper, Nucl. Phys. **B152**, 109 (1979); X. Artru and M. Mekhfi, Z. Phys. C **45**, 669 (1990); J. L. Cortes *et al.*, Z. Phys. C **55**, 409 (1992); R. L. Jaffe and X. D. Ji, Phys. Rev. Lett. **67**, 552 (1991).

[2] For a review, see V. Barone, A. Drago, and P. G. Ratcliffe, Phys. Rep. **359**, 1 (2002).

[3] V. Barone *et al.* (PAX Collaboration), arXiv:hep-ex/0505054.

[4] M. Diehl *et al.*, Phys. Rev. D **59**, 034023 (1999); D. Y. Ivanov *et al.*, Phys. Lett. B **550**, 65 (2002); R. Enberg *et al.*, Eur. Phys. J. C **47**, 87 (2006).

[5] A. Airapetian *et al.*, Phys. Rev. Lett. **94**, 012002 (2005); E. S. Ageev *et al.*, Nucl. Phys. **B765**, 31 (2007).

[6] M. Anselmino *et al.*, Phys. Rev. D **75**, 054032 (2007).

[7] J. C. Collins, Nucl. Phys. **B396**, 161 (1993); P. J. Mulders and R. D. Tangerman, Nucl. Phys. **B461**, 197 (1996); **B484**, 538 (1997); D. Boer and P. J. Mulders, Phys. Rev. D **57**, 5780 (1998).

[8] B. L. Ioffe and A. V. Smilga, Nucl. Phys. **B232**, 109 (1984); I. I. Balitsky, V. M. Braun, and A. V. Kolesnichenko, Nucl. Phys. **B312**, 509 (1989); P. Ball, V. M. Braun, and N. Kivel, Nucl. Phys. **B649**, 263 (2003).

[9] E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. **42**, 940 (1979); P. Hoyer *et al.*, J. High Energy Phys. 10 (2008) 086.

[10] D. Y. Ivanov *et al.*, Phys. Lett. B **478**, 101 (2000); **498**, 295 (2001); V. M. Braun *et al.*, Phys. Rev. Lett. **89**, 172001 (2002).

[11] A. V. Efremov and O. V. Teryaev, Phys. Lett. **150B**, 383 (1985).

[12] A. Brandenburg, D. Mueller, and O. V. Teryaev, Phys. Rev. D **53**, 6180 (1996); A. P. Bakulev, N. G. Stefanis, and O. V. Teryaev, Phys. Rev. D **76**, 074032 (2007).

[13] P. G. Ratcliffe and O. V. Teryaev, arXiv:hep-ph/0703293.

[14] V. M. Belyaev and Y. I. Kogan, Yad. Fiz. **40**, 1035 (1984); I. I. Balitsky, A. V. Kolesnichenko, and A. V. Yung, Sov. J. Nucl. Phys. **41**, 178 (1985).

[15] The sign of χ depends on the sign convention used for the covariant derivative; we use $D^\mu = \partial^\mu + ie_q A^\mu$.

[16] P. V. Buividovich *et al.*, arXiv:0906.0488.

[17] V. Y. Petrov *et al.*, Phys. Rev. D **59**, 114018 (1999); A. E. Dorokhov, W. Broniowski, and E. Ruiz Arriola, Phys. Rev. D **74**, 054023 (2006).

[18] R. L. Jaffe, Phys. Rev. D **4**, 1507 (1971); L. M. Jones *et al.*, Phys. Rev. D **20**, 2749 (1979); **22**, 2922 (1980); I. Kang and C. H. Llewellyn Smith, Nucl. Phys. **B166**, 413 (1980).

[19] J. F. Davis *et al.*, Phys. Rev. Lett. **29**, 1356 (1972).

[20] For a recent review, see, e.g., M. Guidal, Prog. Part. Nucl. Phys. **61**, 89 (2008).

[21] E. R. Berger, M. Diehl, and B. Pire, Eur. Phys. J. C **23**, 675 (2002); B. Pire, L. Szymanowski, and J. Wagner, Phys. Rev. D **79**, 014010 (2009); Nucl. Phys. B, Proc. Suppl. **179–180**, 232 (2008).

[22] S. Stepanyan, Proceedings of the CLAS12 European Workshop, Genova, 2009 (unpublished).

[23] A. Psaker, arXiv:hep-ph/0511283; , Braz. J. Phys. **34**, 944 (2004).

[24] "*The Science Driving the 12 GeV Upgrade of CEBAF*," JLab internal report, 2001.