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DVCS off deuteron and twist three contributions

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We study the deeply virtual Compton scattering off a spin-one particle, which is exemplified by the case of coherent scattering on a deuteron target. We discuss the role of twist three contributions for restoring the QED gauge invariance of the amplitude corresponding to this process. We consider both kinematical and dynamical sources of twist three generalized parton distributions.

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1. Introduction.

Deeply virtual Compton scattering (DVCS) on the deuteron target has recently attracted much attention from the experimental point of view [1, 2]. One of the main reasons of this interest is the fact that the DVCS process gives information about a new type of parton distributions, called generalized parton distributions (GPDs) which allow to extract much information about the quark and gluon structure of hadrons, particularly its spin structure [3], and to allow a femtophotography of nuclei [4].

From the theoretical point of view, the leading twist-2 GPDs for the deuteron were defined in [5] and the DVCS amplitude on the deuteron was discussed at leading order in [6]. However, the leading twist-2 accuracy for the DVCS amplitude is not enough for the study of such processes with significant transverse momenta, because of the QED gauge invariance breaking of the DVCS amplitude in leading twist-2 order in the Bjorken limit and non zero transverse final momenta. This problem was resolved in [7] for a (pseudo)scalar target (pion, He^4), where it was demonstrated that one can restore the gauge invariance of the DVCS amplitude by taking into account the twist-3 contributions, related to the matrix elements of quark-gluon operators. Besides, the relevant additional terms provide the leading contribution to some polarization observables. Then, the same ideas were used and generalized for the nucleon target [8]. We here follow the approach, presented in [7], to make a comprehensive analysis of the twist three contributions to the amplitude of the DVCS off deuteron (or an arbitrary spin-one target).

Let us start with the discussion of the kinematics and approximations which we use in this paper. The process we consider is

$$\gamma^*(q) + D(p_1) \to \gamma(q') + D(p_2),$$

with $q^2 = -Q^2$ large, while $q'^2 = 0$. At the Born level, the Feynman diagrams corresponding to this process are depicted in Fig. 1. We introduce the "plus" and "minus" vectors as $n^\star = \Lambda(1,0,0,1)$, $\quad n = 1/(2\Lambda)(1,0,0,-1)$, $\quad n^\star \cdot n = 1$. We consider the DVCS amplitude up to the twist three accuracy, discarding the contributions associated with the twist four and higher. The hadron relative and transfer momenta can be written as

$$\begin{aligned}
&P = \frac{p_1+p_2}{2} = n^\star + \frac{\bar{M}^2}{2} n \approx n^\star, \quad \Delta = p_2 - p_1 = -2\xi P + 2\xi \bar{M}^2 n + \Delta^T \approx -2\xi P + \Delta^T,\\
&\xi = \frac{(p_1-p_2)^+}{(p_2+p_1)^+}, \quad P\cdot\Delta = 0, \quad \Delta^2 = t = \Delta_T^2 - 4\xi^2 \bar{M}^2 \approx 0.
\end{aligned} \tag{1.1}$$

2. Parameterization of the vector and axial-vector matrix elements

We now introduce the parameterization of all relevant matrix elements up to the twist three accuracy. The parameterization of the twist-2 vector correlators is standard and can be found in [5], for which we will use the shorthand notation:

$$\langle p_2,\lambda_2| \left[\bar{\psi}(0)\gamma_\mu \psi(z)\right]^{tw-2} |p_1,\lambda_1\rangle \stackrel{\mathscr{F}_1}{=} P_\mu H^V_{1,..,5}(e_2^*, e_1; x, \xi, t). \tag{2.1}$$

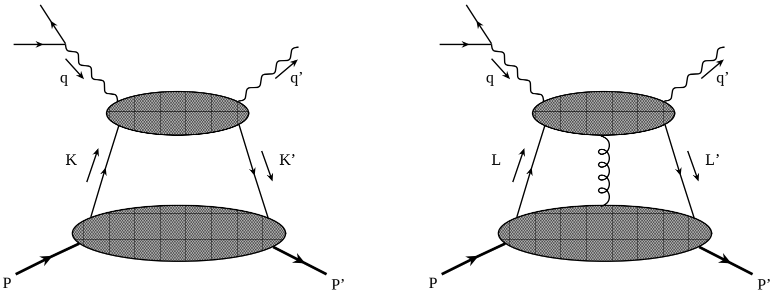

Figure 1: The Feynman diagrams corresponding to deeply virtual Compton scattering. Notations: $P \equiv p_1, \quad P' \equiv p_2, \quad K \equiv k - \Delta/2 \approx xP - \Delta/2, \quad K' \equiv k + \Delta/2 \approx xP + \Delta/2, \quad L \equiv k_1 - \Delta/2 \approx x_1 P - \Delta/2, \quad L' \equiv k_2 + \Delta/2 \approx x_2 P + \Delta/2$. Here, k and k_i correspond to the loop momenta in the diagrams.

We now come to the discussion of the twist-3 operator matrix elements and their parametrizations. We parametrize the vector quark correlator as [1]

$$\langle p_2, \lambda_2 | \left[\bar{\psi}(0)\gamma_\mu \psi(z)\right]^{tw-3} | p_1, \lambda_1 \rangle \stackrel{\mathscr{F}_1}{=} \Delta^T_\mu \, G^V_{1,..,5}(e^*_2, e_1; x, \xi) + e^{*T}_{2\mu}(e_1 \cdot P)\, G^V_6(x,\xi) + \\ e^T_{1\mu}(e^*_2 \cdot P)\, G^V_7(x,\xi) + M^2 \, e^{*T}_{2\mu}(e_1 \cdot n)\, G^V_8(x,\xi) + M^2 \, e^T_{1\mu}(e^*_2 \cdot n)\, G^V_9(x,\xi). \tag{2.2}$$

In the forward limit, where $\Delta = 0$, one has $P_\mu \Rightarrow p_\mu$, $e^*_{2\mu} \Rightarrow e^*_\mu$, $e_{1\mu} \Rightarrow e_\mu$. Therefore, in this limit, the parameterizations (2.1) and (2.2) reduce to the parameterizations with $H^V_1(x,0)$, $H^V_5(x,0)$ and $G^V_8(x,0)$, $G^V_9(x,0)$. The deuteron, as a spin-one particle, has its polarization degrees of freedom described by the spin density matrix: $e^*_\mu e_\nu = P_{\mu\nu}/3 + S_{\mu\nu} + i/(2M)\, \varepsilon_{\mu\nu\alpha\beta} S_\alpha p_\beta$, where $P_{\mu\nu}$ is the well-known unpolarized projector, the vector S_μ represents the vectorial polarization and the tensor $S_{\mu\nu}$ – the tensorial one. With this, one can see that the twist-2 corresponds to either the unpolarized or the tensorial-polarized deuteron, while the twist-3 describes the tensorial or vectorial polarization.

As in [7], we introduce the matrix elements with a transverse derivative (detailed consideration of such matrix elements can be found in [9, 10]). The parameterization of the quark-antiquark correlator with the transverse derivative is written as the following nine terms:

$$\langle p_2, \lambda_2 | \left[\bar{\psi}(0)\gamma_\mu i\partial^T_\rho \psi(z)\right]^{tw-3} | p_1, \lambda_1 \rangle \stackrel{\mathscr{F}_1}{=} P_\mu \Big\{ \Delta^T_\rho \, b^T_{1,..,5}(e^*_2, e_1; x, \xi) + e^{*T}_{2\rho}(e_1 \cdot P)\, b^T_6(x,\xi) + \\ e^T_{1\rho}(e^*_2 \cdot P)\, b^T_7(x,\xi) + M^2 \, e^{*T}_{2\rho}(e_1 \cdot n)\, b^T_8(x,\xi) + M^2 \, e^T_{1\rho}(e^*_2 \cdot n)\, b^T_9(x,\xi) \Big\}. \tag{2.3}$$

In a similar way, we parametrize the quark-antiquark-gluon correlator of genuine twist 3, replacing in the r.h.s. of Eq. (2.3) $b^T_i(x,\xi)$ by $B_i(x_1, x_2, \xi)$.

The twist-2 axial-vector correlator is also standard one and can be parametrized as in [5] by

$$\langle p_2, \lambda_2 | \left[\bar{\psi}(0)\gamma_\mu \gamma_5 \psi(z)\right]^{tw-2} | p_1, \lambda_1 \rangle \stackrel{\mathscr{F}_1}{=} -i \, e^*_{2\alpha} \, \mathscr{A}^{(i),L}_{\alpha\beta,\mu}(n^\star, n, \Delta_T) e_{1\beta} \, H^A_i(x,\xi,t). \tag{2.4}$$

In the forward limit, the twist-2 axial-vector correlator corresponds to the case where the deuteron has the (longitudinal) vectorial polarization. For the twist-3 correlators, we have, using the Schouten

[1] the symbol $\stackrel{\mathscr{F}_1}{=}$ denotes the Fourier transformation with the measure: $dx \exp\{-i(xP - \Delta/2)\cdot z\}$, while $\stackrel{\mathscr{F}_2}{=}$ corresponds to the integration with $dx_1 dx_2 \exp\{-i(x_1 P - \Delta/2)\cdot z_1 - i(x_2 - x_1)P \cdot z_2\}$.

identity to determine the Lorentz independent structures,

$$
\begin{aligned}
& i\langle p_2,\lambda_2|\left[\bar{\psi}(0)\gamma_\mu\gamma_5\psi(z)\right]^{tw-3}|p_1,\lambda_1\rangle \stackrel{\mathscr{F}_1}{=} \varepsilon_{\mu n P e_1^T}(e_2^*\cdot P)\,G_1^A(x,\xi)+\varepsilon_{\mu n P e_2^{*T}}(e_1\cdot P)\,G_2^A(x,\xi) \\
+\; & M^2\,\varepsilon_{\mu n P e_1^T}(e_2^*\cdot n)\,G_3^A(x,\xi)+M^2\,\varepsilon_{\mu n P e_2^{*T}}(e_1\cdot n)\,G_4^A(x,\xi)+\frac{1}{M^2}\,\varepsilon_{\mu\Delta_T P e_2^*}(e_1\cdot P)\,G_5^A(x,\xi)+ \qquad (2.5)\\
& \varepsilon_{\mu\Delta_T P e_2^*}e_1\cdot n\,G_6^A(x,\xi)+\varepsilon_{\mu\Delta_T P e_1}e_2^*\cdot n\,G_7^A(x,\xi)+\varepsilon_{\mu\Delta_T n e_2^*}e_1\cdot P\,G_8^A(x,\xi)+M^2\,\varepsilon_{\mu\Delta_T n e_1}e_2^*\cdot n\,G_9^A(x,\xi).
\end{aligned}
$$

Again, in the forward limit, these twist-3 correlators are related to the tensorial or (transverse) vectorial polarizations of deuteron. The matrix element of the twist-3 operator associated with the quark-antiquark operator containing a transverse derivative reads

$$
\begin{aligned}
& i\langle p_2,\lambda_2|\left[\bar{\psi}(0)\gamma_\mu\gamma_5 i\partial^T_\rho\psi(z)\right]^{tw-3}|p_1,\lambda_1\rangle \stackrel{\mathscr{F}_1}{=} P_\mu\Big\{\varepsilon_{\rho n P e_1^T}(e_2^*\cdot P)\,d_1^T(x,\xi)+\varepsilon_{\rho n P e_2^{*T}}(e_1\cdot P)\,d_2^T(x,\xi) \\
+\; & M^2\,\varepsilon_{\rho n P e_1^T}(e_2^*\cdot n)\,d_3^T(x,\xi)+M^2\,\varepsilon_{\rho n P e_2^{*T}}(e_1\cdot n)\,d_4^T(x,\xi)+\frac{1}{M^2}\,\varepsilon_{\rho\Delta_T P e_2^*}(e_1\cdot P)\,d_5^T(x,\xi) \\
+\; & \varepsilon_{\rho\Delta_T P e_2^*}e_1\cdot n\,d_6^T(x,\xi)+\varepsilon_{\rho\Delta_T P e_1}e_2^*\cdot n\,d_7^T(x,\xi)+\varepsilon_{\rho\Delta_T n e_2^*}e_1\cdot P\,d_8^T(x,\xi) \\
+\; & M^2\,\varepsilon_{\rho\Delta_T n e_1}e_2^*\cdot n\,d_9^T(x,\xi)\Big\}. \qquad (2.6)
\end{aligned}
$$

From (2.6), it is not difficult to parameterize the three-particle correlator with the genuine twist-3.

3. Gauge invariant amplitude of DVCS on the deuteron target

Taking into account both kinematical and dynamical twist-3 contributions and using the QCD equations of motion relating the twist 2 and 3 (see [7]), the gauge invariant expression of the DVCS amplitude takes the form:

$$
T^{(\lambda_1,\lambda_2)}_{\mu\nu}=\frac{1}{2P\cdot Q}\int dx\frac{1}{x-\xi+i\varepsilon}\left(\mathscr{T}^{(1)}_{\mu\nu}+\mathscr{T}^{(2)}_{\mu\nu}+\mathscr{T}^{(3)}_{\mu\nu}+\mathscr{T}^{(4)}_{\mu\nu}\right)^{(\lambda_1,\lambda_2)}+O(\Delta_T^2;\bar{M}^2)+\text{“}crossed\text{”} \qquad (3.1)
$$

where $\bar{Q}=(q+q')/2$ and the structure amplitudes $\mathscr{T}^{(k)}_{\mu\nu}$ read

$$
\begin{aligned}
\mathscr{T}^{(1)}_{\mu\nu} &= H^V_{1,..,5}(x;e_1,e_2^*)\left(2\xi P_\mu P_\nu+P_\mu\bar{Q}_\nu+P_\nu\bar{Q}_\mu-g_{\mu\nu}(P\cdot\bar{Q})+\frac{1}{2}P_\mu\Delta^T_\nu-\frac{1}{2}P_\nu\Delta^T_\mu\right)+ \\
& G^V_{1,..,5}(x;e_1,e_2^*)\left(\xi P_\nu\Delta^T_\mu+3\xi P_\mu\Delta^T_\nu+\Delta^T_\mu\bar{Q}_\nu+\Delta^T_\nu\bar{Q}_\mu\right)+ \\
& \Bigg(M^2(e_1\cdot n)(e_2^*\cdot n)G_9^A(x)-\frac{(e_2^*\cdot P)(e_1\cdot P)}{M^2}G_5^A(x)-(e_2^*\cdot P)(e_1\cdot n)G_6^A(x)- \\
& (e_1\cdot P)(e_2^*\cdot n)\left(G_7^A(x)-G_8^A(x)\right)\Bigg)\left(3\xi P_\mu\Delta^T_\nu-\xi P_\nu\Delta^T_\mu-\Delta^T_\mu\bar{Q}_\nu+\Delta^T_\nu\bar{Q}_\mu\right), \\
\mathscr{T}^{(2)}_{\mu\nu} &= \left((e_1\cdot P)G_6^V(x)+M^2(e_1\cdot n)G_8^V(x)\right)\left(\xi P_\nu e^{*T}_{2\mu}+3\xi P_\mu e^{*T}_{2\nu}+e^{*T}_{2\mu}\bar{Q}_\nu+e^{*T}_{2\nu}\bar{Q}_\mu\right)+
\end{aligned}
$$

$$\left((e_1\cdot P)G_2^A(x)+M^2(e_1\cdot n)G_4^A(x)\right)\left(3\xi P_\mu e^{*T}_{2\nu}-\xi P_\nu e^{*T}_{2\mu}-e^{*T}_{2\mu}\bar{Q}_\nu+e^{*T}_{2\nu}\bar{Q}_\mu\right),$$

$$\mathscr{T}^{(3)}_{\mu\nu}=\left((e_2^*\cdot P)G_7^V(x)+M^2(e_2^*\cdot n)G_9^V(x)\right)\left(\xi P_\nu e^T_{1\mu}+3\xi P_\mu e^T_{1\nu}+e^T_{1\mu}\bar{Q}_\nu+e^T_{1\nu}\bar{Q}_\mu\right)+$$

$$\left((e_2^*\cdot P)G_1^A(x)+M^2(e_2^*\cdot n)G_3^A(x)\right)\left(3\xi P_\mu e^T_{1\nu}-\xi P_\nu e^T_{1\mu}-e^T_{1\mu}\bar{Q}_\nu+e^T_{1\nu}\bar{Q}_\mu\right)$$

$$\mathscr{T}^{(4)}_{\mu\nu}=\varepsilon_{\mu\nu Pn}\left(\varepsilon_{nPe_2^{*T}e_1^T}H_1^A(x,\xi)+\frac{1}{M^2}\varepsilon_{nP\Delta^T e_2^{*T}}(e_1\cdot P)H_2^A(x,\xi)+\right.$$

$$\left.\frac{1}{M^2}\varepsilon_{nP\Delta^T e_1^T}(e_2^*\cdot P)H_3^A(x,\xi)+\varepsilon_{nP\Delta^T e_2^{*T}}(e_1\cdot n)H_4^A(x,\xi)\right)$$

In conclusion, we have taken into account both the kinematical and dynamical twist-3 contributions in order to derive the gauge invariant amplitude of the deeply virtual Compton scattering off a spin-one particle (deuteron).

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