Deeply Virtual Compton Scattering at JLab Hall A

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The deeply virtual Compton scattering reaction has been investigated in the Hall A of the Jefferson Laboratory by measuring longitudinally polarized $(\vec{e},e'\gamma)$ cross sections, in the valence quark region, for protons and neutrons. In the proton channel, experimental results strongly support the factorization of the cross section at Q^2 as low as 2 GeV^2, opening the path to sytematic measurements of generalized parton distributions (GPDs). In the neutron case, preliminary data show sensitivity to the angular momentum of quarks [1].

1 Introduction

Over the ten past years, deeply virtual Compton scattering (DVCS) became the most promising process to explore the partonic structure of the nucleon [2, 3]. Similarly to the diffusion of light by a cristal, which tells about the internal structure and organization of the material, the scattering of energetic photon off the nucleon in the Bjorken regim ($Q^2 >> M^2$ and $t << Q^2$) allows to access the generalized parton distributions (GPDs) which describe the quark and gluon structure of the nucleon [4, 5]. GPDs correspond to the coherence between quantum states of different (or same) helicity, longitudinal momentum, and transverse position and can be interpreted in the impact parameter space as a distribution in the transverse plane of partons carrying longitudinal momentum fraction x [6, 7, 8]. The GPD framework provides a comprehensive picture of the nucleon structure which unifies within the same formalism form factors, structure functions, and partons angular momenta [9].

In the Jefferson Laboratory (JLab) energy range, the Bethe-Heitler (BH) process, where the real photons are emitted either by the incoming or the scattered electrons, contributes significantly to the cross section of the electro-production of photons. However, the BH process is well-known and exactly calculable from the electromagnetic form factors of the nucleon. Then, similarly to holography technique, the BH process is used as a reference amplitude which interferes with the DVCS amplitude and magnifies the underlying effects [10]. In JLab Hall A, two experimental observables have been investigated: the total $(e,e'\gamma)$ cross section

$$\frac{d^5\sigma}{dQ^2 dx_B dt d\phi_e d\varphi} = \mathcal{T}_{BH}^2 + |\mathcal{T}_{DVCS}|^2 + 2\,\mathcal{T}_{BH}\Re e\{\mathcal{T}_{DVCS}\} \,, \tag{1}$$

and the difference of polarized $(\vec{e},e'\gamma)$ cross sections for opposite longitudinal beam helicities

$$\begin{aligned} \frac{d^5\Sigma}{dQ^2 dx_B dt d\phi_e d\varphi} &= \frac{1}{2}\left[\frac{d^5\overrightarrow{\sigma}}{dQ^2 dx_B dt d\phi_e d\varphi} - \frac{d^5\overleftarrow{\sigma}}{dQ^2 dx_B dt d\phi_e d\varphi}\right] \\ &= \mathcal{T}_{BH}\,\Im m\{\mathcal{T}_{DVCS}\} + \Re e\{\mathcal{T}_{DVCS}\}\,\Im m\{\mathcal{T}_{DVCS}\} \,. \end{aligned} \tag{2}$$

While the former gives access to the real part of the DVCS amplitude, that is the integral of a linear combination of GPDs convoluted with a quark propagator, the latter is a direct measurement of its imaginary part, which relates to a linear combination of GPDs in the handbag dominance hypothesis [11]. A dedicated experimental program [12, 13] was set to investigate the DVCS reaction off the proton and off the neutron, with the aim to test factorization in the proton channel and to explore the sensitivity of the neutron channel to E_q, the least known and constrained GPD.

2 Experimental apparatus

A 5.75 GeV/c longitudinally polarized electron beam impinged on 15 cm liquid H_2 and D_2 cells, the latter serving as quasi-free neutron target. Scattered electrons were detected in the left High Resolution Spectrometer (HRS-L) [14] for several Q^2 and constant x_B=0.36. Real photons were detected in a PbF_2 electromagnetic calorimeter organized in an 11×12 array of 3×3×18.6 cm^3 crystals centered around the direction of the virtual photon. The calorimeter front face was 110 cm from the target center supporting the useful t acceptance -0.5 GeV^2 $< t$. Typical beam intensities of 4 μA yielded a 4×10^{37} cm^{-2}·s^{-1} luminosity with 76 % polarized electrons. Three independent reactions were used to calibrate and monitor the calorimeter: H$(e, e'_{\mathrm{Calo.}} p_{\mathrm{HRS}})$, D$(e, e'_{\mathrm{Calo.}} \pi^-_{\mathrm{HRS}})pp$, and H,D$(e, e'_{\mathrm{HRS}} \pi^0_{\mathrm{Calo.}})X$ [15]. It should be emphasized that π^-_{HRS} and $\pi^0_{\mathrm{Calo.}}$ data are taken simultaneously with DVCS data, ensuring a continuous monitoring of the calibration and the resolution of the calorimeter.

3 Factorization in p-DVCS

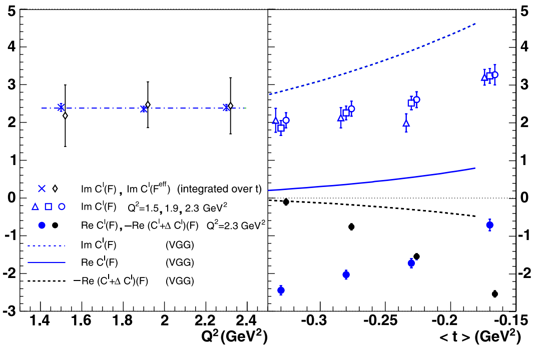

Figure 1: Q^2 and t dependences of the GPDs linear combination extracted from (un)polarized p-DVCS cross sections [16]. The different curves (right panel) are theoretical calculations from a GPD based model [19].

The polarized cross section difference (Eq. 2) for DVCS off the proton (p-DVCS) was measured at three different Q^2 ranging from 1.5 GeV^2 to 2.3 GeV^2 [16], and was analyzed according to the harmonic structure derived in Ref. [11]. The sin(ϕ) and sin(2ϕ) harmonic coefficients (or moments) have been separated. In the context of this experiment, the kinematical factors entering the square of the DVCS amplitude suppress its contribution to $d^5\Sigma$ as compared to the BH·DVCS interference amplitude, leading to a direct measurement of $\Im m\{\mathcal{T}_{DVCS}\}$. The sin($\phi$) moment corresponds then to the imaginary part of the linear combination $C^I(\mathcal{F})$ (Eq. 3) of the Compton form factors (CFFs) $\mathcal{H}$, $\widetilde{\mathcal{H}}$, and $\mathcal{E}$ which relate to GPDs [11]:

$$C^I(\mathcal{F}) = F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E} \; . \tag{3}$$

Figure 1 shows the Q^2 dependence of the twist-2 (Eq. 3) and twist-3 ($\Im m[C^I(\mathcal{F}^{eff})]$) harmonic coefficients of $d^5\Sigma$: the observed independence on Q^2 is an indication for factorization. Furthermore, the contribution of the twist-3 terms to $d^5\Sigma$ was found to be small [16]. These features are a strong indication that factorization applies even at Q^2 as low as 2 GeV^2.

4 Importance of the DVCS amplitude

The unpolarized H$(e, e'\gamma)$p cross section was also measured at the highest Q^2 point. Neglecting the DVCS·DVCS term, the real part of the DVCS amplitude (Eq. 1) was extracted according to the harmonic structure of Ref. [11]. This leads to a $\cos(\phi)$ and $\cos(2\phi)$ dependence, the gluon contribution - which would appear as a $\cos(3\phi)$ term - being negligible in the valence quark region. Experimental data (points) are shown on Fig. 2 as a function of ϕ for the smallest $|t|$-bin. The red curve fitting the data is the sum of the different contributions to the cross section: deviations from the pure BH amplitude (blue solid curve) shows that the DVCS amplitude contributes significantly to $d^5\sigma$. This feature suggests that one should pay attention to the ϕ-dependence of the denominator when extracting GPDs from beam spin asymetries.

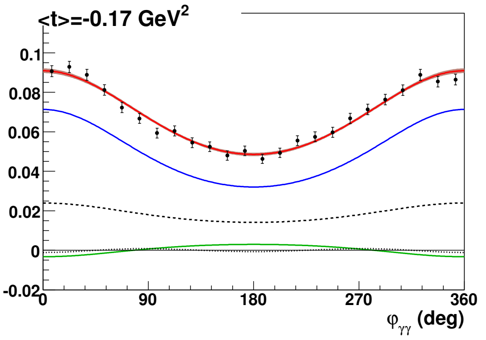

Figure 2: The ϕ-dependence of the $d^4\sigma$ differential cross section (Eq. 1 integrated over ϕ_e) in nb/GeV^4 at Q^2=2.3 GeV^2, decomposed in BH and DVCS contributions [16].

In addition to the real part of the CFFs combination of Eq. 3, the extracted harmonic coefficients give access to the combination

$$C^I(\mathcal{F}) + \Delta C^I(\mathcal{F}) = F_1\mathcal{H} - \frac{t}{4M^2}F_2\mathcal{E} - \xi^2(F_1 + F_2)(\mathcal{H} + \mathcal{E}) \tag{4}$$

which is independent of $\widetilde{\mathcal{H}}$. As for $d^5\Sigma$, the contribution of twist-3 terms to $d^5\sigma$ was found negligible, supporting again factorization [16].

5 Hunting quark angular momentum with n-DVCS

Measuring the DVCS polarized cross section difference on a neutron target (n-DVCS), one can access, similarly to the proton, the combination of Eq. 3. Because of the smallness of the Dirac form factor and the cancellation between the polarized u and d quark distributions in $\widetilde{\mathcal{H}}$, Eq. 3 is dominated by the $\mathcal{E}$ contribution. This spin-flip GPD, which cannot be constrained by deep inclusive scattering, is of particular importance in Ji's sum rule leading to the quark angular momentum [9]. The n-DVCS cross section difference $d^5\Sigma$ was deduced from the subtraction of hydrogen data to deuterium data at Q^2=1.9 GeV^2 and x_B=0.36 [17]. The remaining coherent (d-DVCS) and incoher-

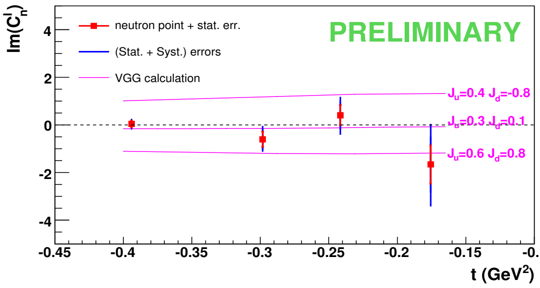

Figure 3: t-dependence of the $\sin(\phi)$ moments of the n-DVCS reaction [15]. The different curves correspond to GPD based calculations for different values of the u and d quarks contributions to the nucleon spin.

ent (n-DVCS) contributions were extracted taking advantage of their $\Delta M_X^2 = -t/2$ kinematical separation [18] in the reconstructed squared missing mass, and the twist-2 (Eq. 3) harmonic coefficient was obtained for several t values, neglecting the higher twist contributions as supported by p-DVCS data. Figure 3 [15] shows the t-dependence of the $\sin(\phi)$ moments extracted for the n-DVCS channel. They appear to be globally compatible with zero. The comparison to GPD based model calculations [19] shows the sensitivity of the present data to the contribution of the u and d quarks to the nucleon spin.

6 Conclusions

The DVCS experimental program at JLab Hall A delivered its first results: the factorization of the cross section was observed, and the power of neutron targets to reach quark angular momenta was proven. These features open unambiguously the era of systematic measurements of generalized parton distributions in DVCS processes at JLab 6 GeV, and 12 GeV in a near future.

Acknowledgments

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