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Deeply Virtual Exclusive Reactions with CLAS

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Abstract

Deeply virtual exclusive reactions offer a unique opportunity to study the structure of the nucleon at the parton level as one has access to Bjorken x_B and momentum transfer to the nucleon t at the same time. Such processes can reveal much more information about the structure of the nucleon than either inclusive electroproduction or elastic form factors alone. Dedicated experiments to study Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) have been carried out in Hall B at Jefferson Lab. DVCS helicity-dependent and helicity-independent cross sections and beam spin asymmetries have been measured with CLAS, as well as cross sections and asymmetries for the π^0 , η , ρ^0 , ρ^+ , ω and ϕ for exclusive electroproduction. The data were taken in a wide kinematic range in $Q^2=1\text{--}4.5\text{ GeV}^2$, $x_B=0.1\text{--}0.5$, and $|t|$ up to 2 GeV^2 . We will discuss the interpretation of these data in terms of traditional Regge and Generalized Parton Distributions (GPDs) models. The successful description of the recent CLAS pseudoscalar meson exclusive production data by GPD-based model provides a unique opportunity to access the transversity GPDs. We view the work presented in this report as leading into the program of the Jefferson Lab 12 GeV upgrade. The increased energy and luminosity will allow us to acquire data at much higher Q^2 and x_B , and perform Rosenbluth L/T separations of the cross sections.

Key words: DVCS, mesons, exclusive, electroproduction, Generalized parton distributions

1. Introduction

The mapping of the nucleon's structure in terms of the Generalized Parton Distributions (GPDs) is one of the major objectives of Jefferson Lab. The GPDs give access to the complex internal structure of the nucleon, such as correlations between parton transverse spatial and longitudinal momentum distributions. They provide a unified picture of the nucleon form factors, polarized and unpolarized parton distributions, and provide access to the contribution of the total parton angular momentum to the nucleon spin. There are four chiral-even GPDs, denoted H^q , $\tilde{H}^q$, E^q and $\tilde{E}^q$, and four chiral-odd GPDs, H_T^q , $\tilde{H}_T^q$, E_T^q and $\tilde{E}_T^q$, which depend on three kinematic variables: x , ξ and t . x is the average momentum fraction and ξ (skewness) is half the difference between the initial and final fractions of the momentum carried by the struck parton. The skewness can be expressed in

terms of the Bjorken variable x_B as $\xi \simeq x_B/(2 - x_B)$. t is the momentum transfer to the nucleon, $t = (p - p')^2$, where p and p' are the initial and final momentum of the nucleon. The H^q and E^q conserve nucleon helicity, while $\tilde{H}^q$ and $\tilde{E}^q$ are associated with a change in nucleon helicity. In the forward limit, $t \rightarrow 0$, H^q and $\tilde{H}^q$ are reduced to the parton density distributions $q(x)$ and parton helicity distributions $\Delta q(x)$. The forward limit of H_T^q is the transversity h_1^q . The first moments of the GPDs are related to the elastic form factors of the nucleon: Dirac form factor $F_1^q(t)$, Pauli form factor $F_2^q(t)$, axial-vector form factor $g_A^q(t)$ and pseudoscalar form factor $h_A^q(t)$.

Hard exclusive processes of meson or photon electroproduction of the nucleon are the key processes to access the GPDs from the experimental observables. At high photon virtuality Q^2 and high energy transfer ν in the Bjorken scaling regime, the scattering amplitude of the hard exclusive processes factorizes

Figure 1: Schematic illustration of the GPD approach to DVCS (left) and DVMP (right).

into a hard scattering part (exactly calculable in QCD) and a nucleon structure part described by the GPDs. Schematic diagrams for Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) in the GPD, or handbag, framework are illustrated in Fig. 1. There are essential differences between DVCS and DVMP. The factorization theorem for DVMP was proven only for longitudinally polarized virtual photons. The direct comparison with the GPD-based model predictions may be done only for experiments that separate σ_L and σ_T cross sections. This can be done using the Rosenbluth method. However, it was proven that in the limit of high Q^2 , the ratio $R = \sigma_T/\sigma_L \sim 1/Q^2$, which may help to separate σ_L and σ_T using a $1/Q^2$ expansion.

The cross section depends actually on the Compton form factors (CFF) and they are the quantities that can be extracted from DVCS and DVMP experiments. In the leading twist, CFFs depend only on ξ (or x_B) and momentum transfer t . The variable x is under the loop integral and is not accessible experimentally. Although DVCS is the cleanest way of accessing GPDs there is no possibility to separate flavors using only this process. The variety of DVMP channels allows one to separate flavor. In addition, DVMP amplitudes involve the axial vector-type GPDs, $\tilde{H}$ and $\tilde{E}$ for pseudoscalar meson production, which gives access to the distribution of quark spin in the proton, and $\tilde{H}$ reduces to the polarized quark/antiquark densities in the limit of momentum transfer $t \rightarrow 0$.

One of the primary goals of the CLAS12 program is to double the Q^2 range of the available data into a region where lower twist corrections become more reliable. Since the extraction of GPDs from electroproduction data can be difficult, a detailed understanding of the reaction mechanism is essential before one can compare with theoretical calculations. It is not yet clear at what values of Q^2 the application of GPDs to meson electroproduction becomes valid [1, 2, 3, 4, 5]. However,

detailed measurements of observables may test model-independent features of the reaction mechanism.

2. Deeply virtual Compton scattering

CLAS has published the DVCS beam-spin asymmetries (BSA) [6, 7] and longitudinally polarized target asymmetries [8]. Figure 2 shows some examples of the published CLAS measured beam-spin asymmetry [7]. By fitting these data in a largely model-independent way, the imaginary parts of the two Compton Form Factors $Im(\tilde{\mathcal{H}})$ and $Im(\mathcal{H})$ were extracted with uncertainties on the order of 30% [9].

In the framework of the dominance of the generalized parton distribution H and twist-2 accuracy, the real and imaginary parts of the Compton Form Factor $\mathcal{H}$ were extracted [10]. In addition to the CLAS data, helicity-independent and helicity-dependent DVCS cross sections were used in this analysis [11]. This is the first attempt to get access to the GPDs from experimental data. The CLAS group is now working on the determination of the absolute DVCS cross sections in a wide kinematic region. The preliminary data are shown in Fig. 3 for six kinematic points. Note the clear signature of the DVCS contribution above the Bethe-Heitler background.

3. Pseudoscalar π^0 and η meson electroproduction

The reactions $ep \rightarrow e'p'\pi^0$ and $ep \rightarrow e'p'\eta$ were measured with the CLAS spectrometer at a beam energy of about 6 GeV. The pions and etas are identified through their 2γ decay channels. This has been made possible by constructing a high quality electromagnetic calorimeter consisting of 424 lead-tungsten crystals covering an angular range from 4.5° to 15° , which was positioned into the existing CLAS large acceptance detector.

Figure 2: Beam-spin asymmetry from the CLAS DVCS experiment. Left: the (x_B, Q^2) acceptance. Middle: beam-spin asymmetry data at two values of t within one Q^2, x_B bin on the left. Right: Extracted beam-spin asymmetry as a function of $-t$ for all kinematic bins. The curves are explained in the graph.

Figure 3: Preliminary DVCS cross section as a function of the angle ϕ for a few of the many kinematic bins in Q^2, x_B and t . The lower black curves are due to a pure BH calculation, the upper curves are fits to the data – the differences are represented in green. Top: $Q^2 = 2.24 \text{ GeV}^2, x_B = 0.25, -t = 0.27, 0.35$ and 0.45 GeV^2 . Bottom: $Q^2 = 2.94 \text{ GeV}^2, x_B = 0.34, -t = 0.35, 0.45$ and 0.62 GeV^2 .

The virtual photon cross section can be written as

$$2\pi \frac{d\sigma}{dtd\phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT} \cos 2\phi +$$

$$\sqrt{2\epsilon(1+\epsilon)/2}\sigma_{LT} \cos \phi_\pi + h \sqrt{\epsilon(1-\epsilon)}\sigma_{LT'} \sin \phi, (1)$$

where ϕ denotes the azimuthal angle between the hadronic and leptonic scattering planes and h is the elec-

Figure 4: Examples of structure functions (preliminary) $\sigma_T + \epsilon\sigma_L$, σ_{LT} , and σ_{TT} as a function of $-t$ for a few kinematic bins: Left: $Q^2 = 1.12$ GeV^2 , $x_B = 0.13$. Middle: $Q^2 = 2.75$ GeV^2 , $x_B = 0.34$. Right: $Q^2 = 3.25$ GeV^2 , $x_B = 0.43$.

tron beam polarization.

The large acceptance of CLAS enabled the grouping of data into about 2000 intervals in Q^2 , t , x_B and ϕ for π^0 and about 1000 bins for η production. For unpolarized electrons ($h = 0$) the separation of the ϕ dependence in *constant*, $\cos \phi$, and $\cos 2\phi$ moments allows us to obtain $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} .

Structure Functions

The structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT} , and σ_{LT} as a function of $-t$ were obtained from fits to the differential cross section data for 17 intervals in Q^2 and x_B (few bins are shown in Fig. 4).

Theoretical calculations based on GPDs found that the leading-twist chirally-even structures in the amplitude do not account for the experimental cross section, even with finite-size corrections through Sudakov form factors [4]. The early efforts to explain π^0, η electroproduction focused on the chiral even GPDs, $\bar{H}, \bar{E}$, as a means to parametrize only the *longitudinal* virtual photon amplitudes [12]. However, in general, there are 8 spin-dependent quark-nucleon GPDs, 4 chiral even and 4 chiral odd [13], and as noted [14] (GL), the quantum numbers and Dirac structure of π^0 electroproduction restrict the possible contributions to the 4 *chiral odd*

GPDs, one of which, H_T , is related to the transversity distribution and the tensor charge.

During the past few years, two parallel approaches - [14, 15, 16] (GL) and [4, 17] (GK) have been developed utilizing chiral odd GPDs in the calculation of pseudoscalar electroproduction. The GL and GK approaches, though differing in detail, leads to sizable *transverse* photon amplitudes, as evidenced in the CLAS data. Both these approaches are evolving as new CLAS data appear.

Inclusion of the chirally-odd twist-3 components of the hard exclusive amplitude gives results in fair agreement with the measured cross sections for both the GL [16] and GK [17] approaches, shown in Fig. 5.

We also display the results of a Regge type analysis [18] of CLAS data in Fig. 6. It appears that the Regge approach can account for the main features of the structure functions, both in their magnitude and their relationships to each other.

t -slopes and Transverse Spatial Structure

The cross sections can be expressed according to the following form: $d\sigma/dt \propto e^{B(x_B, Q^2)t}$. The t slope parameter $B(x_B, Q^2)$ is plotted as a function of x_B for various values of Q^2 in Fig. 7. The fact that the t -slope goes

Figure 5: The structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} as a function of $-t$ at $Q^2 = 2.3 \text{ GeV}^2$ and $x_B = 0.34$ obtained with the CLAS spectrometer. The curves are the results of a GPD-based calculation of Ref. [17], in which the cross section is dominated by the contribution of H_T .

Figure 6: The structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} as a function of t at $Q^2 = 1.38$ and $x_B = 0.17$ obtained with the CLAS spectrometer. The curves are the results of a Regge-based calculation of Ref. [18].

to zero for large x_B may be purely kinematical. However, even taking into account this factor, we note that $B_\perp$ falls with x_B in the region x_B from 0.1 to 0.5 where we have experimental data. This implies that the impact parameter distribution is broadest at lowest x_B and becomes narrower at increasing x_B .

Figure 7: The experimental t -slope parameters (CLAS, preliminary) obtained from fits to the data for various values of Q^2 and x_B .

The ratio of cross sections for η and π^0

Even though current experiments are limited in Q^2 and t , it has been argued [2] that *precocious factorization* ratios of cross sections as a function of x_B could be valid at relatively lower Q^2 than for the cross sections themselves. The ratio of cross sections for π^0 and η electroproduction from a proton is presented in Fig. 8 averaged over x_B and Q^2 as a function of t . This ratio is almost independent of x_B and Q^2 and varies from 0.3 to 0.4 with increasing t [19]. The GPD model [17] is in a good agreement with CLAS data, which can be regarded as an indication of large contributions from the transverse GPDs. We note that the GPD prediction [17] for the η/π^0 ratio at very low t is in agreement with an estimate presented in [2].

Taking into account the good description of CLAS data by GPD models [15, 17] we can make a conclusion that pseudoscalar meson production provides a unique possibility to access the transversity GPDs.

Beam spin asymmetry

The beam spin asymmetry (BSA) is defined by

$$A = \frac{\vec{\sigma} - \overleftarrow{\sigma}}{\vec{\sigma} + \overleftarrow{\sigma}} \sim \alpha \sin\phi. \quad (2)$$

From Eq. 1 the beam spin asymmetry directly yields the $L-T$ interference structure function σ_{LT} . Sizable beam

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Figure 8: The η/π^0 cross section ratio as a function of $-t$. Data points are from CLAS (preliminary) [19] and the curve is from the Ref. [17].

spin asymmetries for exclusive π^0 and η meson electroproduction have been measured above the resonance region over a large number of kinematic bins for the first time [21, 22]. An example of a t distribution of the BSA for π^0 and η production at several kinematic bins is shown in Fig. 9. These large non-zero asymmetries imply that both transverse and longitudinal amplitudes participate in the process.

4. Vector mesons electroproduction

The CLAS collaboration has already published the cross sections for the ρ^0 [23], ω [24] and ϕ [25]. For the ρ^+ channel, the first-ever measurement of its cross section was recently published [26].

Fig. 10 shows the total longitudinal cross section $\sigma_L(\gamma^* p \rightarrow p\rho^0)$ as a function of W for fixed Q^2 . The Regge-based model [27] (the dot-dashed curve) is able to successfully reproduce the cross sections for almost all of our (Q^2, W) range.

In Fig. 10, the dashed line shows the results of the GK model [28], while the thin solid line shows the result of the VGG model [29]. We see that GPD models give a good description of the high and intermediate W region, down to $W \sim 5$ GeV. At high W , the slow rise of the cross section is due to the gluon and sea contributions, while the valence quarks contribute only at small W . At

Figure 9: The t distribution of the beam spin asymmetry for π^0 (open circles) and η (solid triangles, preliminary) at several values of Q^2 and x_B [21, 22]. Error bars are from statistics only, while the gray areas indicate the global systematic uncertainties for the η .

lower W values, where the new CLAS data lie, both the GK and VGG models fail to reproduce the data. This discrepancy can reach an order of magnitude at the lowest W values. The trend of these particular GPD calculations is to decrease as W decreases, whereas the data increase. The same behavior was observed in the low W region for the exclusive electroproduction of the ρ^+ . An attempt to reconcile the GPD calculation with the low W ρ^0 cross sections is presented in Ref. [30]. Through a toy-model, t -channel meson exchanges are included in the GPDs, and the result of this calculation (actually a fit) is illustrated by the thick blue curve in Fig. 10.

Comparison of the t slope for the ρ^0 , ω , ϕ and ρ^+ channels

Fig. 11 shows the slope of the differential cross section $d\sigma/dt$ for the ρ^0 , ω , ϕ and ρ^+ channels as a function of W (on the top part) and as a function of Q^2 (in the bottom part). One can see the same trends of this slope for all mesons channels, which can be interpreted in simple and intuitive terms in the following way:

- The slope increases with W : the size of the nucleon increases as one probes the high W values (i.e. the sea quarks), which could mean that the sea quarks tend to extend to the periphery of the nucleon.
- The slope decreases with Q^2 : as we go to large Q^2 , the resolution of the probe increases and we tend to see smaller and smaller objects.

Figure 10: Longitudinal cross section as a function of W at fixed Q^2 for the reaction $\gamma^* p \rightarrow p p^0$. The dashed curve shows the result of the GK calculation [28] and the thin solid curve shows the result of the VGG calculation [29]. The thick solid curve is the VGG calculation with the addition of the new t -channel meson exchange term. The dot-dashed curve shows the results of the Regge JML calculation.

Figure 11: The t -slope parameter as a function of W (on the top) and as a function of Q^2 (on the bottom) for the ρ^0 , ω , ϕ and ρ^+ channels.

5. Conclusion

Cross sections and asymmetries for $\gamma, \pi^0, \eta, \rho^0, \rho^+, \omega$ and ϕ exclusive electroproduction in a wide kinematic range of Q^2 , t and x_B have been measured with CLAS and initial analyses already are showing remarkable results. The successful description of the CLAS pseudoscalar meson production data by GPD models opens a unique opportunity to access the transversity in the deeply exclusive reactions. We view the work presented here as leading into the program of the Jefferson Lab 12 GeV upgrade. The increased energy and luminosity will allow us to extend the analysis presented here at much higher Q^2 and x_B , as well as to perform Rosenbluth L/T separations.

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References

- [1] J. C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D **56**, 2982 (1997).
- [2] M. I. Eides, L. L. Frankfurt and M. I. Strikman, Phys. Rev. D **59**, 114025 (1999).
- [3] L. Mankiewicz, G. Piller and A. Radyushkin, Eur. Phys. J. C **10**:307-312 (1999).
- [4] S.V. Goloskokov and P. Kroll, Eur. Phys. J. C **65**:137-151 (2010) [0906.0460].
- [5] G.R. Goldstein, and S. Liuti [0908.2197]; S. Ahmad, G.R. Goldstein, and S. Liuti, Phys. Rev. D **79**:054014 (2000).
- [6] S. Stepanyan et al., Phys. Rev. Lett. **87**:182002 (2001).
- [7] F.-X. Girod et al., Phys. Rev. Lett. **100**:162002 (2008).
- [8] S. Chen et al., Phys. Rev. Lett. **97**:072002 (2006).
- [9] M. Guidal, Phys. Lett. B **689**:156 (2010).
- [10] H. Moutarde, Phys. Rev. D **79**:094021 (2009).
- [11] C. Munoz Camacho et al., Phys. Rev. Lett. **97**:262002 (2006).
- [12] K. Goeke, M. V. Polyakov, M. Vanderhaeghen, Prog. Part. Nucl. Phys. **47**, 401-515 (2001), [hep-ph/0106012].
- [13] M. Diehl, Phys. Rept. **388**, 41-277 (2003), [hep-ph/0307382].
- [14] S. Ahmad, G. R. Goldstein, and S. Liuti, Phys. Rev. **D79**, 054014 (2009), [arXiv:0805.3568].
- [15] G. R. Goldstein, J. O. Gonzalez Hernandez, and S. Liuti, *in preparation*.
- [16] G. R. Goldstein, J. O. Gonzalez Hernandez, and S. Liuti, submitted to Phys. Rev. D [arXiv:1012.3776].
- [17] S. Goloskokov and P. Kroll, arXiv:1106.4897.
- [18] J.-M. Laget, [1004.1949] (2010).
- [19] V. Kubarovsky et al. [arXiv:hep-ex/0802.1678].
- [20] A. Afanasev et al., Phys. Rev. D **66**:074004 (2002).
- [21] R. De Masi et al., Phys. Rev. C **77**:042201 (2008).
- [22] K. Joo et al., AIP Conf.Proc.915:607-610 (2007), to be published.
- [23] S. Morrow et al., Eur. Phys. J. A **39**, (2009) 5.
- [24] L. Morand et al., Eur. Phys. J. A **24**, (2005) 445.
- [25] J. P. Santoro et al., Phys. Rev. C **78**, (2008) 025210.
- [26] A. Fradi, thesis Univ. Paris-Sud at Orsay, 2009, [arXiv:hep-ph/1010.1198, hep-ph/1109.3775].
- [27] J.-M. Laget, Phys. Lett. B **489**, (2000) 313.;
F. Cano and J.-M. Laget, Phys. Rev. D **65**, (2002) 074022.;
J. M. Laget, Phys. Rev. D **70**, (2004) 054023.;
F. Cano and J. M. Laget, Phys. Lett. B **551**, (2003) 317.
- [28] S.V. Goloskokov and P. Kroll, Eur. Phys. J.C **42**, (2005) 281; Eur.Phys. J.C **50**, (2007) 829.
- [29] M. Vanderhaeghen, P.A.M. Guichon, and M. Guidal, Phys. Rev. D **60**, 094017 (1999).
- [30] M. Guidal and S. Morrow, *Proceeding of the International Workshop "Exclusive reactions at high momentum transfer", Jefferson Laboratory, Newport-News, Virginia, USA, May 21-24 2007*, World Scientific, [arXiv:hep-ph/0711.3743].