Deeply Virtual Compton Scattering on the neutron in Jefferson Lab Hall A.

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C. Hyde-Wright, Hall A Collaboration Meeting

- Physics case
- n-DVCS experimental setup
- Analysis method
- Results and conclusions
How to access GPDs: DVCS

Deeply Virtual Compton Scattering is the simplest hard exclusive process involving GPDs.

\[ Q^2 = -q^2 = -(k - k')^2 \gg M^2 \]
\[ t = (p - p')^2 = \Delta^2 \ll Q^2 \]

Bjorken regime

Perturbative description (High \( Q^2 \) virtual photon)

Non perturbative description by Generalized Parton Distributions

Handbag diagram
Deeply Virtual Compton Scattering

The GPDs enter the DVCS amplitude as an integral over $x$:

$$
DVCS \text{ amplitude} = P \int_{-1}^{+1} \frac{GPD(x, \xi, t)}{x \pm \xi} \, dx \pm i\pi GPD(x = \pm \xi, \xi, t) + \ldots
$$

$H(x, \xi, 0)$

- Real part
- Imaginary part
Expression of the cross-section difference

\[ d^5 \bar{\sigma} - d^5 \bar{\sigma} \approx 2 \Im m(T^{BH}.T^{DVCS}) + \left[ |\bar{T}^{DVCS}|^2 - |\bar{T}^{DVCS}|^2 \right] \]

\[
\frac{1}{2} \left[ \frac{d^5 \bar{\sigma}}{dQ^2 dx_B dtd\phi_e d\varphi} - \frac{d^5 \bar{\sigma}}{dQ^2 dx_B dtd\phi_e d\varphi} \right] = \frac{\Gamma_3(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)} \left\{ s'_i \sin(\varphi) + s'_2 \sin(2\varphi) \right\} + \frac{s_{1}^{DVCS}}{s_{1}^{DVCS}} \sin(\varphi)
\]

\[ s'_1 = 8Ky(2 - y) \Im m \left\{ C'(\mathcal{F}) \right\} \]

\[ C^I(H, \bar{H}, E) = F_1(t)H(\xi, t) + \xi G_M(t)\bar{H}(\xi, t) + \frac{-t}{4M^2} F_1(t)E(\xi, t) \]

\[ \Im m \{ H \} = \pi \sum_q e_q^2 \left\{ H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right\} \]

GPDs
**Neutron Target**

**Model:**
(Goeke, Polyakov and Vanderhaeghen)

<table>
<thead>
<tr>
<th>Target</th>
<th>H</th>
<th>H̃</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron</td>
<td>0.81</td>
<td>-0.07</td>
<td>1.73</td>
</tr>
</tbody>
</table>

\[
C^I (H, \tilde{H}, E) = F_1(t)H(\xi, t) + \xi G_M(t)\tilde{H}(\xi, t) + \frac{-t}{4M^2} F_1(t)E(\xi, t)
\]

<table>
<thead>
<tr>
<th>(-t)</th>
<th>(F_2^n(t))</th>
<th>(F_1^n(t))</th>
<th>(\left(F_1^n(t) + F_2^n(t)\right) \cdot x_B / (2 - x_B))</th>
<th>(\left(-t / 4M^2\right) \cdot F_2^n(t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>-0.91</td>
<td>-0.04</td>
<td>-0.17</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

\[
\Im C^I = F_1(t)H - \frac{x_B}{2 - x_B} \cdot \left(F_1(t) + F_2(t)\right) \cdot \tilde{H} - \frac{t}{4M^2} F_2(t) \cdot E
\]

\[
\Im C^I = -0.03 + 0.01 - 0.13
\]

\[
Q^2 = 2 \text{ GeV}^2\
x_B = 0.3\
-t = 0.3 \text{ GeV}^2
\]
An **exploratory** experiment was performed at JLab Hall A on hydrogen target and deuterium target with **high luminosity** ($4.10^{37}$ cm$^{-2}$ s$^{-1}$) and **exclusivity**. **Small cross-sections**

**Goal**: Measure the n-DVCS polarized cross-section difference which is mostly sensitive to **GPD E** (less constrained!)

E03-106 (n-DVCS) followed directly the p-DVCS experiment and was finished in December 2004 (started in November).

<table>
<thead>
<tr>
<th>$x_{Bj} = 0.364$</th>
<th>s (GeV$^2$)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$P_e$ (Gev/c)</th>
<th>$\Theta_e$ (deg)</th>
<th>$-\Theta_{y^*}$ (deg)</th>
<th>$\int L dt$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>4.22</td>
<td>1.91</td>
<td>2.95</td>
<td>19.32</td>
<td>18.25</td>
<td>4365</td>
</tr>
<tr>
<td>Deuterium</td>
<td>4.22</td>
<td>1.91</td>
<td>2.95</td>
<td>19.32</td>
<td>18.25</td>
<td>24000</td>
</tr>
</tbody>
</table>
Proton tagger: neutron-proton discrimination

Two scintillator layers:
- **1st layer**: 28 scintillators, 9 different shapes
- **2nd layer**: 29 scintillators, 10 different shapes
Proton tagger

Scintillator S1
Wire chamber H
Wire chamber M
Prototype
Wire chamber B
Scintillator S2
Calorimeter in the black box
(132 PbF2 blocks)

Proton Array
(100 blocks)

Proton Tagger
(57 paddles)

$4.10^{37}$ cm$^{-2}$.s$^{-1}$
Calorimeter energy calibration

2 elastic runs $H(e,e'p)$ to calibrate the calorimeter

Achieved resolution: \[ \frac{\sigma(E)}{E} = 2.4\% \text{ at 4.2 GeV} ; \; \delta x = 2 \text{ mm} \]

Variation of calibration coefficients during the experiment due to radiation damage.

Solution: extrapolation of elastic coefficients assuming a linearity between the received radiation dose and the gain variation

$H(e,e'_{\gamma}p)$ and $D(e,e'_{\gamma}X)$ data measured “before” and “after”
Calorimeter energy calibration

We have 2 independent methods to check and correct the calorimeter calibration.

1st method: missing mass of $D(e,e'\pi^-)X$ reaction.

By selecting $n(e,e'\pi^-)p$ events, one can predict the energy deposit in the calorimeter using only the cluster position. A $\chi^2$ minimisation between the measured and the predicted energy gives a better calibration.
Calorimeter energy calibration

2nd method: Invariant mass of 2 detected photons in the calorimeter ($\pi^0$)

$\pi^0$ invariant mass position check the quality of the previous calibration for each calorimeter region.

Corrections of the previous calibration are possible.

Differences between the results of the 2 methods introduce a systematic error of 1% on the calorimeter calibration.
Identification of n-DVCS events with the recoil detectors is impossible because of the high background rate.

Many Proton Array blocks contain signals on time for each event.

Accidental subtraction is made for p-DVCS events and gives stable beam spin asymmetry results. The same subtraction method gives incoherent results for neutrons.

Other major difficulties of this analysis:

- proton-neutron conversion in the tagger shielding.
  Not enough statistics to subtract this contamination correctly

- The triple coincidence statistics of n-DVCS is at least a factor 20 lower than the available statistics in the double coincidence analysis.
Double coincidence analysis

\[ eD \rightarrow e\gamma X \quad \text{and} \quad eH \rightarrow e\gamma X \]

\[ M_x^2 \text{ cut} = (M_N + M_{\pi})^2 \]

\[ D(e, e'\gamma)X = p(e, e'\gamma)p + n(e, e'\gamma)n + d(e, e'\gamma)d + \ldots \]

- p-DVCS events
- n-DVCS events
- d-DVCS events
- Mesons production
Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity
Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity

2) The missing mass cut must be applied identically in both cases
   - Hydrogen data and Deuterium data must have the same calibration
   - Hydrogen data and Deuterium data must have the same resolution
Double coincidence analysis

Resolution of $\pi^0$ inv. mass (MeV)

Hydrogen
Deuterium

Invariant mass (GeV)

Nh of counts

0 2000 4000 6000 8000 10000 12000 14000 16000

0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24

Invariant mass (GeV)
Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity

2) The missing mass cut must be applied identically in both cases
   - Hydrogen data and Deuterium data must have the same calibration
   - Hydrogen data and Deuterium data must have the same resolution
   - Add nucleon Fermi momentum in deuteron to Hydrogen events
Double coincidence analysis

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3) Remove the contamination of $\pi^0$ electroproduction under the missing mass cut.
\[ M_{\chi}^2 \text{ cut } = (M_p + M_{\pi})^2 \]

\[ \pi^0 \text{ contamination subtraction} \]

Hydrogen data
Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity

2) The missing mass cut must be applied identically in both cases
   - Hydrogen data and Deuterium data must have the same calibration
   - Hydrogen data and Deuterium data must have the same resolution
   - Add nucleon Fermi momentum in deuteron to Hydrogen events

3) Remove the contamination of $\pi^0$ electroproduction under the missing mass cut.

   Unfortunately, the high trigger threshold during Deuterium runs did not allow to record enough $\pi^0$ events.

   **But:**
   \[
   \frac{\sigma(ed \rightarrow e\pi^0 X)}{\sigma(ep \rightarrow e\pi^0 X)} = 0.95 \pm 0.06 \pm \text{sys}
   \]

   In our kinematics $\pi^0$ come essentially from proton in the deuterium

   No $\pi^0$ subtraction needed for neutron and coherent deuteron
Double coincidence analysis

![Graph showing Nb of Counts vs. Mx^2 for Hydrogen data, Deuterium data, Deuterium-Hydrogen, and simulation. Mx^2 cut is indicated at 1.2 GeV^2.](image)
Double coincidence analysis

\[ N^+ - N^- \]

\[ \frac{(N^+ - N^-)}{(N^+ + N^-)} \]

\( \varphi \) (rad)

mm2 (GeV^2)

d-DVCS?
n-DVCS?
Double coincidence analysis

MC Simulation

\[ <t> = 0.3 \text{ GeV}^2 \]
Extraction results

d-DVCS extraction results

**Large error bars (statistics + systematics)**

**Exploration of small \(-t\) regions in future experiments might be interesting**
Neutron contribution is small and close to zero

Results can constrain GPD models (and therefore GPD E)
Systematic errors of models are not shown.
Summary

- n-DVCS is mostly sensitive to GPD E : the least constrained GPD and which is important to access quarks orbital momentum via Ji’s sum rule.

Our experiment is exploratory and is dedicated to n-DVCS.

n-DVCS and d-DVCS contributions are obtained after a subtraction of Hydrogen data from Deuterium data.

The experimental separation between n-DVCS and d-DVCS is plausible due to the different kinematics. The missing mass method is used for this purpose.

To minimize systematic errors, we must have the same calorimeter properties (calibration, resolution) between Hydrogen and Deuterium data.
Outlook

Future experiments in Hall A (6 GeV) to study p-DVCS and n-DVCS

For n-DVCS: Alternate Hydrogen and Deuterium data taking to minimize systematic errors.

Modify the acquisition system (trigger) to record enough $\pi^0$s for accurate subtraction of the contamination.

Future experiments in CLAS (6 GeV) and JLab (12 GeV) to study DVCS and mesons production and many reactions involving GPDs.
VGG parametrisation of GPDs

Non-factorized $t$ dependence

$$H^q(x, \xi, t) = \int_{-1}^{1-|\beta|} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \, \delta(x - \beta - \alpha\xi) F^q(\beta, \alpha, t) + \theta(\xi - |x|) D^q(\frac{x}{\xi})$$

Double distribution:

$$F^q(\beta, \alpha, t) = \frac{1}{|\beta|^{\alpha'} h(\beta, \alpha)} q(\beta)$$

Profile function:

$$h(\beta, \alpha) = \frac{\Gamma(2b + 2)}{2^{2b+1} \Gamma^2(b + 1)} \frac{[(1 - |\beta|)^2 - \alpha^2]^b}{(1 - |\beta|)^{2b+1}}$$

for GPD $E$, the spin-flip parton densities is used: $e_q(\beta)$

Modelled using $J_u$ and $J_d$ as free parameters.
π⁰ electroproduction on the neutron

Amplitude of pion electroproduction:

\[ T(N, \alpha) = \delta(\alpha, 3)T^+ + \tau^\alpha_N T^0 + i\varepsilon_{\alpha\beta} \tau^\beta T^- \]

\(\alpha\) is the pion isospin

\(\tau^\alpha_N\) nucleon isospin matrix

\(\varepsilon_{\alpha\beta}\) is the pion isospin

\(\Delta u\) and \(\Delta d\) are differences in parton distributions

\(\Delta u\) is larger than \(\Delta d\)

\(\pi^0\) electroproduction amplitude (\(\alpha=3\)) is given by:

\[ T(p, 3) = T^+ + T^0 = \frac{2}{3}\Delta u + \frac{1}{3}\Delta d \]

\[ T(n, 3) = T^+ - T^0 = \frac{1}{3}\Delta u + \frac{2}{3}\Delta d \]

\[ \frac{T(p, 3) + T(n, 3)}{2 + \Delta d / \Delta u} \approx \frac{3 + 3\Delta d / \Delta u}{2 + \Delta d / \Delta u} \approx 1.15 \]

Polarized parton distributions in the proton
Triple coincidence analysis

One can predict for each (e, γ) event the Proton Array block where the missing nucleon is supposed to be (assuming DVCS event).
After accidentals subtraction

- proton-neutron conversion in the tagger shielding
- accidentals subtraction problem for neutrons

p-DVCS events (from LD2 target) asymmetry is stable
Time spectrum in the tagger
(no Proton Array cuts)

Entries: 41118
Mean: -1.57
RMS: 6.12
One needs to do a $\pi^0$ subtraction if the only (e,γ) system is used to select DVCS events.

**Symmetric decay**: two distinct photons are detected in the calorimeter $\rightarrow$ No contamination

**Asymmetric decay**: 1 photon carries most of the $\pi^0$ energy $\rightarrow$ contamination because DVCS-like event.
Proton Target

\[ A = F_1(t) \cdot \frac{x_B}{2 - x_B} \cdot \left( F_1(t) + F_2(t) \right) \sim -\frac{t}{4M^2} F_2(t) \]

Proton

<table>
<thead>
<tr>
<th>(-t)</th>
<th>(F_2^p(t))</th>
<th>(F_1^p(t))</th>
<th>((F_1^p(t) + F_2^p(t)) \cdot \frac{x_B}{2 - x_B})</th>
<th>((-t/4M^2) \cdot F_2^p(t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.34</td>
<td>0.81</td>
<td>0.38</td>
<td>0.04</td>
</tr>
<tr>
<td>0.3</td>
<td>0.82</td>
<td>0.56</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td>0.5</td>
<td>0.54</td>
<td>0.42</td>
<td>0.17</td>
<td>0.07</td>
</tr>
<tr>
<td>0.7</td>
<td>0.38</td>
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</tr>
</tbody>
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Model:

\[ Q^2 = 2 \, \text{GeV}^2 \]
\[ x_B = 0.3 \]
\[ -t = 0.3 \]

Target:

<table>
<thead>
<tr>
<th></th>
<th>(H)</th>
<th>(\tilde{H})</th>
<th>(E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>1.13</td>
<td>0.70</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Goeke, Polyakov and Vanderhaeghen
DVCS polarized cross-sections

\[
\frac{d^4 \sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{P_1(\varphi)P_2(\varphi)} \Gamma_1(x_B, Q^2, t) \left\{ c_0^{BH} + c_1^{BH} \cos \varphi + c_2^{BH} \cos 2\varphi \right\} \\
+ \frac{1}{P_1(\varphi)P_2(\varphi)} \Gamma_2(x_B, Q^2, t) \left\{ c_0^I + c_1^I \cos \varphi + c_2^I \cos 2\varphi + c_3^I \cos 3\varphi \right\}
\]

\[
\frac{d^4 \sigma^{-} - d^4 \sigma^{\leftarrow}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)} \left\{ s_1^I \sin \varphi + s_2^I \sin 2\varphi \right\}
\]

Interference term
Calorimeter energy calibration

We have 2 independent methods to check and correct the calorimeter calibration

1st method: missing mass of \(D(e,e'\pi^-)X\) reaction

By selecting \(n(e,e'\pi^-)p\) events, one can predict the energy deposit in the calorimeter using only the cluster position. A \(\chi^2\) minimisation between the measured and the predicted energy gives a better calibration.

2nd method: Invariant mass of 2 detected photons in the calorimeter (\(\pi^0\))

\(\pi^0\) invariant mass position check the quality of the previous calibration for each calorimeter region. Corrections of the previous calibration are possible.

Differences between the results of the 2 methods introduce a systematic error of 1% on the calorimeter calibration.
Analysis method

$$eD \rightarrow e\gamma X$$

**Contamination by**

$$M_x^2 \text{ cut } = (M_N + M_{\pi})^2$$