Deeply Virtual Compton Scattering off the Neutron: measurements with CLAS and CLAS12 at Jefferson Lab

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Wigner distributions

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

*In infinite momentum frame:*

Longitudinal momentum

$$k^+ = xP^+$$

$x$: longitudinal momentum fraction carried by struck parton

**Nucleon structure**

Transverse momentum

Transverse position

Transverse plane

partons

nucleon
Generalised Parton Distributions (GPDs)

- Relate transverse position of partons ($b_\perp$) to longitudinal momentum ($x$).
- Deep exclusive reactions.

Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2k_T$$
Deeply Virtual Compton Scattering

- GPDs relate transverse position of partons to longitudinal momentum. contain information on angular momentum of quarks

- "Golden channel" for GPD extraction: **Deeply Virtual Compton Scattering (DVCS).**

At high exchanged $Q^2$, access to four GPDs: $E_q, \tilde{E}_q, H_q, \tilde{H}_q (x, \xi, t)$

\[
Q^2 = -(p_e - p'_e)^2 \quad t = (p_n - p'_n)^2
\]

Bjorken variable: $x_B = \frac{Q^2}{2 p_n \cdot q}$

$\frac{x \pm \xi}{2}$ longitudinal momentum fractions of quarks

$\xi \equiv \frac{x_B}{2 - x_B}$
Compton Form Factors in DVCS

CFFs: complex functions directly accessible in DVCS cross-sections and spin asymmetries, eg:

\[ A_{LU} = \frac{d\bar{\sigma} - d\bar{\sigma}}{d\bar{\sigma} + d\bar{\sigma}} = \frac{\Delta\sigma_{LU}}{d\bar{\sigma} + d\bar{\sigma}} \]

Related to GPDs:

\[ T_{DVCS}^{\pm} \sim \int_{-1}^{1} \frac{GPDs(x, \xi, t)}{x \pm \xi + i\varepsilon} dx + \ldots \]

\[ P_{DVCS}^{\pm} \sim \int_{-1}^{1} \frac{GPDs(x, \xi, t)}{x \pm \xi} dx \pm i\pi GPDs(\pm \xi, \xi, t) + \ldots \]

Only \( \xi \) and \( t \) are accessible experimentally!
Compton Form Factors in DVCS

- Experimentally accessible in DVCS spin asymmetries, eg:
  \[ A_{LU} = \frac{d\sigma - d\bar{\sigma}}{d\sigma + d\bar{\sigma}} = \frac{\Delta\sigma_{LU}}{d\sigma + d\bar{\sigma}} \]
  \[ \xi = \frac{x_B}{2-x_B} \quad k = t/4M^2 \]

**Beam, target polarisation**

- **Proton**
  \[ \text{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, E_p\} \]
  \[ \text{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, E_n\} \]

- **Neutron**
  \[ \text{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \]
  \[ \text{Im}\{\mathcal{H}_n, E_n, \tilde{E}_n\} \]
  \[ \text{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \]
  \[ \text{Im}\{\mathcal{H}_n, E_n, \tilde{E}_n\} \]
  \[ \text{Im}\{\mathcal{H}_p, E_p\} \]
  \[ \text{Im}\{\mathcal{H}_n\} \]
  \[ \text{Re}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \]
  \[ \text{Re}\{\mathcal{H}_n, E_n, \tilde{E}_n\} \]
Neutron DVCS

- GPDs from proton and neutron: \textbf{flavour separation}
- \textbf{Neutron DVCS} extremely sensitive to $E$, least-known and least-constrained GPD

$\Delta \sigma_{LU} \sim \sin \phi \text{Im}\{F_1H + \xi(F_1+F_2)\tilde{H} - kF_2E\}d\phi$

\textbf{Suppressed} because $F_1(t)$ is small

\textbf{Suppressed} because of cancellation between PDF’s of $u$ and $d$ quarks

- Ji’s “Sum Rule”: $J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^1 xdx \left\{ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right\}$

$J_N = \frac{1}{2} = \frac{1}{2} \Sigma_q + L_q + J_g$

Important missing link in the \textbf{nucleon spin puzzle}!
Neutron DVCS: eg1-dvcs experiment @ Jefferson Lab (Hall B)

Data taken: Feb – Sept 2009

Beam: polarised electrons
- $E_e = 4.7$ to 6 GeV
- polarisation $\sim 85\%$

Longitudinally polarised targets:
- NH$_3$ (95 days)
- ND$_3$ (33 days)
- Proton / neutron pol. $\sim 80 / 40 \%$

Exclusive reconstruction of $e'$, $N$, and $\gamma$.

Spectator proton identified via missing mass.

CLAS → 

Exclusive reconstruction of $e'$, $N$, and $\gamma$.

Spectator proton identified via missing mass.

Inner Calorimeter (IC) → 

High-energy forward photon detection

\[ \bar{e} + d \rightarrow e' + \gamma + n + (p_s) \]
CLAS @ Jefferson Lab (Virginia, USA)

**CEBAF:** Continuous Electron Beam Accelerator Facility:
- Duty cycle: ~ 100%
- Energy up to ~6 GeV
- Electron polarisation up to ~85%

**CLAS in Hall B:**
- Drift chambers
- Toroidal magnetic field
- Cerenkov Counters
- Scintillator Time of Flight
- Electromagnetic Calorimeters

Extremely large angular coverage
DVCS on different targets

**Free proton** in nuclear medium

**H₂**

**Free proton in** nuclear medium

**NH₃**

**Calculate DVCS on a “free” neutron**

**n**

**Quasi-free proton in deuterium and in heavier nuclear medium**

**ND₃**

**Quasi-free neutron in deuterium and in heavier nuclear medium**

**ND₃**

F.-X. Girod et al, PRL. 100 (2008) 162002
$A_{LU}$ – check on proton DVCS in $\text{NH}_3$ and $\text{ND}_3$

Previously measured result on $H_2$ is in range $0.2 - 0.3$.

F.-X. Girod et al, PRL. 100 (2008) 162002

$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.23 \pm 0.02$$

Uncorrected for $\pi^0$ contamination

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Deuterium target – smearing due to Fermi motion requires wider data cuts.

$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.16 \pm 0.02$$

$\pi^0$ contamination more significant

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$\chi^2 / \text{ndf}$

$\chi^2 / \text{ndf}$

$\text{NH}_3$

$\text{ND}_3$

Fit: $A = \frac{p_0 \sin \varphi}{1 + p_1 \cos \varphi}$

$A = \frac{0.2316 \pm 0.0173}{0.1862 \pm 0.1151}$

$A = \frac{0.1618 \pm 0.0158}{-0.09654 \pm 0.19034}$
Neutron DVCS in ND$_3$ – identifying reaction

“Deep Inelastic Scattering” cuts:

- $W > 2\text{ GeV/c}^2$ where $W$ is the missing mass of $(eN \rightarrow e'X)$, isolate resonance region of remaining $\gamma N$
- $Q^2 > 1\text{ GeV}^2$
- $Q^2 > -t$ Region where factorisation applies

Additional DVCS cuts:

- $E_\gamma > 1\text{ GeV}$
- $p_n > 0.4\text{ GeV/c}$

Recoiling nucleon should not have a low $p$
Exclusivity cuts: spectator

Use \( \text{NH}_3 \) data to subtract the nuclear background from the \( \text{ND}_3 \) distributions:

- **Missing momentum** from \( ed \rightarrow e'N'\gamma X \) should be low for spectator nucleon in quasi-free reaction: \( p_X < 0.2 \text{ GeV/c} \)

- **Missing mass** of spectator from \( ed \rightarrow e'N'\gamma X : 0.5 < |m_X^2| < 2 \text{ GeV}^2/c^4 \)

![Graphs showing \( m_X^2 \) for \( \text{ND}_3 \) and \( \text{NH}_3 \) with exclusivity cuts applied]
Exclusivity cuts: angular distributions

- $|\Delta \phi| < 5^\circ$
  - Coplanarity between $\gamma$ and $N$

- $\gamma$ cone angle $< 3^\circ$
  - Difference between calculated and measured $\gamma$ direction
After exclusivity cuts

- **Missing mass** from \( eN \rightarrow e' \gamma X \)
  (should correspond to recoil neutron)

- **Missing mass** from \( eN \rightarrow e' N \gamma X \)
  (should correspond to nothing)

Distributions shown after nuclear background subtraction.
A<sub>LU</sub> in neutron DVCS on ND<sub>3</sub>

- **Beam-spin asymmetry (A<sub>LU</sub>):**

  One previous measurement from Hall A @ JLab, \( A_{LU} \sim 0 \). Big statistical and systematic uncertainties, slightly different kinematic region.

  (M. Mazouz et al, PRL 99 (2007) 242501)

  \[ A_{LU} = p_0 \sin \varphi \]

  \[ \frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.20 \pm 0.05 \]

  Uncorrected for \( \pi^0 \) contamination, which has an asymmetry of its own!
\( A_{UL} \) in neutron DVCS on ND\(_3\)

Target-spin asymmetry \( (A_{UL})\):

\[
A_{UL} = \frac{p_0 \sin \varphi}{1 + p_1 \cos \varphi}
\]

Fit:

- \( p_0 < 0 \)
- \( p_1 \) small

Uncorrected by the dilution factor due to the nuclear background!
Jefferson Lab @ 12 GeV

- **CEBAF**: Continuous Electron Beam Accelerator Facility, upgrade from current 6 GeV to **12 GeV** underway.

- Open up much larger phase space in $Q^2$ and $x_B$.

- Hall B – 11 GeV to the upgraded detector system **CLAS12**

- CLAS12 experiments: expected 2016
$A_{LU}$ in Neutron DVCS @ 11 GeV

$E_e = 11$ GeV

VGG Model (calculations by M. Guidal)

Fixed kinematics: $x_B = 0.17$, $Q^2 = 2$ GeV$^2$, $t = -0.4$ GeV$^2$

- At 11 GeV, beam spin asymmetry ($A_{LU}$) in neutron DVCS is very sensitive to $J_u, J_d$
- Wide coverage needed!
- Exclusive reconstruction of the DVCS process $en \rightarrow e'n'\gamma$ requires detection and measurement of all three final state particles.

$J_u = 0.3, J_d = -0.1$  $J_u = 0.3, J_d = 0.1$
$J_u = 0.1, J_d = 0.1$  $J_u = 0.3, J_d = 0.3$
CLAS12: base detectors

Design luminosity
$L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

Acceptance for charged particles:
- Central (CD), $40^\circ < \theta < 135^\circ$
- Forward (FD), $5^\circ < \theta < 40^\circ$

Acceptance for photons:
- IC $2^\circ < \theta < 5^\circ$
- EC, $5^\circ < \theta < 40^\circ$

High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes
Recoil DVCS neutrons in CLAS12

Simulation of nDVCS neutrons at $E_e = 11$ GeV.

Over 80% of neutrons recoil at $\theta_{\text{lab}} > 40^\circ$ with peak momentum at $\sim 0.4$ GeV/c.

Neutron detector for CLAS12: 3-layer scintillator barrel, 48 paddles/layer.

Light-guides

U-turn light guide

Scintillators

Limitations of space and high magnetic field (5T) in central region necessitate a u-turn geometry.

- Neutron efficiency $\sim 8$-$9\%$

- $\frac{\sigma_p}{p} \approx 5$-$12\%$

- $\sigma_\theta \approx 2$-$3^\circ$

- $\sigma_\phi = 3.75^\circ$
$\bar{e} + d \rightarrow e' + n + \gamma + (p_s)$  The **most sensitive** observable to the GPD $E$

80 days of data taking  
$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}$

CLAS12 +  
Forward Calorimeter +  
Neutron Detector

Experiment approved, detector constructed.
Neutron DVCS with polarised targets

- DVCS transverse target spin asymmetry: $ep^\uparrow \rightarrow ep\gamma$

  Transverse-target spin asymmetry is highly sensitive to the u-quark contributions to proton spin.

  LOI approved at PAC38, target R&D under way.

- DVCS on longitudinally polarised (ND3) target: proposal submitted to PAC40 (July 2015).

  Crucial for flavour-decomposition of the GPDs.

Projected results:

- $Q^2 = 2.2 \text{ GeV}^2$, $x_B = 0.25$, $-t = 0.5 \text{ GeV}^2$

  - $A_{UTx}$ Target polarization in scattering plane
  - $A_{UTy}$ Target polarization perpendicular to scattering plane
Summary

- **GPDs** provide a 3D image of the internal dynamics of the nucleon and carry information on the composition of nucleon spin. They are experimentally accessible in exclusive reactions such as DVCS.

- Exclusive measurements of the *beam- and target-spin asymmetries in DVCS* on the **neutron** in the kinematic range opening up with CLAS12, in conjunction with those on the proton, will provide flavour decomposition of the GPDs and yield insight on the total angular momentum contribution of u, d quarks.

- An extraction of DVCS on **deuterium @ 6GeV** is underway – indications of a very low but measurable beam-spin asymmetry from the neutron and a first measurement of a target-spin asymmetry in nDVCS.

*Thank you!*
Back-up slides
Wigner function: full phase space parton distribution of the nucleon

\[ \int d^2 k_T \]

Generalised Parton Distributions (GPDs)

contain information on angular momentum of quarks

\[ \int d^2 b_T \]

Transverse Momentum Distributions (TMDs)

\[ \int dx \]

Form Factors

\[ \int d^2 k_T \]

Parton Distribution Functions (PDFs)
A 100 views of the nucleon...

...or “the story of the blind men and the elephant”

- Elastic scattering
- Deep Inclusive Scattering (DIS)
- Semi-inclusive DIS
- Deep exclusive reactions

G. Renee Guzlas, artist.
Views of a nucleon: I

Wigner function: full phase space parton distribution of the nucleon

\[ \int d^2b_T \]

Semi-inclusive Deep Inelastic Scattering:

Transverse Momentum Distributions (TMDs)
Views of a nucleon: I

Wigner function:
full phase space parton
distribution of the nucleon

\[
\int d^2 b_T
\]

Transverse
Momentum
Distributions
(TMDs)

Deep
Inelastic
Scattering

\[
\int d^2 k_T
\]

Parton Distribution
Functions (PDFs)
Views of a nucleon: II

Wigner function:
full phase space parton distribution of the nucleon

Generalised Parton Distributions (GPDs)

\[ \int d^2 k_T \]

Form Factors

\[ G_E, G_M \]

Elastic scattering

\[ \int dx \]

Fourier Transform of electric Form Factor:
transverse charge density of a nucleon

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)
**Measuring DVCS**

- Process measured in experiment:

\[
\begin{align*}
\sigma &\propto |T_{DVCS}|^2 + |T_{BH}|^2 + T_{BH}T_{DVCS}^* + T_{DVCS}T_{BH}^* \\
\end{align*}
\]

- DVCS

- Bethe - Heitler

- Amplitude parameterised in terms of Compton Form Factors
- Amplitude calculable from elastic Form Factors and QED!
- Interference term

\[
|T_{DVCS}|^2 \ll |T_{BH}|^2
\]
Which DVCS experiment?

\[ H(x, \xi, t) : \] Independent of quark helicity, unpolarised GPDs

\[ E(x, \xi, t) : \]

\[ \tilde{H}(x, \xi, t) : \] Helicity-dependent, polarised GPDs.

\[ \tilde{E}(x, \xi, t) : \]

Beam, target polarisation

\[ e^- \rightarrow p/n \]

\[ e^- \rightarrow \]

\[ \text{Proton} \hspace{1cm} \text{Neutron} \]

\[ \text{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\} \]

\[ \text{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\} \]

\[ \text{Re}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \]

\[ \text{Re}\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\} \]

Independent of quark helicity, unpolarised GPDs
Particle ID – Electrons

- $q$ and $p$ from track-curvature through drift chambers in magnetic field

- Separation from $\pi$: on basis of energy deposit in electromagnetic calorimeter (EC) and number of photoelectrons produced in Cerenkov counters (CC).

# of photoelectrons (x10) in CC

E deposit in EC / $p$ vs. $p$
Particle ID – Photons and Neutrons

- $\beta$ from neutral particles’ time of flight to EC
- Forward, low-angle photons in additional Inner Calorimeter

Hits in IC with E deposit > 1 GeV

- Neutrons: $p_n = \frac{\beta m_n}{\sqrt{1 - \beta^2}}$, $E_n = \sqrt{m_n^2 + p_n^2}$
- Photons: $E$ deposited in calorimeter
Neutron Detector for CLAS12

Available:
- 10 cm of radial space
- in a high magnetic field (~5T)

Detector proposal approved:
- Plastic scintillator barrel: 3 layers, 48 paddles in each
- Length ~ 70 cm, inner radius 29 cm
- Long (~1.5 m) light-guides
- PMT read-out upstream, out of high B field

Light guides

PMT 1

PMT 2

Scintillators

U-turn light guide
CND Simulation (Geant 4)

- Neutron efficiency ~ 8-9 %
- Good separation of neutrons and γ up to ~ 1 GeV/c
- $\frac{\sigma_p}{p} \approx 5 - 12\%$  $\sigma_\theta \approx 2 - 3^\circ$
- 1 – 3% contamination from mis-reconstructed hits