Neutrons in a Spin: Nucleon Structure at Jefferson Lab

Daria Sokhan

University of Glasgow, UK

on behalf of the CLAS Collaboration

IoP Nuclear Physics Group Conference, York – 8th April 2013
Nucleon structure

Lepton (eg: electron, neutrino) scattering off a nucleon reveals different aspects of nucleon structure.

**Elastic Scattering**

Cross-section parameterised in terms of Form Factors

Transverse quark distributions: charge, magnetisation.
Charge density inside a nucleon

Proton

Neutron

negative inner core

positive outer surface

Deep Inelastic Scattering

First experimental evidence of partons inside a nucleon

Cross-section parameterised in terms of Structure Functions

Longitudinal momentum distributions of partons
Parton Distribution Functions

Momentum distributions of quarks and gluons within a nucleon.

\( x \): longitudinal momentum of parton as a fraction of nucleon’s momentum.
Deep Exclusive Reactions

Generalised Parton Distributions (GPDs) relate transverse position of partons, $b_\perp$, to their longitudinal momentum.

Tomography: 3D image of the nucleon.
The Nucleon Spin Puzzle

What contributes to nucleon spin?

1980’s: European Muon Collaboration (EMC) measures contribution of valence quarks to proton spin to be $\sim 30\%$. Subsequent deep inelastic scattering (DIS) experiments confirm.

Where is the rest? Proton spin crisis!

**Quark spin:** extracted from helicity distributions measured in polarised DIS.

$$J_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g$$

**Gluon spin:** measurements of DIS and polarised proton collisions indicate $\Delta G$ is very small.

**Quark orbital angular momentum:** can be accessed via GPDs, which contain information on total angular momentum, $J_q$.

Caveat:
The three terms not yet accessible within a single formalism.
Deeply Virtual Compton Scattering

One of the cleanest experimental processes in which GPDs can be accessed is **Deeply Virtual Compton Scattering** (DVCS).

\[
Q^2 = -q^2 = -(e - e')^2 \quad t^2 = -(p - p')^2
\]

**Bjorken variable**
\[
x_B = \frac{Q^2}{2p \cdot q}
\]

\( x \pm \xi \): longitudinal momentum fractions of struck quark

\[
\xi \approx \frac{x_B}{2 - x_B}
\]

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

* DVCS and Bethe-Heitler (BH) experimentally indistinguishable.

Process measured in experiment:

\[
\frac{d\sigma}{d\Omega} \propto |T_{DVCS}|^2 + |T_{BH}|^2 + T_{BH} T^{*}_{DVCS} + T_{DVCS} T^{*}_{BH}
\]

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

|\[|T_{DVCS}|^2 \ll |T_{BH}|^2\]|
Experimentally, access Compton Form Factors (CFF), which are combinations of GPDs integrated over $x$ and functions of GPDs at $x=\xi$. Only $\xi$ and $t$ are thus experimentally directly accessible!

\[ T_{DVCS} \propto \int_{-1}^{1} \frac{GPDs(x, \xi, t)}{x \pm \xi} dx \pm i\pi \; GPDs(\pm \xi, \xi, t) + \ldots \]
**Extracting Compton Form Factors**

* For example, from DVCS spin asymmetries:

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

Beam, target polarisation

\[\Delta\sigma_{LU} \sim \sin\phi \text{ Im}\{F_1 \mathcal{H} + \xi (F_1+F_2) \mathcal{\bar{H}} - kF_2 E\} d\phi \]

\[\xi = x_B/(2-x_B) \quad k = t/4M^2\]

\[\Delta\sigma_{UT} \sim \cos\phi \text{ Im}\{k(F_2 \mathcal{H} - F_1 E) + \ldots\} d\phi\]

\[\Delta\sigma_{LL} \sim (A+B\cos\phi) \text{ Re}\{F_1 \mathcal{\bar{H}} + \xi (F_1+F_2) (\mathcal{H} + x_B/2E)\ldots\} d\phi\]

**Proton** \(\text{Neutron}\)

\[\text{Im}\{\mathcal{H}_p, \mathcal{\bar{H}}_p, E_p\}\]

\[\text{Im}\{\mathcal{H}_n, \mathcal{\bar{H}}_n, E_n\}\]

\[\text{Im}\{\mathcal{H}_p, E_p\}\]

\[\text{Im}\{\mathcal{H}_n\}\]

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

\[\text{Re}\{\mathcal{H}_n, E_n, \mathcal{\bar{E}}_n\}\]
Neutron DVCS

- GPDs from proton and neutron: **flavour separation**
- **Neutron DVCS** extremely sensitive to $E$, least-known and least-constrained GPD.

![Diagram of Neutron DVCS](image)

**Polarized beam, unpolarized neutron target:**

$$ \Delta\sigma_{LU} \sim \sin\phi \text{ Im} \{ F_1 H + \xi(F_1 + F_2) \tilde{H} - kF_2 E\} d\phi $$

**Suppressed** because $F_1(t)$ is small

**Suppressed** because of cancellation between PDF’s of $u$ and $d$ quarks

**Ji’s “Sum Rule”:**

$$ J_q = \frac{1}{2} - J_g = \frac{1}{2} \int_{-1}^{1} x dx \left\{ H_q(x, \xi, 0) + E_g(x, \xi, 0) \right\} $$

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

Important missing link in the **nucleon spin puzzle**!
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
Neutron DVCS: Eg1-dvcs experiment

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.

CLAS → Inner Calorimeter (IC) → high-energy forward photon detection
Particle ID in CLAS

- $q$ 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).

- $\beta$ from neutral particles’ time of flight to EC

- Forward, low-angle photons in additional Inner Calorimeter
Reaction Identification

Select kinematic region where GPD formalism holds:
- $Q^2 > 1 \text{ GeV}^2$
- $E_\gamma > 1 \text{ GeV}$
- $p_n > 0.4 \text{ GeV}/c$
- $W > 2 \text{ GeV}/c^2$ where $W$ is the missing mass of $(eN \rightarrow e' X)$, remove resonance region of remaining $\gamma N$

Additionally, require:
- Coplanarity between $\gamma$ and $N$
- Missing momentum from $ed \rightarrow e' N' \gamma X$
  Should be low for spectator nucleon in quasi-free reaction
- Missing mass from the above reaction should correspond to mass of nucleon.
- Difference between calculated and measured $\gamma$ direction should be low.
DVCS on different targets

- **Free proton** in nuclear medium
- **H₂**
- **NH₃**
- **ND₃** Quasi-free proton in deuterium and in heavier nuclear medium
- **ND₃** Quasi-free neutron in deuterium and in heavier nuclear medium
- Calculate DVCS on a “free” neutron

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

$\rightarrow$ actual $A_{LU}$ larger!

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

$\rightarrow$ measured $A_{LU}$ lower than on NH$_3$. 

Fit: $A = \frac{p_0 \sin \varphi}{1 + p_1 \cos \varphi}$
**$A_{LU}$ and $A_{UL}$ in neutron DVCS on ND$_3$**

- **Beam-spin asymmetry:**
  
  One previous measurement from Hall A @ JLab, $A_{LU} \approx 0$. Big statistical and systematic uncertainties, slightly different kinematic region.

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

  $$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.06 \pm 0.02$$

- **Target-spin asymmetry:**

  First measurement!

  Uncorrected for $\pi^0$ contamination, includes neutrons from N!

  $p_0 \approx 0.077 \pm 0.06 \quad p_1 \approx 0.11 \pm 0.06$
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

- Scheduled completion ~ 2014
$A_{LU}$ in Neutron DVCS @ 11 GeV

At 11 GeV, beam spin asymmetry ($A_{LU}$) in neutron DVCS is very sensitive to $J_u, J_d$

Wide coverage needed!

VGG Model (calculations by M. Guidal)

Fixed kinematics: $x_B = 0.17$  $Q^2 = 2$ GeV$^2$  $t = -0.4$ GeV$^2$
CLAS12

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

- Beam-spin asymmetry in neutron DVCS at 11 GeV – extremely sensitive to $J_q$
- Exclusive reconstruction of the DVCS process $e n \rightarrow e' n' \gamma$
  require detection and measurement of all three final state particles.

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

Requires central neutron
detector sensitive to
$0.2 < p_n < 1.2$ GeV/c.

Simulation at $E_e = 11$ GeV
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 28.5 cm
- Long (~ 1.5 m) light-guides
- PMT read-out upstream, out of high B field

Light guides

U-turn light guide

Scintillators
CND Simulation (Geant 4)

- Neutron efficiency $\sim 8-9\%$
- Good separation of neutrons and $\gamma$ up to $\sim 1$ GeV/c

$\sigma_p/p \approx 5 - 12\% \quad \sigma_\theta \approx 2 - 3^\circ$

- 1 – 3% contamination from mis-reconstructed hits

Detector under construction at IPN Orsay, France, for 2014.
In Conclusion:

★ GPDs provide a 3D image of the internal dynamics of the nucleon and are experimentally accessible in exclusive reactions such as DVCS.

▶ More on testing GPD predictions in talk by J. Sjögren: Mon 14.45, Session 2

★ Beam-spin asymmetry in DVCS on the neutron, particularly in the kinematic range opening up with CLAS12, will offer vital information on the composition of nucleon spin.

★ The Central Neutron Detector is under construction – to allow exclusive reconstruction of neutron DVCS with CLAS12 at Jefferson Lab.

★ A preliminary extraction of DVCS on deuterium @ 6GeV is underway – indications of a low measurable beam-spin and target-spin asymmetry on the neutron.
Thank you!
Back-up slides
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: $p_\gamma = E$ deposited in calorimeter
Neutron DVCS in ND$_3$ – data cuts II

- $p_n > 0.4$ GeV/c  Recoiling nucleon should not have a low $p$
- $|\Delta \varphi| < 10^\circ$  Coplanarity between $\gamma$ and $N$
- $\gamma$ cone angle < 5°  Difference between calculated and measured $\gamma$ direction
- Missing momentum from $ed \rightarrow e'N'\gamma X$
  Should be low for spectator nucleon in quasi-free reaction
First measurement of nDVCS: Hall A

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

\[ E_e = 5.75 \text{ GeV/c} \quad P_e = 75\% \]
\[ L = 4 \cdot 10^{37} \text{ cm}^{-2} \cdot \text{s}^{-1}/\text{nucleon} \]

\[ Q^2 = 1.9 \text{ GeV}^2 \]
\[ x_B = 0.36 \]
\[ 0.1 \text{ GeV}^2 < -t < 0.5 \text{ GeV}^2 \]

Analysis done in the impulse approximation:
\[ D(e, e' \gamma)X = p(e, e' \gamma)p + n(e, e' \gamma)n + d(e, e' \gamma)d + \cdots \]

Subtraction of quasi-elastic proton contribution deduced from $H_2$ data convoluted with initial motion of the nucleon

Twist-2

\[
\frac{d^5 \Sigma_{D-H}}{d^5 \Phi} = \frac{1}{2} \left[ \frac{d^5 \sigma^+}{d^5 \Phi} - \frac{d^5 \sigma^-}{d^5 \Phi} \right]
\]

\[
= \left( \Gamma_d \Im \{ C_d \}^{\exp} + \Gamma_n \Im \{ C_n \}^{\exp} \right) \sin(\phi_{\gamma\gamma})
\]
**nDVCS in Hall A: results**

\[ Q^2 = 1.9 \text{ GeV}^2 - x_B = 0.36 \]

\[
[C^I_n]^{exp} \simeq [C^I_n] = F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}
\]

**Im(C^I_n)** compatible with zero \((\rightarrow \text{too high } x_B ?)\)

Strong correlation between \(\text{Im}[C^I_d]\) and \(\text{Im}[C^I_n]\)

Big statistical and systematic uncertainties (mostly coming from \(H^2\) and \(\pi^0\) subtraction)

Model dependent extraction of \(J_u\) and \(J_d\)

---

**Im(C^I_n)** compatible with zero \((\rightarrow \text{too high } x_B ?)\)

Strong correlation between \(\text{Im}[C^I_d]\) and \(\text{Im}[C^I_n]\)

Big statistical and systematic uncertainties (mostly coming from \(H^2\) and \(\pi^0\) subtraction)
**A_LU from neutron DVCS with CLAS12**

\[
\bar{e} + d \rightarrow e' + n + \gamma + (p_s)
\]

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

CLAS12 +
Forward Calorimeter +
Neutron Detector

Model predictions (VGG) for different values of quarks’ angular momentum:

\[
\Delta \sigma_{LU} \sim \sin \phi \text{ Im} \{F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} \mathcal{K} F_2 \mathcal{E} \} \, d\phi
\]

The most sensitive observable to the GPD $E$