A view into the nucleon: electron scattering at Jefferson Lab

Daria Sokhan
University of Glasgow, UK

International School of Nuclear Physics: 38th Course
Erice, Sicily — 21st September 2016
Prologue...
The nucleon through the electromagnetic lens

- Present day state (since ~1ms after the Big Bang).
- Cold: quarks in confinement.
- Abundant: almost all of the visible mass of the universe.
- Not well-understood: perturbative QCD cannot describe it. What makes up its spin? Why is its mass so large? ...


What your room-temperature nucleon looks like today
Scales of resolution – an elephantine analogy

Lyuba, baby mammoth found in Siberia, imaged with visible light...

International Mammoth Committee

\[ Q^2 \sim \text{MeV}^2 \]
Scales of resolution – an elephantine analogy

Lyuba, baby mammoth found in Siberia, imaged with visible light...
... and X-rays.

International Mammoth Committee

Equivalent wavelength of the probe:

$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$
Scales of resolution – an elephantine analogy

Lyuba, baby mammoth found in Siberia, imaged with visible light...
... and X-rays.

Equivalent wavelength of the probe:

\[ \lambda \approx \frac{1}{\sqrt{Q^2}} \]

What you see depends on what you use to look...
Electron scattering

Electromagnetic interaction: sensitive to distributions of charge and magnetisation — information on quark structure of the hadron at different energy scales.

Deep inelastic scattering (DIS):

- Inclusive — only the electron is detected.
- Semi-inclusive — electron and typically one hadron detected.
- Exclusive — all final state particles detected.
- Polarised electrons / hadrons — sensitivity to helicity distributions.
- Cross-sections, cross-section differences and asymmetries.

Measurements:

Complementary information on the nucleon’s structure.
Structure of the nucleon
What we would really like to know...

Wigner distributions

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

or your favourite representation...

$x$: longitudinal momentum fraction carried by struck parton
What we do know…

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

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

G. Renee Guzlas, artist.
What we do know…

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

What you see depends also on how you to look…

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

G. Renee Guzlas, artist.
Different views of the nucleon: I

Wigner function: full phase space parton distribution of the nucleon

\[ \int d^2 b_T \]

Transverse Momentum Distributions (TMDs)

*Semi-inclusive DIS*
Different views of the nucleon: II

Wigner function:
full phase space parton
distribution of the nucleon

\[ \int d^2 b_T \]

Transverse
Momentum
Distributions
(TMDs)

\[ \int d^2 k_T \]

Parton Distribution
Functions (PDFs)
Different views of the nucleon: II

Wigner function:
full phase space parton
distribution of the nucleon

\[ \int d^2 b_T \]

Transverse Momentum Distributions (TMDs)

\[ \int d^2 k_T \]

Parton Distribution Functions (PDFs)

Deep Inelastic Scattering
Different views of the nucleon: III

Wigner function:
full phase space parton
distribution of the nucleon

\[ \int d^2 k_T \]

Generalised Parton Distributions (GPDs)

- relate transverse position of partons \((b_\perp)\) to longitudinal momentum \((x)\).

* Deep exclusive reactions
Different views of the nucleon: IV

Wigner function:
full phase space parton
distribution of the nucleon

\[ \int d^2 k_T \]

Generalised Parton
Distributions (GPDs)

\[ \int dx \]

Form Factors
eg: \( G_E, G_M \)

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

proton

neutron

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)
What do GPDs tell us?

- **Tomography** of the nucleon: transverse spacial distributions of quarks and gluons in longitudinal momentum space.

- Small changes in nucleon transverse momentum allows mapping of transverse structure at large distances: **confinement**.

- For additionally small $x$ can image the pion cloud: chiral symmetry breaking.

- Provide information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

- Using transversely polarised targets can map transverse shift of partons due to the polarisation: combine with TMDs to access **spin-orbit correlations** of quarks and gluons, study non-perturbative interactions of partons.
Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%
- Three experimental fixed-target halls

Hall A:
- High resolution ($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS
- Very large acceptance, detector array for multi-particle final states.

Hall C:
- Two movable spectrometer arms, well-defined acceptance, high luminosity.
Jefferson Lab: 12 GeV era

- Maximum electron energy: 12 GeV to new Hall D
- 11 GeV deliverable to Halls A, B and C

Hall A: High resolution spectrometers, large installation experiments

**Hall B: CLAS12**

Very large acceptance, high luminosity

**Hall D:** 9 GeV tagged polarised photons, full acceptance detector

Hall C:

Super-high Momentum Spectrometer added, very high luminosity
Deeply Virtual Compton Scattering
Deeply Virtual Compton Scattering

the "golden channel" for GPD extraction

At high exchanged $Q^2$ and low $t$ access to four GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t)$$

Can be related to PDFs:

$$H(x, 0, 0) = q(x) \quad \tilde{H}(x, 0, 0) = \Delta q(x)$$

and form factors:

$$\int_{-1}^{+1} H \, dx = F_1 \quad \int_{-1}^{+1} \tilde{H} \, dx = G_A$$

$$\int_{-1}^{+1} E \, dx = F_2 \quad \int_{-1}^{+1} \tilde{E} \, dx = G_P$$

(Dirac and Pauli) (axial and pseudo-scalar)

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

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

\[ x \pm \xi \text{ longitudinal momentum fractions of quarks} \quad \xi = \frac{x_B}{2 - x_B} \]
Measuring DVCS

Process measured in experiment:

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

- Amplitude calculable from elastic Form Factors and QED
- Interference term

Amplitude parameterised in terms of Compton Form Factors
Compton Form Factors in DVCS

Experimentally accessible in DVCS cross-sections and spin asymmetries, eg:

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

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

Only \(\xi\) and \(t\) are accessible experimentally!

To get information on \(x\) need extensive measurements in \(Q^2\).

Need measurements off proton and neutron to get flavour separation of CFFs.
GPDs and the spin puzzle

* Total angular momentum of a nucleon: 

\[ J_N = \frac{1}{2} = \frac{1}{2} \sum q + L_q + J_g \]

* Ji’s relation:

\[ J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{1} x dx \left\{ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right\} \]

Need measurements at low $t$, across wide $Q^2$, of a range of observables to extract both $H$ and $E$.

Need flavour separation of GPDs.
What should we measure?

Real parts of CFFs accessible in cross-sections and double polarisation asymmetries, imaginary parts of CFFs in single-spin asymmetries.

Beam, target polarisation

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

Proton

Neutron

\[ \Im \{ H_p, H_p, E_p \} \]
\[ \Im \{ H_n, H_n, E_n \} \]
\[ \Im \{ H_p, H_p \} \]
\[ \Im \{ H_n, E_n, E_n \} \]

\[ \Re \{ H_p, E_p \} \]
\[ \Re \{ H_n \} \]
\[ \Re \{ H_p, H_p \} \]
\[ \Re \{ H_n, E_n, E_n \} \]
First DVCS cross-sections in valence region

- Hall A, ran in 2004, high precision, narrow kinematic range. Data recently re-analysed. \( Q^2: 1.5 - 2.3 \text{ GeV}^2, \ x_B = 0.36. \)

- CFFs show scaling in DVCS: leading twist (twist-2) dominance at moderate \( Q^2 \) (1.5 - 2.3 GeV^2).

- GPDs can be extracted at JLab kinematics

- Extraction of \( |T_{DVCS}|^2 \) amplitude as well as interference terms.

- Strong deviation of DVCS cross-section from BH: experiment probing its energy-dependence under analysis.

What do the CFFs from the cross-sections tell us?

- High-statistics measurement across a wide kinematic range:
  

- Slope in $t$ becomes flatter at higher $x_B$

- Valence quarks at centre, sea quarks at the periphery.
**DVCS Cross-sections @ 11 GeV**

*Experiments:*
E12-06-114 (Hall A, 100 days),
E12-13-010 (Hall C, 65 days)
at a range of beam energies.

- Azimuthal, energy and helicity dependencies of cross-section to separate $|T_{DVCS}|^2$ and interference contributions in a wide kinematic coverage.
Beam and target-spin asymmetries

\[ A = \frac{\alpha \sin \phi}{1 + \beta \cos \phi} \]

GGL: Goldstein, Gonzalez, Liuti

GK: Kroll, Moutarde, Sabatié

KMM: Kumericki, Mueller, Murray

S. Pisano et al (CLAS Collaboration), **PRD 91** (2015) 052014

Double-spin Asymmetry ($A_{\text{LL}}$)

Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.

CFF extraction from three spin asymmetries at common kinematics.

What can we learn from the asymmetries?

Information about the relative spread of the axial and electric charges in the nucleon?

\[ H^q(x, 0, 0) = f_1(x) \]
\[ \tilde{H}^q(x, 0, 0) = g_1(x) \]

Asymmetries in Proton-DVCS with CLAS12

Approved experiment (E12-06-119):

\[ P_{\text{beam}} = 85\% \]
\[ L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]
\[ 1 < Q^2 < 10 \text{ GeV}^2 \]
\[ 0.1 < x_B < 0.65 \]
\[ -t_{\text{min}} < -t < 2.5 \text{ GeV}^2 \]

120 days (polarised target)

\[ P_{\text{target}} = 80\% \]
Statistical error: 2% - 15%
on \( \sin \phi \) moments
Systematic uncertainties: ~ 6 - 8%

85 days (unpolarised target):
Statistical error: 1% - 10%
on \( \sin \phi \) moments
Systematic uncertainties: ~ 6 - 8%

Impact of CLAS12 DVCS \( A_{LU} \) data on model-independent fit to extract \( \text{Im}(H) \)
DVCS with transversely polarised target at CLAS12

E12-12-010: transversely polarised HD target.

$$\Delta \sigma_{UT} \sim \cos \phi \, \text{Im}\{k(F_2H - F_1E) + \ldots\} \, d\phi$$

Sensitivity to $\text{Im}(E)$

![Graphs showing sensitivity to $\text{Im}(E)$ at different $x$ values and $Q^2$ values.](image)
Neutron DVCS

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

\[ \Delta \sigma_{LU} \sim \sin \phi \ \text{Im} \{ F_1 H + \xi (F_1 + F_2) \tilde{H} - k F_2 E \} \, d\phi \quad \rightarrow \quad \text{Im} \{ E_n \} \ \text{dominates.} \]

- Ji’s relation:

\[ J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{1} x dx \ \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\} \]

\[ J_N = \frac{1}{2} = \frac{1}{2} \sum_q + L_q + J_g \]

Important missing link in the nucleon spin puzzle…

- First measurement in Hall A, consistent with zero: M. Mazouz et al, PRL 99 (2007) 242501
- Analysis on CLAS data in a different kinematic region ongoing…
**A_{LU} in Neutron DVCS @ 11 GeV**

$E_e = 11 \text{ GeV}$

**Graph**

- $J_u = 0.3$, $J_d = -0.1$
- $J_u = 0.3$, $J_d = 0.1$
- $J_u = 0.1$, $J_d = 0.1$
- $J_u = 0.3$, $J_d = 0.3$

- 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:** $x_B = 0.17$, $Q^2 = 2 \text{ GeV}^2$, $t = -0.4 \text{ GeV}^2$
The most sensitive observable to the GPD $E_n$

$e + d \rightarrow e' + \gamma + n + (p_s)$

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

CLAS12 +
Forward Calorimeter +
Neutron Detector

Simulated statistical sample:
Neutron Detector for CLAS12

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

Detector design
★ 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
DVCS on the neutron with a longitudinally polarised deuterium target

In combination with pDVCS, allow flavour-separation of CFFs. Expected sensitivities:
To conclude...

- Electron scattering is a clean and versatile probe into the **structure of the nucleon**.

- The past decade saw the start of **3D imaging** of the nucleon and the experimental programme at **Jefferson Lab** will study the **valence region** in detail.

- A wide programme planned for Halls A, B and C in the **11 GeV era**: higher luminosity, higher precision, wider reach of phase space, greater range of observables.

- A full understanding of the nucleon requires diverse measurements, for example **form factors** in elastic scattering, structure functions (for **PDFs**) in DIS, Compton form factors (for **GPDs**) in exclusive reactions and a variety of different functions in SIDIS (for **TMDs**). Data is required across a **wide range of Q^2** to image the nucleon at all depths.
Thank you
Looking to the future: Electron-Ion Collider

“Understanding the glue that binds us all”

- Two sites considered: JLab and Brookhaven National Lab
- Polarised $e$ and light nuclei, unpolarised heavy nuclei
- Centre of mass energy range: 20 - 140 GeV
- High luminosity ($10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
- High resolution detectors

- Gluon contribution to nucleon spin
- Tomography of the quark-gluon sea
- Saturation of gluon density
- Colour charge propagation in the nuclear medium
Workshop on Physics & Engineering Opportunities at the Electron-Ion Collider 2016

13 – 14 October 2016, Ross Priory on Loch Lomond, Scotland

https://ukeicworkshop2016.wordpress.com