Nucleon structure studies with CLAS: current status and prospects after 12 GeV Upgrade

V.I. Mokeev

Collaboration between SINP at MSU and Hall B at Jefferson Lab
Nucleon structure studies with CLAS

• Parton distributions, twist decomposition from the studies of inclusive polarized and unpolarized structure functions

• Transversity, quark orbital angular momentum from semi-inclusive meson electroproduction

• GPD studies: 3-dimensional image of nucleon, full access to quark total angular momentum, mass and ‘pressure’ distributions in the ground nucleon state

• The studies of excited nucleon state (N*) structure through the data on transition N-N* form factors

Access to non-perturbative strong interaction mechanisms, that are responsible for baryon formation from quarks and gluons and their relation to QCD
Dressed quark properties and transition from non-perturbative to perturbative regimes of strong interactions

• ~few MeV current quark mass is approached at asymptotically high momentum \( p \) running over quark
• sharp mass evolution at \( p<2.0 \) GeV reflects transition between non-perturbative/perturbative regime of strong interaction
• mass dependence is directly related to QCD \( \beta \)-function
• >98% of nucleon mass comes from dynamical dressing of current quarks

The studies of the ground and excited nucleon state structure allow us to access properties and interactions of dressed quarks at various distance scales

Key part in the studies of quark confinement in baryons!
$E_{\text{max}} \sim 6 \text{ GeV}$

$I_{\text{max}} \sim 200 \mu\text{A}$

Duty Factor $\sim 100\%$

$\sigma_{E/E} \sim 2.5 \times 10^{-5}$

Beam P $\sim 80\%$

$E_g^\text{(tagged)} \sim 0.8 - 5.5 \text{ GeV}$
CEBAF Large Acceptance Spectrometer

**Torus magnet**
6 superconducting coils

**Liquid D₂ (H₂) target +**
γ start counter; e minitorus

**Drift chambers**
argon/CO₂ gas, 35,000 cells

**Time-of-flight counters**
plastic scintillators, 684 PMTs

**Large angle calorimeters**
Lead/scintillator, 512 PMTs

**Gas Cherenkov counters**
e/π separation, 216 PMTs

**Electromagnetic calorimeters**
Lead/scintillator, 1296 PMTs
12 GeV

Enhance equipment in existing halls

Add new hall

Add 5 cryomodules

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

CHL-2

Enhance equipment in existing halls
Central Detector

Forward Detector

2m
- Charged particle tracking in 5T field
- \[\Delta T < 60\text{psec}\] in for particle id
- Moller electron shield
- Polarized target operation \[\Delta B/B < 10^{-4}\]
World data on polarized structure function $g_{1p}(x,Q^2)$

CLAS provides a large body of precise $g_1$ data in the DIS and transition regions that can be used to improve knowledge of twist-2 PDFs.

Spin structure functions – Hall B

LO extraction of quark polarization

\[ A_{i}^{LO}(x, Q^2) = \frac{\sum e_{i}^{2} \Delta q_{i}(x, Q^2)}{\sum e_{i}^{2} q_{i}(x, Q^2)} \]

Effect of these data on NLO analysis

\[ \text{\textbullet} \quad \text{High discriminating power of the different models} \]
\[ \text{\textbullet} \quad \text{High sensitivity to } \Delta G \text{ even if probes the valence region} \]
Spin structure functions – Hall B

- 30 days on NH$_3$ (P=0.8)
- 50 days on ND$_3$ (P=0.4)
- $L = 10^{35}$/cm$^2$/s @ 11 GeV

$A'_l = D(A_1(x, Q^2) + \eta A_2(x, Q^2))$

$W > 2$ GeV; $Q^2 > 1$ GeV$^2$

**Proton**

- $Q^2 = 1.2$ GeV$^2$
- $Q^2 = 2.5$ GeV$^2$
- $Q^2 = 5.9$ GeV$^2$
- $Q^2 > 9$ GeV$^2$

**Deuteron**

- $Q^2 = 1$-2 GeV$^2$
- $Q^2 = 2.5$ GeV$^2$
- $Q^2 = 5$-9 GeV$^2$
- $Q^2 >$ GeV$^2$

pQCD

SU(6)
SIDIS and TMDs

- Semi-inclusive DIS allows separation of different quark contributions
- Also gives the transverse momentum distribution of quarks
- Spin-orbit correlations through azimuthal distributions
  → requires non zero OAM

\[
\begin{array}{|c|c|c|c|}
\hline
\text{N/q} & \text{U} & \text{L} & \text{T} \\
\hline
\text{U} & f_1 & & h_{1T} \\
\text{L} & & g_1 & h_{1L} \\
\text{T} & f_{1T} & g_{1T} & h_1 & h_{1T} \\
\hline
\end{array}
\]

\[
S \cdot (P \times k_T)
\]

\[
\sigma_{UU}^{\cos 2\phi} \propto 2(1 - y) \cos 2\phi \sum_{q,\bar{q}} e_q^2 x h_{1T}^q(x) H_1^{Lq}(z)
\]

\[
\sigma_{UL}^{\sin 2\phi} \propto S_L 2(1 - y) \sin 2\phi \sum_{q,\bar{q}} e_q^2 x h_{1L}^{\perp q}(x) H_1^{Lq}(z)
\]

→ Mesure single & double spin asymmetries on pions
→ Large acceptance needed (CLAS12)
SIDIS and TMDs

- 30 days on NH\(_3\) (P=0.8)
- 50 days on ND\(_3\) (P=0.4)
- \(L = 10^{35}/\text{cm}^2/\text{s} @ 11\ \text{GeV}\)

\[
A_{UL}^{\sin^2\phi} \propto \sum_{q, \bar{q}} e_q^2 x h_{1L}^\perp (x) H_1^\perp (z)
\]

\[
A_p^{\pi^+ - \pi^-} = \frac{4\Delta u_V (x) - \Delta d_V (x)}{4 u_V (x) - d_V (x)}
\]

\[
A_d^{\pi^+ - \pi^-} = \frac{\Delta u_V (x) + \Delta d_V (x)}{u_V (x) + d_V (x)}
\]
Introduction to GPDs

Observables are integrals, in $x$, of GPDs

Deconvolution needed

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

Elastic form factors

$\int H(x, \xi, t)dx = F(t)$ $(\forall \xi)$

Ji’s sum rule

$2J_q = \int x(H+E)(x,\xi,0)dx$

$\frac{1}{2} = (\frac{1}{2}\Delta \Sigma + L_q) + (\Delta G + L_\xi)$

“Ordinary” parton distributions

$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$
Introduction to GPDs

Form factors

Transverse charge distribution (coordinate space)

GPD

Correlation between longitudinal momentum & transverse spatial distributions

Parton distributions

Longitudinal momentum distribution (momentum space)
Physical content of GPD $E$ & $H$

Nucleon matrix element of the Energy-Momentum Tensor of QCD contains three scalar form factors (R. Pagels, 1965) and can be written as (X. Ji, 1997):

$$\langle p_2 | \hat{T}^q_{\mu\nu} | p_1 \rangle = \bar{U}(p_2) \left[ M_2^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho}) \Delta^\rho}{2M} + d_1^q(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{5M} \right] U(p_1)$$

$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Forces and pressure distribution

GPDs are related to these form factors through 2$^{nd}$ moments

$$J^q(t) = \frac{1}{2} \int_{-1}^{1} dx \, x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right] , \quad M_2^q(t) + \frac{4}{5} d_1(t) \xi^2 = \frac{1}{2} \int_{-1}^{1} dx \, x H^q(x, \xi, t)$$

$t=0$: Ji's Angular Momentum Sum Rule

To determine $J(t)$ we need to measure the $x$ and $t$ dependence of GPDs. To separate $M_2(t)$ and $d_1(t)$ we need measurements at small and large $\xi(x_B)$. 

DVCS and GPDs

- Deep Virtual Compton Scattering is the most suitable process to probe GPDs
- Factorization theorem states that the « handbag » diagram is the only contribution to the DVCS amplitude in the suitable asymptotic limit

\[ \Rightarrow \text{requires high } Q^2, \nu \text{ with } t \ll Q^2 \]

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

\[ = p \int_{-1}^{1} \frac{GPD(x, \xi, t)}{x - \xi} \, dx - i\pi GPD(x = \xi, \xi, t) + \ldots \]

Experimentally: DVCS cannot be distinguished with BH process

\[ \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T_{DVCS} + T_{BH}|^2 \]

\[ T_{BH} \text{ calculable from elastic form factors} \]

Interference gives direct access to DVCS amplitude
Extraction of GPDs

Different combinations of GPDs can be accessed with polarized beam or target

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma} \]

- **Polarized beam, unpolarized target (BSA):**
  \[ \Delta\sigma_{LU} \sim \sin\phi\{F_1H + \xi(F_1+F_2)\tilde{H} + kF_2E\} \]
  Kinematically suppressed

- **Unpolarized beam, longitudinal target (TSA):**
  \[ \Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E) - \ldots\} \]
  Kinematically suppressed

- **Unpolarized beam, transverse target (TSA):**
  \[ \Delta\sigma_{UT} \sim \sin\phi\{k(F_2H - F_1E) + \ldots\} \]
  Kinematically suppressed
DVCS – Hall B

- 80 days of polarized beam on LH$_2$ target (BSA)
- $L = 10^{35}$ /cm$^2$/s @ 11 GeV

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\Delta\sigma_{LU} \sim \sin\phi F_1 H + \ldots$$

→ Extraction of H
The studies of both the ground and excited nucleon structure are needed in order to understand how non-perturbative strong interactions create nucleons and how they emerge from QCD.
The studies of excited nucleon state structure in meson electroproduction with CLAS

OEPVAYa Seminar (led by B.S.Ishkhanov) June 23, 4pm, Bld #19, room #215
Nucleon Resonance Studies with CLAS12


JLab PAC 34, January 26-30, 2009
Approved for 60 days beamtime

Argonne National Laboratory (IL, USA)1, Excited Baryon Analysis Center (VA, USA)2, Fairfield University (CT, USA)3, George Washington University (DC, USA)4, Idaho State University (ID, USA)5, Jefferson Lab (VA, USA)6, Moscow State University (Russia)7, Rensselaer Polytechnic Institute (NY, USA)8, University of Connecticut (CT, USA)9, University of South Carolina (SC, USA)10, and Yerevan Physics Institute (Armenia)11

Spokesperson
Contact Person*
For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the $Q^2$ regime of 5 GeV$^2$ to 10 GeV$^2$, where the quark degrees of freedom are expected to dominate. Our experimental proposal “Nucleon Resonance Studies with CLAS12” was approved by PAC34 for the full 60-day beamtime request.  
[http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf]
Conclusions and outlook

The 6 GeV Program provided:
• comprehensive data on various inclusive structure functions, their moments and improve considerably our knowledge on parton distributions
• extensive information on N-N* transition amplitudes for several excited proton states at $Q^2<5.0 \text{ GeV}^2$ for the first time determined with CLAS
• first information on various SIDIS polarization observables needed to access parton transverse distributions and quark orbital momentum in nucleons
• first data on DVCS asymmetries allowing us to access GPD structure functions

After 12 GeV Upgrade CLAS12 will be only facility foreseen worldwide, that will be capable to study nucleon structure at still fully unexplored area of $5.0<Q^2<14 \text{ GeV}^2$, where quark degrees of freedom are expected to dominate. Nucleon structure studies in this area will allow us to understand dressed quark interactions, that are responsible for nucleon formation and their emergence from QCD.
Backup
# Overview of Technical Performance Requirements

<table>
<thead>
<tr>
<th>Hall D</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall A</th>
</tr>
</thead>
<tbody>
<tr>
<td>excellent hermeticity</td>
<td>luminosity $10 \times 10^{34}$</td>
<td>energy reach</td>
<td>installation space</td>
</tr>
<tr>
<td>polarized photons</td>
<td>hermeticity</td>
<td>precision</td>
<td></td>
</tr>
<tr>
<td>$E_\gamma \sim 8.5-9$ GeV</td>
<td></td>
<td>11 GeV beamline</td>
<td></td>
</tr>
<tr>
<td>$10^8$ photons/s</td>
<td></td>
<td>target flexibility</td>
<td></td>
</tr>
<tr>
<td>good momentum/angle resolution</td>
<td></td>
<td>excellent momentum resolution</td>
<td></td>
</tr>
<tr>
<td>high multiplicity reconstruction</td>
<td></td>
<td>luminosity up to $10^{38}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>particle ID</td>
<td></td>
</tr>
</tbody>
</table>
### DOE critical decision schedule

<table>
<thead>
<tr>
<th>CD-0 Mission Need</th>
<th>MAR-2004 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-1 Preliminary Baseline Range</td>
<td>FEB-2006 (A)</td>
</tr>
<tr>
<td>CD-2 Performance Baseline</td>
<td>NOV-2007 (A)</td>
</tr>
<tr>
<td>CD-3 Start of Construction</td>
<td>SEP-2008 (A)</td>
</tr>
<tr>
<td>CD-4A Accelerator Project Completion and Start of Operations</td>
<td>DEC-2014</td>
</tr>
<tr>
<td>CD-4B Experimental Equipment Project Completion and Start of Operations</td>
<td>JUN-2015</td>
</tr>
</tbody>
</table>

*Now split in two to ease transition into operations phase*

(A) = Actual Approval Date

**Nucleon structure at 12 GeV**

GHP09, 04/29/2009

S.Procureur
Measurements of Form Factors

Nucleon structure at 12 GeV

GHP09, 04/29/2009

S.Procureur
Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

The 12 GeV Upgrade is well matched to GPD studies in the valence quark regime.

Study of high $x_B$ domain requires high luminosity.
DVCS and GPDs

\[ H(x, \xi, 0) \]

**DVCS asymmetry**

Cross section