Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Physics with CLAS at JLab

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These are preliminary lecture notes, intended only for distribution to participants
Physics with CLAS at JLab
(selected topics)

Hadron structure studies,

Electron elastic scattering

Inelastic scattering
($\gamma N, eN$)

Deeply inelastic scattering

Form factors

Excited states (resonances)

Parton distributions,
Transverse Momentum Distr.
Generalized Parton Distr.

... a word on Color Transparency

... and a blink into the future:
CLAS12
The specificities of CLAS

♠ **High luminosity x acceptance**
  compensates relatively low energy
  (for example, for exclusive measurements,
  same $Q^2$ as high energy machines are achieved)

♥ **Large $x$ range**
  and from resonance region to DIS

♦ **Good resolution**
  truly exclusive measurements

♣ **Experimental equipment**
  highly polarized electron beam (now 85% routinely),
  tagged photon beam,
  with new capability for linear polarization (> 90%)
  longitudinally polarized target (+ new plans),
  specific equipment for dedicated experiments
  (GDH at low $Q^2$, DVCS, BoNuS, etc)
Neutron magnetic form factor

\[ R = \frac{\frac{d\sigma}{d\Omega}(D(e, e' p))}{\frac{d\sigma}{d\Omega}(D(e, e' n))} = a(Q^2) \frac{G_{Ep}^2 + \tau G_{Mp}^2}{1 + \tau} + 2\tau G_{Mn}^2 \tan^2 \left( \frac{\Theta}{2} \right) \]

\[ \frac{G_{Ep}^2 + \tau G_{Mp}^2}{1 + \tau} + 2\tau G_{Mn}^2 \tan^2 \left( \frac{\Theta}{2} \right) \]

Graphical representation of the neutron magnetic form factor with data from different experiments (CLAS Preliminary, Lung, Xu, Anikin, Kubon, Arnold) and error bars.
Fits of dynamical pion models to $\pi$ photoproduction data suggest 30-50% of M1 photocoupling strength near $Q^2=0$ due to meson rescattering at EM vertex.
Fits of dynamical pion models to $\pi$ photoproduction data suggest 30-50% of $M_1$ photocoupling strength near $Q^2=0$ due to meson rescattering at EM vertex.

Small quadrupole transitions and new data

Fits of dynamical pion models to $\pi$ photoproduction data suggest 30-50% of $M_1$ photocoupling strength near $Q^2=0$ due to meson rescattering at EM vertex.
**Pentaquark:**

*not declared dead, but in deep coma*

<table>
<thead>
<tr>
<th>Reaction channel</th>
<th>Non dedicated experiments</th>
<th>Dedicated experiments</th>
</tr>
</thead>
</table>

![Graph showing events per 10 MeV/c^2](image)
**Pentaquark:**
*not declared dead, but in deep coma*

<table>
<thead>
<tr>
<th>Reaction channel</th>
<th>Four new results (and more to come) from 2 dedicated high statistics runs put stringent limits on Θ⁺ and Θ++ production</th>
<th>Dedicated experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>γd → nK⁺K⁻p</td>
<td></td>
<td>hep-ex/0603028</td>
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<td>(accepted in PRL)</td>
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<tr>
<td>γp → π⁺K⁻K⁺⁺n</td>
<td></td>
<td>Expt in 2007</td>
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<tr>
<td>γd → ΛK⁺⁺n</td>
<td></td>
<td>hep-ex/0604047</td>
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<td>(submitted to PRL)</td>
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<tr>
<td>γp → pK⁺K⁻</td>
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<td>hep-ex/0605001</td>
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<td>(submitted to PRL)</td>
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</tbody>
</table>
In the quark parton model
\[
g_1(x) = \frac{1}{2} \sum_{q, \bar{q}} e_q^2 \left[ q^\uparrow (x) - q^\downarrow (x) \right] = \frac{1}{2} \sum_{q, \bar{q}} e_q^2 \Delta q(x)
\]
how does the quark spin contribute to the nucleon spin?
New results for $A_1^d$ at high $x$

CLAS, nucl-ex/0605028, submitted to PLB
(M. Ripani’s talk last Tuesday)

Nicely complement new results at low $x$

COMPASS, PLB 612 (2005)
Flavour decomposition from p/n

Since \( \frac{\Delta q + \Delta \bar{q}}{q + \bar{q}} \approx \frac{\Delta q_v}{q_v} \) in our x-range, extract polarized valence quark distributions

(at \( Q^2 = 2.5 \text{ GeV}^2 \), using evolution only at LO for CLAS data)

(adapted from Review of Particle Properties, PLB 592; Hall A & CLAS results calculated by MG – not official collaborations results)
**Goal:** Unpolarized structure function on loosely bound neutrons from $e^- d \rightarrow e^- p_{\text{back}} X \rightarrow$ determination of $d(x)/u(x))$

**Method:** Detection of backward protons of momenta as low as 70 MeV/c (spectators), with Radial Time Projection Chamber (RTPC, built around thin $D_2$ ($H_2$) target, placed inside solenoid for Møller background suppression and momentum analysis)

**Run:** Fall 2005

See also, with standard CLAS setup, PRC 73, 035212 (2006) (p-spectator > 280 MeV/c)
**SIDIS Double Spin Asymmetries**

Detect the hadron from the current fragmentation and measure the **double spin asymmetry** $A_{\parallel}^h$ in the semi-inclusive process $eN \rightarrow e\ h\ X$.

Assuming leading order (naïve) $x$-$z$ factorization, get for each species $h$:

$$A_{1N}^h(x, Q^2, z) \equiv \frac{\Delta \sigma^h(x, Q^2, z)}{\sigma^h(x, Q^2, z)} = \frac{\sum_q e_q^2 \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) \cdot D_q^h(z, Q^2)}$$


---

**SIDIS Single Spin Asymmetries**

Beam or Target **single spin asymmetries** ($A_{LU}/A_{UL}$)

...can also be expressed in terms of

quark distributions $x$ fragmentation functions

(P. Bosted’s talk last Tuesday)
Several studies (at CLAS and in other JLab expts) show that *Leading-order x-z factorization is not (much) violated at 6 GeV*

- Rich phenomenology associated with various SSA
- SSA linked to transverse momentum distributions (TMD) of partons in the nucleon

- SSA ↔ orbital angular momentum
  ↔ GPD $E$, Pauli form factor $F_2$

*CLAS, PRD 69 (2004)*
+ P. Bosted’s talk last Tuesday
From “ordinary” Parton Distributions to…”

\[
\psi^*(x+\xi) \cdot \psi(x-\xi)
\]

... or interference, between states of different longitudinal momenta, + t-dependence related to transverse distributions

→ Generalized parton distributions (GPD)

\(H, \bar{H}, E, \bar{E} (x,\xi,t)\)

measured in exclusive reactions (D.E.S.)
Generalized Parton Distributions: a richer concept of nucleon structure

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

$x - \xi$ correlations

$x - t$ correlations

$\mathcal{F}\{H(x,0,t)\}$

$H^u$,

$H^d$
Deeply virtual exclusive reactions (DES)

- Leading order/twist accessible at moderate $Q^2$,
- Interference with Bethe-Heitler process,
- Different observables have different sensitivity to the four GPDs,

\[
\begin{align*}
\gamma^*_T & \rightarrow \gamma \\
\gamma^*_L & \rightarrow \rho_L, \omega_L, \pi, \eta...
\end{align*}
\]

Factorization theorems

\[\text{Beam spin asymmetry} \]

- Handbag diagram dominance expected to be reached at higher $Q^2$
  (but asymmetry ratios may be less sensitive to higher twist contributions)
- Allows a separation $(H,E) \leftrightarrow (\tilde{H},\tilde{E})$ and according to quark flavors,
- Necessary to extract longitudinal contribution to observables $(\sigma_L, \ldots)$.

Deeply virtual Compton (DVCS)

Deeply virtual exclusive reactions (DES)

- Leading order/twist accessible at moderate $Q^2$,
- Interference with Bethe-Heitler process,
- Different observables have different sensitivity to the four GPDs,
GVCS beam spin asymmetry from high-statistics $ep \rightarrow epX$

$$BSA \propto F_1(t) \cdot \mathcal{H} + \frac{x_B}{2 - x_B} \left[ F_1(t) + F_2(t) \right] \cdot \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2(t) \cdot \mathcal{E}$$

$$(\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}) = \pi \sum_q e_q^2 \left[ GPD^q(\xi, \tilde{\xi}, t) \pm GPD^q(-\tilde{\xi}, \tilde{\xi}, t) \right]$$

$0.15 < x_B < 0.4$
$1.50 < Q^2 < 4.5 \text{ GeV}^2$
$-t < 0.5 \text{ GeV}^2$

$\pi^0$ are suppressed due to analysis cuts (only low $t$), residual contribution ($\pi/\gamma \sim 5-15\%$) estimated from MC
$TSA \propto F_1 \cdot \tilde{H} + \frac{x_B}{2-x_B} \left[ F_1 + F_2 \right] \cdot \tilde{H} + \frac{x_B}{2-x_B} \left[ \frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2 \right] \cdot E$

$ep \rightarrow ep \gamma$ on longitudinally polarized NH$_3$ target

(S. Chen et al., hep-ex/0605012, submitted to PRL)
## JLab experiments dedicated to the study of GPDs

<table>
<thead>
<tr>
<th>GPD</th>
<th>Reaction</th>
<th>Obs.</th>
<th>Hall</th>
<th>E</th>
<th>Expt#</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(\pm \xi, \xi, t)$</td>
<td>$ep \rightarrow ep\gamma$</td>
<td>$\Delta \sigma, \sigma$</td>
<td>Hall A</td>
<td>5.75 GeV</td>
<td>E-00-110</td>
<td>Fall 04</td>
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<td>5.75 GeV</td>
<td>E-01-113</td>
<td>Spring 05</td>
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<td></td>
<td></td>
<td></td>
<td>5.75 GeV</td>
<td>E-2003</td>
<td>2007</td>
</tr>
<tr>
<td>$H + \tilde{H}(\pm \xi, \xi, t)$</td>
<td>$ep \rightarrow ep\gamma$</td>
<td>$\Delta \sigma, \sigma$</td>
<td>Hall A</td>
<td>5.75 GeV</td>
<td>E-00-114</td>
<td>2008</td>
</tr>
<tr>
<td>$E(\pm \xi, \xi, t)$</td>
<td>$e(n) \rightarrow en\gamma$</td>
<td>$\sigma_L$</td>
<td>CLAS</td>
<td>5.75 GeV</td>
<td>E-00-106</td>
<td>Fall 04</td>
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New results demonstrate that scaling regime is reached in DVCS around 2 GeV²! (M. Mazouz’ talk on Tuesday)

Preliminary results (+ HERMES) in qualitative agreement with GPD-based calculation

Published results demonstrate that scaling regime is NOT reached in $\omega$ production

... + other meson production channels

\( \pi, \eta, \Phi \) under analyses in the three Halls.
• Larger acceptance for γ
• Higher luminosity e e' p γ → Inner calorimeter (PbWO4)
  Superconducting solenoid magnet

Dedicated, high statistics, DVCS experiments → Virtual Compton scattering at the quark level → If scaling laws are observed (up to Q2 ~ 5 GeV^2), or deviations thereof understood, first significant measurement of GPDs. → Large kinematical coverage in xB and t leads to 3D-picture of the nucleon.
Exclusivity
→ resolution
→ redundant constraints

High $Q^2$
→ luminosity $\times$ acceptance

$e p \rightarrow e \gamma X$
HERMES
28 GeV

$e p \rightarrow e p \gamma$
Hall A & CLAS
5.75 GeV

D.E.S.: an experimental challenge

(M. Mazouz’ talk on Tuesday)

First results coming in a few months
Equivalent 60 full days of beam time at $L = 2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ and $P_e = 0.8$

$x_B$ dependence at

$\phi = 90^\circ$, 

$t = -0.325 \text{ GeV}^2$

and 3 values of $Q^2$

$A_{LU}$: Expected results from CLAS

Each point in this graph corresponds to 1 of $\sim 372$ elementary bins in $(Q^2, x_B, t, \Phi)$ space

$\sim 45\%$ of this statistics accumulated in Spring 05 run,

Preliminary results in a few months
Deeply virtual meson production

Meson and Pomeron (or two-gluon) exchange ...

<table>
<thead>
<tr>
<th></th>
<th>2u+d, 9g/4</th>
<th>2u-d, 3g/4</th>
<th>s, g</th>
<th>u-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho^0)</td>
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<tr>
<td>(\omega)</td>
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<tr>
<td>(\Phi)</td>
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<tr>
<td>(\rho^+)</td>
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... or scattering at the quark level?

Flavor sensitivity of DVMP on the proton:

\[
\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4} \left[ \frac{\alpha_s}{Q} \sum \int \frac{\psi_M(z)}{z} \frac{1}{x \pm \xi \mp i\epsilon} (aH+bE)(x,\xi,t)dx dz \right]_{\xi}^2 \propto \frac{f(\xi,t)}{Q^6}
\]
Deeply virtual $\omega$ production at 5.75 GeV

Analysis of cross sections from for $ep \rightarrow ep\pi^+X$ configurations

- Cross sections larger than anticipated at high $t$ (see J.-M. Laget, PRD 70, 054023)
- SCHC does not seem to hold $\rightarrow$ not possible to extract $\sigma_L$
  handbag diagram estimated to contribute only about 1/5 of measured cross sections
$\rightarrow$ $\omega$ most challenging/difficult channel to access GPD
- Evidence for unnatural parity exchange $\rightarrow$ $\pi^0$ exchange very probable even at high $Q^2$

Analysis of $\omega$ polarization from $ep \rightarrow ep\pi^+\pi^-X$ configurations
(for the first time for this channel above $Q^2 \sim 1\text{ GeV}^2$)

$Q^2$ from 1.6 to 5.6 GeV$^2$
$x_B$ from 0.16 to 0.70

$\omega$ peak in MM[epX] for ($Q^2$, $x_B$) bins
Deeply virtual $\rho$ production at 5.75 GeV

- s-channel helicity conserved
- $R = \sigma_L / \sigma_T$ measured
- New results for $\sigma_L$

$\sigma_L(W)$ for various bins in $Q^2$

Red curve from GPD model ($q$)
Green curve from GPD model ($g$)

+ earlier results at 4.2 GeV
C. Hadjidakis et al., PLB 605 (2005)
Color Transparency in $\rho$ production

Study of

$$e + N \rightarrow e' + N + \rho^0$$

in the nuclear medium

The signature of CT is the rising of the nuclear transparency

$$T(A,Q^2) = \frac{\sigma_A}{A\sigma_N}$$

with increasing hardness of the reaction

(for fixed coherence length)

Complete transparency

N. Bianchi’s talk last Tuesday
B. Kopeliovich’s talk last Wednesday
Color Transparency in $\rho$ production

Solid targets

$\Delta E = \nu - E_p + t/2M_p$

$W > 2 \text{ GeV}$

$-0.5 < t < -0.1$

$|\Delta E| < 0.1 \text{ GeV}$

(Analysis in progress)
Measure attenuation and transverse momentum broadening of hadrons (π, K) in DIS kinematics. Compare absorption in deuterium, carbon, iron, tin, and lead. Huge statistics accumulated.
CEBAF@11GeV and CLAS12
$A_1^p$ at 11 GeV with CLAS12
DVCS/BH projected for CLAS12 at 11 GeV

972 data points measured simultaneously.

\[ A(Q^2, x_B, t) \]
\[ \Delta \sigma(Q^2, x_B, t) \]
\[ \sigma(Q^2, x_B, t) \]
$\rho^0/\omega$ production with transverse polarized target

Asymmetry depends linearly on the GPD $E$, which enters in Ji’s sum rule. High $x_B$ contribute significantly.

$$A_{UT} \propto \frac{\text{Im}(\tilde{\rho})}{|\tilde{\rho}|^2 (1 - \xi^2) - |\tilde{\omega}|^2 (\xi^2 + t/4M^2) - 2\xi^2 \text{Re}(\tilde{\rho} \tilde{\omega})^2}$$

$$\tilde{\rho} = \int_{-1}^{+1} dx \left( e_u H^u - e_d H^d \right) \left[ (x - \xi + i\epsilon)^{-1} + (x + \xi - i\epsilon)^{-1} \right]$$

$\omega_L$ has similar sensitivity to proton quark spin.
Conclusions and outlook (1)

Nucleon structure:

Precise and exciting new data coming now and in the near future:

*Form factors, (polarized) parton distributions,*

*\( k_T \)-dependent parton distributions, GPD,…*

Baryon spectroscopy:

Signals for *pentaquarks* not present in dedicated high statistics experiments. Stringent upper limits on production in different channels.

Extensive set of data in *photo- and electroproduction of resonances.* Excited Baryon Analysis Center (T.-S. H. Lee *et al.*) launched.
Conclusions and outlook (2)

Other research topics at CLAS

Transition from resonance to D.I.S. region,
  higher-twist, duality.
Search for “missing” resonances
  e.g. in $2\pi$ channels.
The nucleus as a QCD laboratory,
  color transparency in $\rho$ production,
  quark propagation.
N-N correlations in nuclei.

Experimental outlook:

“Complete” experiments for baryon spectroscopy
  (new frozen spin target for photon experiments)

12 GeV upgrade on tracks
First 12 GeV proposals will be examined in August
CLAS (and other Halls at JLab) actively preparing such proposals:

• DVCS
• Deep exclusive $\pi^0$ & $\eta$ production
• Azimuthal moments in pion production in SIDIS
• $A_1 / g_1$ at high $x$
• DIS on the neutron ($p$ spectator tagging)
• Study of nuclear transparency in exclusive $\rho$ electroproduction
• Quark propagation and hadron formation in electroproduction of hadrons (including strange mesons and hyperons) from nuclei.
• Study of short-range properties of nucleons at $Q^2 < 12$ GeV$^2$ using D(e,e’p)n

CLAS12 detector being designed now

A good time to join!