Physics Prospects with the JLab 12 GeV Upgrade

Gluonic Excitations
3-dim view of the Nucleon
Valence Structure of the Nucleon

Elton S. Smith
Jefferson Lab

PANIC02
Osaka
CEBAF @ JLab Today

- **Main physics programs**
  - nucleon electromagnetic form factors (including strange form factors)
  - $N \rightarrow N^*$ electromagnetic transition form factors
  - spin structure functions of the nucleon
  - form factors and structure of light nuclei

- **Superconducting recirculating electron accelerator**
  - max. energy \(5.7\) GeV
  - max current \(200\ \mu\)A
  - e polarization 80%

- **Simultaneous operation in 3 halls**
  - 2 High Resolution Spectrometers (\(p_{\text{max}}=4\) GeV/c) \(10^{39}\)
  - 2 spectrometers (\(p_{\text{max}}=7\) and 1.8 GeV/c) + special equipment \(10^{39}\)
  - Large Acceptance Spectrometer for e and $\gamma$ induced reactions \(10^{34}\)
12 GeV CEBAF

- Upgrade magnets and power supplies
- Add Hall D (and beam line)
- Enhance equipment in existing halls
- Add 5 cryomodules
- 20 cryomodules
- Add arc
- CHL-2

Elton S. Smith     PaNic02, Sep 30 – Oct 4, 2002
Gluonic Excitations

Dynamical role of Glue
Confinement
Lattice QCD

Flux tubes realized

Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

→ Flux Tube Model

From G. Bali
Understanding Confinement

The Ideal Experiment

\[ E (\text{GeV}) \]

\[ 2 \]

\[ 1 \]

\[ 0 \]

free gluons

flux tube

quarks fixed

1 fm

The Real Experiment

quark motion plus flux tube excitation
Hybrid Mesons

Transverse phonon modes

\[ \pi/r \]

ground state

Hybrid mesons

1 GeV mass difference (\(\pi/r\))

Normal mesons
Normal Mesons – q\bar{q} color singlet bound states

Spin/angular momentum configurations & radial excitations generate our known spectrum of light quark mesons.

Starting with u - d - s we expect to find mesons grouped in nonets - each characterized by a given J, P and C.

\[ S = S_1 + S_2 \]
\[ J = L + S \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]

\[ J^{PC} = 0^{--} 0^{+-} 1^{--} 1^{+-} 2^{++} \ldots \]

Not-allowed: exotic

\[ J^{PC} = 0^{--} 0^{+-} 1^{--} 1^{+-} 2^{++} \ldots \]

Allowed combinations
Quantum Numbers of Hybrid Mesons

Excited Flux Tube

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Excited Flux Tube</th>
<th>Hybrid Meson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S = 0$</td>
<td>$J^{PC} = 0^{--}$</td>
<td>$J^{PC} = \begin{cases} 1^{--} \ 1^{++} \end{cases}$</td>
</tr>
<tr>
<td>$L = 0$</td>
<td>$J^{PC} = 1^{--}$</td>
<td>$J^{PC} = \begin{cases} 0^{--} \ 1^{--} \ 1^{++} \ 2^{++} \end{cases}$</td>
</tr>
</tbody>
</table>

Flux tube excitation (and parallel quark spins) lead to exotic $J^{PC}$
Each box corresponds to 4 nonets (2 for L=0)

Radial excitations

qq Mesons

(L = qq angular momentum)

Mass (GeV)

1.0 1.5 2.0 2.5

Radial excitations

L = 0 1 2 3 4

exotic nonets

0 –+ 0 + – 1 + + 1 + – 1–+ 2 –+ 2 + – 2 + + 0 –+ 2 –+ 0 + + 2 + – 1 ++ 1 + – 1 + + 1 –– 0 + – 0 + +

Glueballs

Hybrids

Lattice

1++ 1.9 GeV
2++ 2.1 GeV
0++ 2.3 GeV
Exotic Signal $J^{PC}=1^{−+}$

E852 $\pi_1(1600) \rightarrow \eta' \pi^−$

$\downarrow \eta \pi^+\pi^−$

$\downarrow \gamma\gamma$

$M = 1.60 \pm 0.05$

$\Gamma = 0.34 \pm 0.06$

PRL 86, 3977 (2001)
Families of Exotics

\[ \pi_1 \text{ I}^G(J^{PC})=1^{-}(1^{-+}) \]

\[ \eta_1 \text{ I}^G(J^{PC})=0^{+}(1^{-+}) \]

\[ \eta_1 \text{ I}^G(J^{PC})=0^{+}(1^{-+}) \]

Couple to V.M + e

\[ \pi_1 \leftrightarrow \rho \pi \]

\[ \eta_1 \leftrightarrow \rho \eta, \omega \phi \]

\[ \eta_1' \leftrightarrow \phi \omega \]
Strategy for Exotic Meson Search

- Use photons to produce meson final states
  - tagged photon beam with 8 – 9 GeV
  - linear polarization to constrain production mechanism

- Use large acceptance detector
  - hermetic coverage for charged and neutral particles
  - typical hadronic final states:
    - $f_1\eta \rightarrow K\bar{K}\eta \rightarrow K\bar{K}\pi\pi\pi$
    - $b_1\pi \rightarrow \omega\pi \rightarrow \pi\pi\pi\pi$
    - $\rho\pi \rightarrow \pi\pi\pi$
  - high data acquisition rate

- Perform partial-wave analysis
  - identify quantum numbers as a function of mass
  - check consistency of results in different decay modes
This technique provides requisite energy, flux and polarization

12 GeV electrons

Incoherent & coherent spectrum

40% polarization in peak

collimated

tagged

with 0.1% resolution

Coherent Bremsstrahlung

electrons in

photons out

diamond crystal

spectrometer
**GlueX / Hall D Detector**

- Coherent Bremsstrahlung Photon Beam
- Barrel Calorimeter
- Lead Glass Detector
- Solenoid
- Tracking
- Target
- Time of Flight
- Cerenkov Counter

Note that tagger is 80 m upstream of detector
Finding an Exotic Wave

An exotic wave ($J^{PC} = 1^{-+}$) was generated at level of 2.5 % with 7 other waves. Events were smeared, accepted, passed to PWA fitter.

$$X(\text{exotic}) \rightarrow \rho \pi \rightarrow 3 \pi$$

**Mass**

**Input:** 1600 MeV  
**Output:** 1598 +/- 3 MeV

**Width**

**Input:** 170 MeV  
**Output:** 173 +/- 11 MeV

Statistics shown here correspond to a few days of running.

**Double-blind M. C. exercise**
Detector Designed to do Partial Wave Analysis

Double blind studies of $3\pi$ final states

$\gamma \rightarrow \rho \pi \pi \pi \pi X$

Linear Polarization

$m_{3\pi} \text{[GeV/c}^2\text{]}$

$\phi_{GJ}$

$\eta=+1$

$\eta=-1$

$\eta=+1$

$\eta=-1$

$\eta=+1$

$\phi_{GJ}$

Events/20 MeV

Mass [MeV/c$^2$]

Phase Difference

Mass [MeV/c$^2$]
3-dimensional view of the Nucleon

Deep Exclusive Scattering
Generalized Parton Distributions

The GPDs Define Nucleon Structure

- GPD’s provide access to fundamental quantities such as the quark orbital angular momentum that have not been accessible

\[ J_{\text{quark}} = \frac{1}{2} \Delta \Sigma + L^q = \frac{1}{2} \int_{-1}^{+1} dx x \left[ H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0) \right] \]

- and the GPD’s unify the description of inclusive and exclusive processes, connecting directly to the “normal” parton distributions:

\[ G_E(-t) = \int_{-1}^{1} dx \sum_q \left[ H^q(x, \xi, t) + \frac{t}{4M^2} E^q(x, \xi, t) \right] \] (for example),
Limiting Cases for GPDs

Ordinary Parton Distributions \((\Delta, t, \xi \to 0)\)

\[
H_0(x,0) = q(x) \quad \text{unpolarized} \quad \tilde{H}_0(x,0) = \Delta q(x) \quad \text{polarized}
\]

Nucleon Form Factors (Sum Rules)

\[
\int H_\xi(x,t)dx = F_1(t) \quad \text{Dirac}
\]

\[
\int \tilde{H}_\xi(x,t)dx = g_A(t) \quad \text{Axial vector}
\]

\[
\int E_\xi(x,t)dx = F_2(t) \quad \text{Pauli}
\]

\[
\int \tilde{E}_\xi(x,t)dx = h_A(t) \quad \text{Pseudoscalar}
\]

\[
\xi = \frac{\Delta \cdot z}{P \cdot z} \quad t = \Delta^2
\]
GPDs Contain Much More Information than DIS

DIS only measures a cut at $\xi=0$

Quark distribution $q(x)$

Antiquark distribution $\bar{q}(x)$

$H(x, \xi, 0)$
Measuring the GPD’s

- Key experimental capabilities include:
  - CW (100% duty factor) electron beams
    (permits fully exclusive reactions)
  - modern detectors
    (permit exclusive reactions at high luminosity)
  - adequate energy
    (~10 GeV to access the valence quark regime)

 measurements of the GPD’s are now feasible
Interpretation of the GPD’s

Analogy with form factors

$$F(\bar{q}) = \int d^3 r e^{-i \bar{q} \cdot \bar{r}} \rho(\bar{r})$$

Charge ↔ Form Factor

$r$ measured relative to $R_{cm} = \sum \frac{m_i r_i}{M}$

Parton Distribution ↔ GPD’s

$$H(x, q_{\perp}) = \int d^2 b_{\perp} e^{-i q_{\perp} \cdot b_{\perp}} f(x, b_{\perp}) \quad @ \xi = 0$$

$b_{\perp}$ measured relative to $R_{CM}^{CM} = \sum x_i r_{i\perp}$

where $f(x, b_{\perp})$ is a parton density of quarks with momentum fraction $x$ at a $\perp$ distance $b_{\perp}$ from $R_{CM}^{CM}$

Ref. Burkardt
Meson Production as a Filter

- Use quantum numbers of meson to select appropriate combinations of parton distributions in nucleon.

Pseudo-scalars (polarized)

- \( \pi^0 \): \( \Delta u_v - \frac{1}{2} \Delta d_v \)
- \( \eta \): \( \Delta u_v - \frac{1}{2} \Delta d_v + 2 \Delta s_v \)

Vector Mesons (unpolarized)

- \( \rho_L^0 \): \( u + \bar{u} + \frac{1}{2} (d + \bar{d}) \); g
- \( \omega_L^0 \): \( u + \bar{u} - \frac{1}{2} (d + \bar{d}) \); g
- \( \phi_L^0 \): \( s + \bar{s} \); g
Program to determine GPD’s

\[ ep \rightarrow ep \rho^0 \rightarrow H^2, E^2 \]
\[ \rightarrow \pi^+ \pi^- \]
\[ en \pi^+ \rightarrow \tilde{H}^2, \tilde{E}^2 \]
\[ e p \gamma \rightarrow H^2, E^2, \tilde{H}^2, \tilde{E}^2 \]
\[ \bar{e} p \rightarrow e p \gamma \rightarrow H, E, \tilde{H}, \tilde{E} \]
\[ e p \rightarrow en \pi^+ \rightarrow \tilde{H} * \tilde{E} \]

Other Channels

\[ \bar{e} p \rightarrow eN (\eta, \pi) \]
\[ e \Delta \pi \]
\[ e N\omega \]
\[ e (\Lambda, \Sigma) K \]
Deep Virtual Compton Scattering: A Window on Quark Correlations

DIS is limited by the fact that it can only measure longitudinal distributions averaged over all quarks in the nucleon

Deep Inclusive Scattering \Rightarrow Deep Compton Scattering

- DIS corresponds exactly to the imaginary part of the Deep Compton Scattering amplitude
- Add determination of the final state (by exclusive reactions such as DVCS) and we can (finally!) probe nucleon quark structure and correlations at the amplitude level

Deep Virtual Compton Scattering (DVCS)

\[ \xi = \text{momentum imbalance} \]
DVCS Single-Spin Asymmetry

\[ Q^2 = 5.4 \text{ GeV}^2 \]
\[ x = 0.35 \]
\[ -t = 0.3 \text{ GeV}^2 \]

CLAS experiment

\[ E_0 = 11 \text{ GeV} \]
\[ P_e = 80\% \]
\[ L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]
Run time: 2000 hrs

\[ 2000 \text{ hours at } L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]
\[ Q^2 = 5.4 \text{ (GeV/c)}^2 \]
\[ x_B = 0.35 \]
\[ -t = 0.3 \text{ (GeV/c)}^2 \]
Hard Meson Electroproduction ($\rho^o$)

- Physics issue: map out GPD’s (need to isolate $\sigma_L$)
- Technique: determine $\sigma_L$ from $\rho \rightarrow \pi\pi$ decay angle distribution
- CLAS at 11 GeV
  400 hrs at $L = 10^{35}$ cm$^{-2}$s$^{-1}$
Valence Quark Structure of the Nucleon

Parton Distributions at large x
12 GeV will access the valence quark regime for $x > 0.3$

where constituent quark properties are not masked by the sea quarks
Predictions for large $x_{\text{Bj}}$

Proton Wavefunction (Spin and Flavor Symmetric)

$$\left| p^\uparrow \right\rangle = \frac{1}{\sqrt{2}} \left| u^\uparrow (ud)_{S=0} \right\rangle + \frac{1}{\sqrt{18}} \left| u^\uparrow (ud)_{S=1} \right\rangle - \frac{1}{3} \left| u^\downarrow (ud)_{S=1} \right\rangle$$

$$- \frac{1}{3} \left| d^\uparrow (uu)_{S=1} \right\rangle - \frac{\sqrt{2}}{3} \left| d^\downarrow (uu)_{S=1} \right\rangle$$

<table>
<thead>
<tr>
<th>Nucleon Model</th>
<th>$F_2^n/F_2^p$</th>
<th>d/u</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6)</td>
<td>2/3</td>
<td>1/2</td>
<td>0</td>
<td>5/9</td>
</tr>
<tr>
<td>Valence Quark</td>
<td>1/4</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pQCD</td>
<td>3/7</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Valence Quark Distribution

- **Physics issue:**
  - compare behavior of u and d quarks as $x_{Bj} \to 1$

- **Experimental problem:**
  - extract information from comparison of hydrogen and deuterium data
  - need to correct for nuclear effects in D

- **Solution for CEBAF upgrade:**
  - compare DIS off $^3$He and $^3$H (nuclear effects ~ same)
The Neutron Spin Asymmetry $A_1^n$

$A_1^n$ Measures the Spin Response:

- Study of spin structure functions has been limited to the low-$x$ region
- JLab at 12 GeV with its high luminosity is a prime facility for measurements at large $x$
Flavor Decomposition: \( (e,e'\pi^+)/ (e,e'\pi^-) \)

\[
\frac{\Delta q}{q} = \frac{\Delta u + \Delta \bar{u}}{u + \bar{u}}
\]

\[
\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}}
\]

\[
\frac{\Delta \bar{q}}{\bar{q}}
\]
12 GeV Upgrade Project Status

- Developed by CEBAF User Community in collaboration with JLab
- Nuclear Science Advisory Committee, NSAC
  - plan presented during last 5-year Long Range Plan
  - recommended by NSAC for new construction
- Plan presented to Department of Energy
  - presently waiting for CD-0 (determination of ‘mission need’)
- Detailed report is being prepared to be reviewed by Jlab PAC in January
- Construction
  - construction start expected in FY2007 (October 2006)
  - 3 year construction project
Hall A Floor Plan with MAD Spectrometer
CLAS++ Detector

- Forward Cerenkov
- Forward DC
- Inner Cerenkov
- Central Detector
- Torus Cold Ring
- Forward TOF
- Preshower EC
- Inner Calorimeter
SHMS - HMS Spectrometers After Upgrade

<table>
<thead>
<tr>
<th></th>
<th>Before Upgrade</th>
<th>After Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Central Momentum</td>
<td>11 GeV/c</td>
<td>9 GeV/c</td>
</tr>
<tr>
<td>Min. Scattering Angle</td>
<td>5.5 deg</td>
<td>10 deg</td>
</tr>
<tr>
<td>Momentum Resolution</td>
<td>.15% -.2%</td>
<td>10 deg</td>
</tr>
<tr>
<td>Solid Angle</td>
<td>2.1 msr</td>
<td>4.4 msr</td>
</tr>
<tr>
<td>Momentum Acceptance</td>
<td>20%</td>
<td>40%</td>
</tr>
<tr>
<td>Target Length Acceptance</td>
<td></td>
<td>50 cm</td>
</tr>
<tr>
<td>Opening Angle with HMS</td>
<td>25 deg</td>
<td>16 deg</td>
</tr>
<tr>
<td>Configuration</td>
<td>QQ(DQ)</td>
<td></td>
</tr>
<tr>
<td>Bend Angle</td>
<td>18.4 deg</td>
<td></td>
</tr>
</tbody>
</table>

HMS 7.3 GeV/c

SHMS 11 GeV/c

Beam Dump

Quads similar to HMS "Slim" Q1

Combined Function Superconducting Quad/Dipole

Beam Direction

Scale: 10 feet
Physics Program at 12 GeV

Gluonic Excitations
Valence Structure of the Nucleon
3-dim view of the Nucleon

Exciting

Compelling
In view of recent progress in lattice calculations

Timely
Electron-Light Ion Collider Layout

Ion Source

RFQ  DTL  CCL

Snake

IR

IR

Snake Solenoids

5 GeV electrons

100 GeV light ions

5 GeV CEBAF with Energy Recovery

100 MV cryomodules

Beam Dump

Luminosity = \(10^{35}\text{cm}^{-2}\text{s}^{-1}\)

Lia Merminga