Physics Potential of the Jefferson Lab 12 GeV Upgrade

Garth Huber

CAP Congress, Laval University, Quebec City, June 11, 2008.
Two Cold Superconducting Linacs
Continuous Polarized Electron Beam

\[ E \rightarrow 6 \text{ GeV} \]

\[ > 100 \ \mu\text{A} \]

up to 80% polarization concurrent to 3 Halls

First beam delivered in 1994
JLab 12 GeV Upgrade

Add new hall

Upgrade magnets and power supplies

Add 5 cryomodules

Enhance equipment in existing halls

Add arc

20 cryomodules

CHL-2

20 cryomodules

Add 5 cryomodules

CD 2 granted: Nov/07
First 12 GeV beam: mid-2013
Our ability to answer the question:

**How do the nucleon’s properties (mass, spin, charge radius, etc.) arise from its quark and gluon constituents?**

requires that we develop a quantitative (as opposed to qualitative) understanding of non-perturbative QCD.

98% of the proton’s mass is not due to the “rest mass” of its valence constituents, and hence does not rise directly from the Higgs mechanism.

⇒ The proton’s mass arises dynamically through the quark and gluon interactions of Quantum Chromo-Dynamics (QCD).
Why electron scattering experiments?

Transition from pQCD to Strong QCD needs data with high precision for a quantitative understanding of confinement.

Ongoing Advancements:
Intense CW electron beams.
Polarized targets/polarimetry.
Improvement in polarized e⁻ sources.

Luminosity:
(SLAC, 1978) ~ 8 x 10³¹ cm⁻²s⁻¹
(JLab, 2000) ~ 4 x 10³⁸ cm⁻²s⁻¹

\[ d = 1 \rightarrow 0.1 \text{ fm} \iff Q^2 = 0.1 - 10 \text{ GeV}^2 \]

- JLab 12 GeV Upgrade will play a crucial role towards our better understanding of hadron structure.
- On world scene, JLab program complements the work at J-PARC and GSI as well as radioactive beam facilities.
# 12 GeV Approved Experiments to Date

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NUCLEON AND MESON ELECTROMAGNETIC STRUCTURE

e.g. Charged Pion Form Factor to High $Q^2$
  (E12-06-101, Hall C)
Excellent opportunity for studying the QCD transition from the strong QCD regime to the hard QCD regime.

Jefferson Lab is the only facility capable of the necessary measurements.

The positronium atom of QCD

The $\pi^+$ Electric Form Factor and QCD

The simple $\bar{q}q$ valence quark structure of mesons presents the ideal laboratory for testing our understanding of bound quark systems.

→ all hadronic structure models use the $\pi^+$ as a test case.

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
At low $Q^2<0.3$ GeV$^2$, the $\pi^+$ form factor can be measured exactly using high energy $\pi^+$ scattering from atomic electrons. $\Rightarrow F_\pi$ determined by the pion charge radius $0.657\pm0.012$ fm.

To access higher $Q^2$, one must employ the $p(e,e'\pi^+)n$ reaction.

- the $t$-channel process dominates $\sigma_L$ at small $-t<0.02$ GeV$^2$.

\[
\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m^2_\pi)} g_{\pi NN}^2(t) F_\pi^2(Q^2,t)
\]

**In the actual analysis**, a model incorporating the $\pi^+$ production mechanism and the `spectator' nucleon is used to extract $F_\pi$ from $\sigma_L$. 

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Extraction of $F_\pi$ from JLab 6 GeV Data

**Technique:**

\[
\frac{d\sigma}{dt} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \ldots
\]

- Rosenbluth separation required to isolate $\sigma_L$.
  - Measure cross section at fixed ($W, Q^2, -t$) at 2 beam energies.
  - Simultaneous fit at 2 $\varepsilon$ values to determine $\sigma_L$, $\sigma_T$, and interference terms.

- Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in L/T separation.
  - Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …

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Fit of VGL Regge model to $\sigma_L$ gives $F_\pi$ at each $Q^2$.

\[
F_\pi = \frac{1}{1 + \frac{Q^2}{\Lambda_\pi^2}}
\]

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Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
The role of Soft and Hard QCD in $F_\pi$

**pQCD LO+NLO Calculation:**

Analytic perturbation theory at the parton amplitude level.


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**SOFT QCD:**
- Extra piece needed to describe data.
- Model-dependent.
- Estimated from local quark-hadron duality model.

**HARD QCD:** pQCD LO+NLO

- JLab 6 GeV $F_\pi$ results are far from the values predicted by pQCD.
- At the distance scales probed by the experiment (0.15<r<0.30 fm), the $\pi^+$ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.
$F_{\pi^+}(Q^2)$ after JLab 12 GeV Upgrade

JLab Upgrade will allow our measurements to be extended shorter distance scales to discover the scale where valence quarks dominate pion’s structure.

→ **Different theoretical viewpoints on whether higher-twist mechanisms dominate until very large momentum transfer or not.**
Experimental Hall C

At the present 6 GeV Beam Energy

Add a Super-High Momentum (12 GeV) Spectrometer for studying:

- Super-fast \( x_B \) quarks.
- Form factors of simple quark systems.
- The transformation of quarks into hadrons.
- Quark-quark correlations.

Hall C’s High Momentum Spectrometer, Short Orbit Spectrometer and specialized equipment for studying:

- The strange quark content of the proton.
- Form factors of simple quark systems.
- The transition from hadrons to quarks.
- Nuclei with a strange quark embedded.

After the 12 GeV Upgrade
Super-High Momentum Spectrometer (SHMS)

Focal Plane Detectors

- Argon/Neon Cerenkov
- Drift Chambers
- HERMES Lead Glass Calorimeter
- C$_4$F$_{10}$ Cerenkov
- Argon/Neon Cerenkov
- Future Aerogel Cerenkov
- Hodoscopes

Thomas Jefferson National Accelerator Facility
GENERALIZED PARTON DISTRIBUTIONS

e.g. $1/Q^n$ Scaling Test of the L-T Separated Pion Electroproduction Cross Section
(E12-07-105, Hall C)
Generalized Parton Distributions offer a 3D description of hadron structure.

**Elastic Scattering**
(form factors)
transverse parton distribution in Coordinate space

**DIS**
(structure functions)
longitudinal parton distribution in momentum space

**DES (GPDs)**
Fully-correlated parton distribution in both coordinate and momentum space
Generalized Parton Distributions (GPDs)

- GPDs are universal quantities and reflect the structure of the hadron independently of the probing reaction.

- GPD picture applies strictly to the hard-scattering regime, where the interaction can be clearly separated into perturbative (pQCD) and non-perturbative factors.
  - GPD contains the non-perturbative part of the interaction and represents the interference of parton wave functions, differing by momentum fraction $\xi$.

$$F_\pi(Q^2) = \frac{1}{Q^2} \sum_{q} H^q_{\pi}(\xi, x, Q^2) dx$$
Deeply Virtual Exclusive Processes -
Kinematics Coverage of the 12 GeV Upgrade

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Hard-Soft Factorization

• To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies.
  – Determining the applicability of the GPD mechanism at higher $x_{Bj}$ is a high priority for the JLab 12 GeV program.
  – Only if hard-soft factorization applies can GPDs be extracted.

One of the most stringent tests of factorization is the $Q^2$ dependence of the $\pi^+$ electroproduction cross section.
  – $\sigma_L$ scales to leading order as $Q^{-6}$.
  – $\sigma_T$ scales as $Q^{-8}$.
  – As $Q^2$ becomes large: $\sigma_L >> \sigma_T$. 

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
1/Q^n Scaling Test after JLab 12 GeV Upgrade

- Measure separated cross sections for the p(e,e'\pi^+)n reaction at three values of x_Bj.
- QCD scaling predicts \(\sigma_L \sim Q^{-6}\) and \(\sigma_T \sim Q^{-8}\).
- The Q^2 coverage is a factor of 3-4 larger compared to 6 GeV.

“A detailed study to determine whether or not meson electroproduction can provide information on GPDs is important.”

-- JLab PAC32
EXOTIC MESONS

Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons

(E12-06-102, Hall D)
Mesons in QCD

Conventional Meson

\[ \begin{align*}
q & \quad \underline{g} \\
\bar{q} & \quad g
\end{align*} \]

\[ 3 \otimes 3 = 1 \oplus 8 \]

Glueball Meson

\[ \begin{align*}
g & \quad g \\
g & \quad g \\
g & \quad g
\end{align*} \]

\[ 8 \otimes 8 = 1 \oplus 8 \oplus \ldots \]

\[ (8 \otimes 8) \otimes 8 = 1 \oplus \ldots \]

Hybrid Meson

\[ \begin{align*}
q & \quad \underline{g} \\
\bar{q} & \quad g \\
\bar{q} & \quad g
\end{align*} \]

\[ (3 \otimes 3) \otimes 8 = 1 \oplus \ldots \]

4-quark Meson or Molecule

\[ \begin{align*}
q & \quad \underline{g} \\
\bar{q} & \quad g \\
\bar{q} & \quad g
\end{align*} \]

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Hybrid Meson Mass Prediction

Lattice QCD computations in heavy-quark sector:

- Insight into excitations of gluon string binding the $qq$
- For heavy quarks, energy associated with “excited string” of around 1 GeV.
  - Lowest $1^{-+}$ state around 1.8-2.0 GeV:
    - plus chiral correction ~ -0.1 to -0.2 GeV.
Conventional Light Mesons

\[
\vec{J} = \vec{L} + \vec{S}
\]

\[
P = (-1)^{L+1}
\]

\[
C = (-1)^{L+S}
\]

\[J^{PC} = 0^{--} : \pi, K\]

\[J^{PC} = 1^{--} : \rho, K^*, \gamma\]

Certain spin-parity combinations are not allowed - exotic:

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

For light quarks (u, d, s) and fixed J, P and C we expect nonets of mesons:

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Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Production of Hybrid Mesons

Combine excited glue QN \( J^{PC} = 1^{+-} \text{ or } 1^{-+} \) with those of the quarks:

- \( \bar{L} = 0, \bar{S} = 0 \)

\[ J^{PC} = 1^{--} \text{ or } 1^{++} \]

- \( \bar{L} = 0, \bar{S} = 1 \)

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

\[ J^{PC} = 0^{+-}, 1^{-+}, 2^{+ -} \text{ exotic} \]

\( \pi/K \text{ Beam} \)

- Excite the glue

\( \pi (K) \text{ (X)} \)

- Produced hybrids are not expected to be exotic

\( \gamma \text{ (X)} \)

- Produced hybrids can be exotic

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Coherent Photon beam and Experimental Hall D

Top View

75 m

Electron beam

Tagger Area

Collimator

Solenoid-based detector

Coherent Bremsstrahlung photon beam

Experimental Hall D

beam flux (GeV/100)

12 GeV electrons

collimated

uncollimated

photon energy (GeV)
Hall D: GlueX Detector

- BCAL
- FCAL
- TOF Wall
- FDC/CDC Inside BCAL
- Upstream platform
- Photon Beam
- Target/Start counter
- SLAC/LASS Solenoid

Hall D: GlueX Detector

- Beam
- Target/Start counter
- SLAC/LASS Solenoid
- BCAL
- TOF Wall
- FDC/CDC Inside BCAL
- Upstream platform
- Photon Beam
GlueX Experiment Goals

FIRST 5 YEARS:

- Establish the existence of a $J^{PC}=1^{-+}$ or $2^{+-}$ exotic meson in several decay channels if it is present at a level of a few % of conventional mesons.
  - If exotics are not present, the few % level exclusion limit would indicate problems with the QCD-based models made to date.

- Measure branching modes for established exotic states to validate QCD predictions.

- Add to the knowledge of conventional meson spectroscopy that straddles the light and heavy quark sectors.
12 GeV Upgrade: Phases and Schedule

(based on funding guidance provided by DOE-NP in June-2007)

- **2009-2013 Construction** – *starts in ~6 months!*
  - Parasitic machine shutdown – May 2011 through Oct 2011 (6 months)
  - Accelerator shutdown start mid-May 2012
  - Accelerator commissioning mid-May 2013

- **2013-2015 Pre-Operations** (beam commissioning)
  - Hall A commissioning start ~October 2013
  - Hall D commissioning start ~April 2014
  - Halls B and C commissioning start ~October 2014