Precise Electro-Weak Studies: An Essential Component of the World-Wide Nuclear Physics Program

Anthony W. Thomas

D. Allan Bromley Memorial Symposium: Yale December 8-9, 2005
Building Blocks of the Universe

- Each quark comes in 3 “colours”: red, green and blue.
- Leptons do not carry color charge.

These are the building blocks of matter!
The massless photon mediates the long-range e.m. interactions.

Gluons carry color and mediate the strong interaction.

The very massive $W^-$, $W^+$, and $Z^0$ bosons mediate the weak interaction.
Quantum Chromodynamics (QCD)

- Photons do not carry electric charge.
- Gluons do carry colour charge!
- Gluons can directly interact with other gluons!
- This is new!

A red quark emitting a red anti-blue gluon to leave a blue quark.

Quark-quark force grows WEAKER as quarks come close ≡ “Asymptotic Freedom”
QCD and the Origin of Mass

\[ u + u + d = \text{proton} \]

mass: \[ 0.003 + 0.003 + 0.006 \neq 0.938 \]

HOW does the rest of the proton mass arise?
Lattice QCD Simulation of Change of Vacuum Structure in a Nucleon

Leinweber, Signal et al.

\[
<r> = 0.16 \text{ fm}
\]
Electron Scattering Provides an Ideal Microscope for Nuclear Physics

- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary $q$ to map out Fourier Transforms of charge and current densities:
  \[ \lambda \approx 2\pi/q \quad (1 \text{ fm} \leftrightarrow 1 \text{ GeV/c}) \]

\[ S_{fi} = \frac{-e^2}{\Omega} \bar{u}(k_2) \gamma^\mu u(k_1) \frac{1}{q^2} \int e^{iq \cdot x} \langle f | \hat{J}_\mu(x) | i \rangle d^4x \]

$Q^2 = -q^2$ = 4-Momentum Transfer

CEBAF’s $\vec{e}$ and CW beams dramatically enhance the power of electron scattering
JLab: Unique Forefront Capabilities for Science

An aerial view of the recirculating linear accelerator and 3 experimental halls.

Cryomodules in the accelerator tunnel

Superconducting radiofrequency (SRF) cavities undergo vertical testing.

CEBAF Large Acceptance Spectrometer (CLAS) in Hall B
Program Central to all of Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement

Exotic mesons and baryons

Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in-medium
Effective NN (+ HN) force

Precise few-nucleon calculations
Model-independent analysis ⇒ accurate results on charge distributions
(e,e’p) \Rightarrow \text{Nucleon Momentum Distributions, Shell-by-Shell}

\[ p_m = E_e - E_{e'} - p = q - p \]
\[ E_m = \omega - T_p - T_A - 1 = E_{sep} + E_{exc} \]
Initial Investigation of Charge vs Current in the Proton at SLAC

- Distribution of charge and magnetization in the proton seemed identical

- The experiments were limited by the precision of absolute cross section measurements
JLab Data Rewrote the Text Book

- High Intensity
- High Duty Factor
- High Polarization
⇒ Revolutionized our knowledge

\[ \mu G_{Ep}/G_{Mp} \]

\[ Q^2 \text{ in GeV}^2 \]

\[ \rho_{\text{magn}}, \rho_{\text{charge}} \]

Proton densities

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
CEBAF at 12 GeV

- Add new hall
- Upgrade magnets and power supplies
- Enhance equipment in existing halls
- Add 5 cryomodules
- Add arc
- Add 5 cryomodules
- 20 cryomodules
- 20 cryomodules

CHL-2
6 GeV Highlights Leading to the 12 GeV Upgrade

• Parton Distribution Functions

• Form Factors

• Generalized Parton Distributions

• Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum

• Nuclei at the level of quarks and gluons

• Tests of Physics Beyond the Standard Model
Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

• In over 35 years of study of DIS no-one has had the facilities to map out the crucial valence region

• Region is fundamental to our understanding of hadron structure: i.e. how nonperturbative QCD works!

Role of di-quark correlations?

Role of hard scattering: pQCD / LCQCD guidance?

Breaking of SU(6) symmetry?

Moments of PDFs (and GPDs) from Lattice QCD….
12 GeV : Unambiguous Flavor Structure $x \rightarrow 1$

Hall C 11 GeV with HMS

HallB 11 GeV with CLAS12

Initial investigation with BONUS early 06
6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- Generalized Parton Distributions
- Exotic Meson Spectroscopy: Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model
Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

- Perdrisat et al. E01-109 — will increase range of $Q^2$ by 50% in 2007 (range of $Q^2$ for n will double over next 3-4 years)
- With 12 GeV and SHMS in Hall C
Strangeness Widely Believed to Play a Major Role – Does It?

• As much as 100 to 300 MeV of proton mass:

\[ M_N = \langle N(P) \rangle - \frac{9 \alpha_s}{4 \pi} \text{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u \bar{\psi}_u \psi_u + m_d \bar{\psi}_d \psi_d + m_s \bar{\psi}_s \psi_s |N(P)\rangle \]

\[ \Delta M_{s-\text{quarks}}^N = \frac{ym_s}{m_u + m_d} \sigma_N \]

Through proton spin crisis:
• as much as 10% of the spin of the proton

HOW MUCH OF THE ELECTRIC & MAGNETIC FORM FACTORS?
MIT-Bates & A4 at Mainz
Strange Quark Form Factors at $Q^2 = 0.1$ GeV$^2$

$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31 \mu_N$

Theories
1. Leinweber, et al.
   PRL 94 (05) 212001
2. Lyubovitskij, et al.
   PRC 66 (02) 055204
3. Lewis, et al.
   PRD 67 (03) 013003
   PRD 65 (01) 014016
Significance & Comparison with Lattice QCD

Size and sign of the strange magnetic moment is astonishing!

- Experimental \textit{isoscalar} nucleon moment is 0.88 $\mu_N$
  
c.f. this result which is (G0) - 0.54 $\mu_N$: i.e. - 60% !!

- Also remarkable versus lattice QCD which gives
  $+0.03 \pm 0.01 \mu_N$ (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of valence quark moments by $\sim 70%$!
Parity Violating Studies on $^1$H and $^4$He

$3 \text{ GeV beam in Hall A}$ \hspace{1cm} $\theta_{\text{lab}} \sim 6^\circ$ \hspace{1cm} $Q^2 \sim 0.1 \ (\text{GeV/c})^2$

<table>
<thead>
<tr>
<th>target</th>
<th>$A_{PV}$</th>
<th>Stat. Error (ppm)</th>
<th>Syst. Error (ppm)</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>-1.6</td>
<td>0.08</td>
<td>0.04</td>
<td>$\delta(G^s_E+0.08G^s_M) = 0.010$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>+7.8</td>
<td>0.18</td>
<td>0.18</td>
<td>$\delta(G^s_E) = 0.015$</td>
</tr>
</tbody>
</table>

Septum magnets (not shown)  
High Resolution Spectrometers detectors

Hall A at Jlab

Brass-Quartz integrating detector

Elastic Rate:  
$^1$H: 120 MHz  
$^4$He: 12 MHz

Background $\leq 3\%$
G0 and HAPPEx will define these form factors up to 1 GeV$^2$ over the next 2 years.
PREX: $^{208}$Pb Radius Experiment

Low $Q^2$ elastic e-nucleus scattering

$(E = 850 \text{ MeV}, \Theta=6^\circ)$

$Z^0$ (Weak Interaction) couples mainly to neutrons

Measure a Parity Violating Asymmetry

\[
A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]
\]

Applications:

- Fundamental check of Nuclear Theory
- Input to Atomic PV Expts
- Neutron Star Structure
Nuclear Structure

After more than 70 years, the neutron density of a heavy nucleus is a fundamental nuclear-structure observable that remains elusive!

- As fundamental as the charge density of a heavy nucleus
  - *cf.* proton and neutron electromagnetic structure
- Reflects a poor understanding of the symmetry energy of NM
  - *Symmetry energy penalty imposed for breaking* $N=Z$ balance
- Pure neutron matter well constrained at $\rho \approx (2/3)\rho_0$
- Slope is completely unconstrained by available nuclear data!

Adding the neutron radius of a single heavy nucleus to the database will eliminate the large dispersion in the plot!
Neutron Skin and Neutron Stars
(Nuclear Astrophysics at Jefferson Lab)

The neutron skin of $^{208}$Pb and the crust of a neutron star are made up of similar material: neutron-rich matter at (slightly) subnuclear densities

- Neutron stars contain a solid crust above a uniform liquid mantle
- The stiffer the EOS the lower the transition to non-uniform matter
  - Energetically unfavorable to separate into low- and high-density regions
- The stiffer the EOS the larger the neutron skin of a heavy nucleus

A powerful data-to-data relation: The thicker the neutron skin of a heavy nucleus, the lower the transition density from uniform to non-uniform neutron-rich matter ...
6 GeV Highlights Leading to the 12 GeV Upgrade

• Parton Distribution Functions

• Form Factors

• Generalized Parton Distributions

• Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum

• Nuclei at the level of quarks and gluons

• Tests of Physics Beyond the Standard Model
Studies of the Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

Quark angular momentum (Ji’s sum rule)

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


X. Ji & A. Radyushkin (1996)
The Next Generation of Proton Structure Experiments

Elastic Scattering
transverse quark distribution in Coordinate space

DIS
longitudinal quark distribution in momentum space

GPDs
The fully-correlated Quark distribution in both coordinate and momentum space
6 GeV Highlights Leading to the 12 GeV Upgrade

• Parton Distribution Functions

• Form Factors

• Generalized Parton Distributions

• Exotic Meson Spectroscopy: Confinement and the QCD vacuum

• Nuclei at the level of quarks and gluons

• Tests of Physics Beyond the Standard Model
QCD: Unsolved in Nonperturbative Regime

- 2004 Nobel Prize awarded for “asymptotic freedom”

- BUT in nonperturbative regime QCD is still unsolved

- One of the top 10 challenges for physics!

- Is it right/complete?

- Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?

JLab at 12 GeV is uniquely positioned to answer!
Quark-Anti-Quark Flux Tube: “String”
Glueballs and hybrid mesons

Initial search
FY07 – G12 (CLAS)

Colin Morningstar: Gluonic Excitations workshop, 2003 (Jlab)
6 GeV Highlights Leading to the 12 GeV Upgrade

• Parton Distribution Functions
• Form Factors
• Generalized Parton Distributions
• Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
• Nuclei at the level of quarks and gluons
• Tests of Physics Beyond the Standard Model
The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified the** HEP and Nuclear communities 20 years ago

- Nearly 1,000 papers have been generated.....

- What is it that alters the quark momentum in the nucleus?

---

![Graph showing the ratio of cross sections for iron (SLAC E139) and copper (EMC) nuclei.](image)

$g_1(A)$ – “Polarized EMC Effect”

- New calculations indicate larger effect for polarized structure than unpolarized: scalar field modifies lower cpts of Dirac wave function
  
  (Cloet, Bentz, AWT, Phys Rev Lett 95 (2005) 0502302)

- Spin-dependent parton distribution functions for nuclei unknown
Microscopic Origin of Skyrme Force

<table>
<thead>
<tr>
<th></th>
<th>QMC</th>
<th>Skyrme III</th>
<th>QMC(N=3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\sigma (MeV)$</td>
<td>600</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>$t_0 (MeV fm^3)$</td>
<td>-1082</td>
<td>-1129</td>
<td>-1047</td>
</tr>
<tr>
<td>$x_0$</td>
<td>0.59</td>
<td>0.45</td>
<td>0.61</td>
</tr>
<tr>
<td>$t_3 (MeV fm^6)$</td>
<td>14926</td>
<td>14000</td>
<td>12996</td>
</tr>
<tr>
<td>$M_{\text{eff}}/M$</td>
<td>0.814</td>
<td>0.763</td>
<td>0.821</td>
</tr>
<tr>
<td>$5t_2 - 9t_1 (MeV fm^5)$</td>
<td>-4330</td>
<td>-4030</td>
<td>-4036</td>
</tr>
<tr>
<td>$W_0 (MeV fm^5)$</td>
<td>97</td>
<td>120</td>
<td>91</td>
</tr>
</tbody>
</table>

\[
\frac{M_{\text{eff}}}{M} = \left(1 + \frac{(3t_1 + 5t_2)M\rho_0}{8}\right)^{-1}
\]

Guichon & Thomas, PRL 93 (2004) 132502
Major Challenges for Nuclear Physics

- Origin of Nuclear Saturation

- EOS ... as $\rho \uparrow$; as $T \uparrow$
  as $S \uparrow$; as $N-Z \uparrow$

- Phase Transition to:
  - quark matter (QM),
  - superconducting QM, strange condensate
  - related to nuclear astrophysics; n-stars....
Hyperons enter at just 2-3 $\rho_0$

Hence need effective $\Sigma$-N and $\Lambda$-N forces in this density region!

$\Xi$ - Hypernuclear data is important input: we have none!
Present Installation: HKS

Present Hypernuclear Spectroscopy equipment combination is beam splitter, Enge (e⁻), HKS (K⁺)

Installation ongoing in Hall C (April 13)

Installation completed (early June)
Time Frame for 12 GeV & Advances in Lattice QCD ⇒ Wonderful synergy!

That is: Our growing ability to use lattice QCD to calculate the unambiguous consequences of nonperturbative QCD is beautifully matched to the capacity of Jlab at 12 GeV to measure the corresponding observables with precision!

….and hence really test if QCD is the complete theory of the strong interaction
Advances in Lattice QCD

- Inclusion of Pion Cloud
- Actions with exact chiral symmetry
- Precise computations at Physical Pion Mass
- Advances in high-performance computing
Octet Magnetic Moments

Leinweber . Young et al., PRL 94 (2005) 212001
Moments of Flavor-NS PDFs and GPDs - I

- Lattice QCD can compute both moments of GPD’s with respect to $x$, and $t$-dependence

$$A^q_{n0}(-\Delta_T^2) = \int d^2b_\perp e^{i\Delta_\perp \cdot b_\perp} \int_{-1}^{1} dx x^{n-1} q(x, b_\perp)$$

Lattice data: $m_\pi = 740$ MeV

Decrease slope: decreasing transverse size as $x \to 1$

Burkardt

From: LHPC & SESAM
Plus: In 2005 JLab SRF Institute demonstrated near theoretical maximum field in single grain cavities ⇒ may be crucial for ILC
World’s Highest Average Power Light Sources

![Graph showing power vs. wavelength for various light sources]

- JLab FEL
- Jlab THz
- UV Upgrade Harmonics
- IR Upgrade
- JLabTHz Source

Key: Jlab Upgrade FEL, Jlab THz, Auston switch, Heat Capacity, MIRACL, NACL, CO2, Excimer, YAG, Argon, Ti:Sapphire T3, COIL, Copper Vapor, APS, LCLS Proposed, TTF FEL Proposed, NIF Proposed.
JLab FEL Power from THz to UV

For information: [www.jlab.org/FEL](http://www.jlab.org/FEL)
Forefront Condensed Matter and Life Sciences

Nano-Fluids
in New Technologies, in Chemistry, Bio Medicine, Geology

From Micro- to Nano-Gears
Nano Tubes
Lubrication in Nano Slits

Chemistry Lab of Tomorrow: On a Chip
Blood/Fat Flow in Capillaries
World Community in 2012 and Beyond

• With Upgrade will have three major new facilities investigating nuclear physics at hadronic level (QCD): GSI (Germany), J-PARC (Japan) and JLab*

• Complementary programs (e.g. charmed vs light-quark exotics, hadrons in-medium....)

• Wonderful opportunities to build international community and take our field to a new level

* Unique: only electromagnetic machine
Long-term Landscape: ELIC/eRHIC

- Ion Linac and pre-booster
- Electron Cooling
- Solenoid
- Snake
- 3-7 GeV electrons
- 30-150 GeV light ions
- Electron Injector
- CEBAF with Energy Recovery
- Beam Dump

More in talk of Sam Aronson tomorrow
Luminosity vs CM Energy

- **ELIC at Jlab**
  - 3-7 GeV $e^-$ on 30-150 GeV $p$
    - (both polarized)
  - 20-65 GeV CM Energy
  - Polarized light ions
  - Luminosity as high as $0.8 \times 10^{35}$ cm$^{-2}$ sec$^{-1}$

- **eRHIC at BNL**
  - 5-10 GeV $e^-$ on 50-150 GeV $p$
    - (both polarized)
  - 30-100 GeV CM Energy
  - Polarized light ions
  - Heavy ion beams available
  - Luminosity from $10^{33}$ to perhaps as high as $10^{34}$
"Quarks, neutrinos, mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them."