Nuclear Physics and the Science of Emerging Programs

(Jefferson Lab, Past, Present & Future)

Anthony W Thomas
JLab is the Current International Flagship for Hadron Physics

• Important competition in limited areas from Bates, Elsa, Hermes, MAMI, Spring 8….

• Complementary work at: Compass, IKP Jülich, Fermilab, RHIC…

• Through C12, IUPAP has initiated work on International Cooperation in Nuclear Physics (Committee chaired by AWT meets at INPC2004 in Göteborg, June 27 – follows earlier work by Feshbach and later Frois)
JLab Program Touches Key Problems in Nuclear & Particle Physics & Beyond

- Origin of nuclear forces: QCD and nuclear saturation
- Hadron properties in-medium: precursors of quark-gluon phase transition at RHIC and astrophysics of “n-stars”
- Matter with strangeness and role of heavy quarks in “normal matter”
- Exploration of new phenomena in QCD – exotic/new mesons and baryons and nature of confinement
- Search for physics beyond Standard Model
JLab Data Reveal Deuteron’s Size and Shape

Combined Data -> Deuteron’s Intrinsic Shape

For elastic e-d scattering:

\[
\frac{d\sigma}{d\Omega} = \sigma_M \left[ A + B \tan^2 \frac{\theta}{2} \right]
\]

\[ A(Q^2) = G_C^2 + \frac{8}{9} \tau^2 G_Q^2 + \frac{2}{3} \tau G_1 \]

\[ B(Q^2) = \frac{4}{3} \tau (1+\tau) G_M^2 \]

- 3rd observable needed to separate \( G_C \) and \( G_Q \)

\( \rightarrow \) tensor polarization \( t_{20} \)

The nucleon-based description works down to < 0.5 fm
Charged Pion Electromagnetic Form Factor

\[ Q^2 F_\pi \]

- Amendolia \( \pi^+ e \) elastics
- Ackermann \( p(e,e \pi^+)n \)
- Brauel \( p(e,e \pi^+)n \) Reanalyzed
- JLab E93-021

- Maris & Tandy BSE+DSE
- Nesterenko & Radyushkin QSR
- Donoghue & Na_Disp.Rel.
- Cardarelli CQM
- Stefanis pQCD

[Graph showing data points and curves for various models and measurements, with labels for different datasets and model predictions.]
Partially Quenched DWF Form Factor

- DWF $F_\pi(Q^2,t)$: LHPC (Edwards, Richards ....)
  
  - Smaller mass close to experimental VMD.

- Charge radius (crude analysis):
  
  - Exp. $r^2 = 0.439(8)\text{fm}^2$, VMD $0.405\text{fm}^2$
  
  - Statistical: $0.156(5)\text{fm}^2$, $0.310(6)\text{fm}^2$ strong mass dependence

\[
\frac{\partial F(Q^2)}{\partial Q^2} \bigg|_{Q^2=0} = \frac{1}{6} \langle r^2 \rangle \quad \Rightarrow \quad \langle r^2 \rangle = \frac{6}{m_V^2}
\]
G0 Experiment in Hall C
Strange Form Factors $G_E^s$ and $G_M^s$

Expected Forward Angle Results by late 2003

$G_E^s + \alpha G_M^s$

Lattice QCD (Liu, 1998)

- HAPPEX, published
- MAMI, expected
- G0 (FORWARD ONLY), expected
- HAPPEX II, expected

$Q^2 (\text{GeV}^2)$
$s_\ell$ may be estimated from the Kaon loop integrals

- Regulated by a dipole form factor with $\Lambda = 0.8$ GeV

$$\ell R_d^s = \frac{s_\ell}{d_\ell} = \frac{-0.036}{-0.258} = 0.140$$

- Repeating the calculation for $\Lambda = 0.8 \pm 0.2$ GeV provides

$$\ell R_d^s = \frac{s_\ell}{d_\ell} = 0.140 \pm 0.040$$

Hence $G_M^s = -0.051 \pm 0.021 \mu_N$

(dots are steps of 0.01 $\mu_N$)

Non-trivial that intersection lies on constraint line!
Use Happex to Extract Strangeness Charge Radius

\[ G_E^s + 0.39 \, G_M^s = 0.025 \pm 0.020 \pm 0.014 \text{ at } 0.4 \text{ GeV}^2 \]

(HAPPEX)

Plus lattice calculation of \( G_M^s \) and assumed dipole form

\[ \Rightarrow \quad <r^2>_s = -0.021 \pm 0.015 \text{ fm}^2 \]

c.f. \( <r^2> = -0.113 \text{ fm}^2 \) in case of the neutron
Cosmology & Physics Beyond the Standard Model

• “Unified theories applied to cosmology suffer generically from a problem of predicting time-dependent coupling constants”

• “...in cosmology with extra dimensions people try to find solutions with external dimensions expanding while extra dimensions remain static. But at present no mechanism for keeping internal spatial scale static has been found.
  Li & Gott, Phys. Rev. D58 (1998) 103513

• “$d R_{KK} / dt \neq 0$ ... could give rise to observable time variation in the fundamental ‘constants’ of our 4D world and thereby provide a window to the extra dimensions”
  Marciano, PRL 52 (1984) 489
Recent Evidence for $d\alpha / dt$

Quasar (QSO) absorption spectra

$$\Delta \alpha / \alpha = -1.9 \pm 0.5 \times 10^{-5} \quad \text{for } z > 1$$

Webb, Flambaum, Churchill, Drinkwater, Barrow, PRL 82 (1999) 884

But if $\alpha$ varies so do other ‘constants’…


$$\delta \Lambda_{QCD} / \Lambda_{QCD} \approx 34 \delta \alpha / \alpha ; \quad \delta m / m \approx 70 \delta \alpha / \alpha$$

$$\delta(m/\Lambda_{QCD}) / (m/\Lambda_{QCD}) \approx 35 \delta \alpha / \alpha$$

N.B. values are highly model dependent BUT large coefficients are generic for GUTS!
Limits on Variation of $m_q/\Lambda_{\text{QCD}}$

• Big Bang Nuclear-Synthesis

• Oklo Natural Reactor

• Quasar absorption spectra

• Laboratory clock experiments!

N.B. Precision of $10^{-15}$ possible
c.f. $10^{-5}$ in $10^9$ years!

e.g. Karshenboim, Can. J. Phys. 78 (2000) 639

Ratios of hyperfine structure levels in different atoms very
Sensitive to changes in magnetic moments
Limits from Atomic Hyperfine Structure

1st limits: Flambaum & Shuryak, PR D65 (2002) 103503

Using H, Cs, Hg\(^+\) \quad \delta \ln \left( \frac{m_q}{\Lambda_{QCD}} \right) < 5 \times 10^{-13}

More recently: Flambaum, Leinweber, Thomas & Young, hep-ph/0402098

Updated F&S and derived new limits for hyperfine transitions in: H, Rb, Cs, Yb\(^+\), Hg\(^+\) and optical transition in Hg
Sample Results

Cs clock, frequency standard

\[ V(\text{Cs}) = \alpha^{2.83} \left( \frac{m_q}{\Lambda_{QCD}} \right)^{0.110} \left( \frac{m_s}{\Lambda_{QCD}} \right)^{0.017} \frac{m_e}{m_p} \]

Use ratio of hyperfine frequencies:

\[ V(Cs/Rb) = \frac{V(Cs)}{V(Rb)} = \alpha^{0.49} \left[ \frac{m_q}{\Lambda_{QCD}} \right]^{0.174} \left[ \frac{m_s}{\Lambda_{QCD}} \right]^{0.027} \]

\[ \sim \alpha^8 \text{ under quoted GUT scenario} \]

Current best experimental determination:

\[ \frac{1}{X(Cs/Rb)} \frac{dX(Cs/Rb)}{dt} = (0.2 \pm 7) \times 10^{-16} \text{/year} \]

\[ V(\text{Hg}^+) = \alpha^{4.3} \left( \frac{m_q}{\Lambda_{QCD}} \right)^{-0.118} \left( \frac{m_s}{\Lambda_{QCD}} \right)^{0.0013} \frac{m_e}{m_p} \]

\[ V(\text{Yb}^+) = \alpha^{3.5} \left( \frac{m_q}{\Lambda_{QCD}} \right)^{-0.118} \left( \frac{m_s}{\Lambda_{QCD}} \right)^{0.0013} \frac{m_e}{m_p} \]

\[ V(\text{Cd}^+) = \alpha^{2.6} \left( \frac{m_q}{\Lambda_{QCD}} \right)^{-0.118} \left( \frac{m_s}{\Lambda_{QCD}} \right)^{0.0013} \frac{m_e}{m_p} \]

\[ \delta \alpha / \alpha < 10^{-16} \text{/year under GUT scenario} \]

H. Marion, PRL 90 (2003) 150801
Measured \( R = \sigma_L / \sigma_T \) in Resonance Region

\[ R = \frac{\sigma_L}{\sigma_T} \]

+ Low-\( Q^2 \) Moments

- Previous Worlds Data for \( Q^2 < 9 \)
- E94110 (\( Q^2 = 2.0 \))
Important Spin-Off on Proton Form Factor Issue

As spin-off, L/T separations in the elastic channel agree with those from previous SLAC experiments, confirming the discrepancy with the polarization transfer technique (submitted to PRC)

Upcoming Experiment:
Access ratio with Polarization Transfer Technique to $Q^2 = 9$
(Using 200 msr Calorimeter)
Estimate of 2-photon Exchange Effects

$\mu_p G_E / G_M$ vs. $Q^2 (GeV^2)$

Blunden, Melnitchouk, Tjon PRL (2003)

N only... so far
Quark Level Description of Finite Nuclei
(e.g. Quark Meson Coupling Model)

• MAJOR CONCEPTUAL CHANGE:
  What occupies shell model orbits are nucleon-like quasi-particles

• Have: new mass, $M_N^*$; new form factors, etc.

• EXPERIMENTAL EVIDENCE?

• First have to ask the question!

• Changes are subtle:

Jefferson Lab & Mainz

Full theoretical analysis: Udias et al.
Chiral Extrapolation of $G_M^p$

![Graph showing $G_M^p$ vs. $Q^2$ (GeV^2)](image)

Finest lattice $a \approx 0.05$ fm

Ashley et al., 2003 (QCDSF data)
CLAS++ : Neutron $G_M^n$

With 12 GeV Upgrade

Diagram showing data points and curves for various experiments including CLAS++, Lung, Rock, Bartel, and Arnold. The graph plots $G_{Mn} / \mu G_D$ against $Q^2 (\text{GeV}^2)$.
Structure of “Free” Neutrons - e.g. $F_2^n$

Requires detection of a slow recoil proton at backward angles and with momenta ~60-150MeV/c

Measure $Q^2$ dependence simultaneously
Extending DIS to High $x$:
The Neutron Asymmetry $A_1^n$

12 GeV will access the valence quark regime ($x > 0.3$), where constituent quark properties are not masked by the sea quarks and glue
New E99-117 data provide first indication that $A_1^n$ deviates from 0 at large $x$, but are clearly at variance with pQCD prediction assuming Hadron Helicity Conservation.
Unified Description of Hadron Structure via Generalized Parton Distributions

Transverse momentum of partons

Quark angular momentum

Quark spin distributions

Pion distribution amplitudes

Form factors (transverse Quark distributions)

Pion cloud

Quark longitudinal momentum distributions

H, E, \( \hat{H}, \hat{E} \) - unpolarized, \( \hat{H}, \hat{E} \) - polarized GPD

The GPDs Define Nucleon Structure

\[ \xi = \frac{x_B}{2-x_B} \]
GPDs: Much More Information than DIS

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

Quark distribution $q(x)$

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

$H(x, \xi, 0)$

$q\bar{q}$ distribution
Proton Properties Measured in Different Experiments

Elastic Scattering
transverse quark
distribution in Coordinate space

DIS
longitudinal quark distribution in momentum space

DES (GPDs)
Fully-correlated quark distribution in both coordinate and momentum space
DVCS: Single-Spin Asymmetry in $ep \rightarrow epg$

Measures phase and amplitude directly

**DVCS and Bethe-Heitler are coherent**

$\Rightarrow$ can measure amplitude AND phase

**DVCS at 11 GeV can cleanly test correlations in nucleon structure**

(data shown – 2000 hours)
Color Transparency – Now and at 12 GeV

Hall C (e,e’p) experiments at 4 and 5.5 GeV show no evidence for color transparency

Extending these data to 12 GeV will either reveal color transparency or force us to rethink our understanding of quark-based models of the nucleus

12 GeV will also permit similar measurements using the (e,e’p) reaction, which is expected to show color transparency at lower Q²
Determine Fundamental Parameters of the Standard Model

Primakoff Effect Measurements:

\[ \Gamma(\eta \rightarrow \gamma \gamma) \quad \text{and} \quad \Gamma(\eta' \rightarrow \gamma \gamma) \quad \Rightarrow \quad \eta \eta' \text{ mixing and quark mass ratio} \]

SM Tests
And Test Its Predictions: The $Q^p_{\text{Weak}}$ Experiment

“Physics beyond the Standard Model at the TeV Scale”

- Extracted values of $\sin^2 \theta_W$ must agree with Standard Model or new physics is indicated.

\[ Q^p_{\text{weak}} = 1 - 4\sin^2 \theta_W \sim 0.072 \]

- A 4% $Q^p_{\text{Weak}}$ measurement probes for new physics at energy scales to:

\[ \frac{\Lambda}{g} \sim \frac{1}{\sqrt{2}G_F |\Delta Q^p_W|} \approx 4.6 \text{ TeV} \]

$Q_{\text{weak}}$ will provide a stringent stand alone constraint on Lepto-quark based SM extensions.

With APV and SLAC E158 results $Q_{\text{weak}}$ will constrain SM extensions based on extra Z’s.
Plans for 12 GeV Began With The Equipment in the Existing Experimental Halls

Hall A (2 HRS)

Hall B (CLAS)

Hall C (SOS/HMS)
And Ended With Enhanced and/or Complementary Equipment in Halls A, B, & C and a New Hall D

A

Medium Acceptance Detector (MAD) high luminosity and intermediate angles

B

CLAS upgraded to higher ($10^{35}$) luminosity and coverage

C

Super High Momentum Spectrometer (SHMS) high luminosity and forward angles

D

9 GeV tagged polarized photons and a $4\pi$ hermetic detector

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Entirely new forms of matter

- Gauge-field configurations provide confining potential
  - States of pure glue exist
    - Exotic states not light
    - Others mix with $q\bar{q}$
  - Glue may not be in ground state
    - Hybrid mesons: exotic quantum numbers
    - Hybrid baryons: no exotics, mix with $qqq$
Glueballs and hybrid mesons

Colin Morningstar: Gluonic Excitations workshop, 2003 (Jlab)
Applied Science Program at JLab

• All physical properties (except density) of materials determined by the electrons & phonons & their dynamics.

• New generations of tools allow deeper understanding of properties of materials.

• JLab’s FEL allows us to probe:

  - **timescales** upon which electrons/phonons react to their environment
  - **energy scales** upon which correlated electron-electron and phonon-vibrational excitations occur.

• Multiple photons allow controlled out-of-equilibrium dynamics to be investigated.
Examples of Discovery Class Proposals

• Chemical reactions and molecular dynamics

• Protein function

• Superconducting bandgaps

• Giant magnetoresistance, correlated electron effects and coupling to phonon bands
Benefits of multiple photons, tunability, short pulses

Bob Jones UVa

Dance of the electrons. In the experiment by Pisharody and Jones (1), a sequence of four laser pulses excites the two valence electrons into radial wave packets whose corresponding classical orbits are indicated. The outer electron (orange) is shown both in terms of one of its classical orbits and in terms of its radial wave packet. The electron excited into the lower energy orbit (blue) is shown in one of its classical orbits. Varying the timing of the pulses allows control of the collision dynamics of the two electrons.

Probing Two-Electron Dynamics of an Atom

S. N. Pisharody and R. R. Jones*

Coherent short-pulse laser excitation has been used to control the approximate energy and relative proximity of two valence electrons within the same alkaline-earth atom, thereby providing insight into the dynamical evolution of a three-body Coulomb system. Our time-domain experiments enable direct experimental study of the electron dynamics at the classical limit of a two-electron atom. As an example, we look at the mechanism of autoionization for one two-electron configuration class and find that the doubly excited atom decays through a single violent electron-electron collision rather than a gradual exchange of energy between the electrons.
Benefits of High Repetition Rate & Tunability

Dissociative chemisorption of a CH$_4$ molecular beam incident on a Ni(100) surface with and without laser excitation.

IR-laser pumping increases reaction probability by many orders of magnitude!

Ian Harrison, UVa

Microcanonical Unimolecular Rate Theory at Surfaces – IR Photochemistry in Catalysis
Non-linear Dynamical Effects Using High Field THz Light

High electric fields are predicted to generate localized modes!


JLab collaboration with Al Sievers, Cornell U.
Thomas Jefferson National Accelerator Facility
Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Science addressed by the second Upgrade:

- How do quarks and gluons provide the binding and spin of the nucleons?
- How do quarks and gluons evolve into hadrons?
- How does nuclear binding originate from quarks and gluons?
NSAC Facilities Subcommittee Conclusions

• **SCIENCE (Category 1 – Absolutely Central)** The research program of this type of facility at JLab, similar in many ways to the electron-ion collider EIC that received a preliminary endorsement in LRP 2002, will be absolutely central to nuclear physics.

• **READINESS (Category 3 - mission and/or technical requirements not yet fully defined)** This project is still in an early stage of development.

• **Indeed case for 25 GeV fixed target vs e-ion collider needs to be worked through carefully over next 5 years.**
World Community in 2011 and Beyond

• Three major new facilities investigating nuclear physics at hadronic level (QCD):
  GSI (Germany), JHF (Japan) and JLab*

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

• GSI and ISAC (TRIUMF) also overlap RIA

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

* Unique: only electromagnetic machine