Overview of Jefferson Lab Physics Program

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HUGS
Why are we here?

- Describe how the fundamental building blocks of the nucleus, the protons and neutrons, are built from the primordial quarks and gluons - the fundamental fields of Quantum Chromodynamics (QCD).
- What are the effective degrees of freedom of QCD?
- Explain how the force that binds nucleons into nuclei arises from QCD
- Search for evidence of physics beyond the “Standard Model” of particle physics – complementary to the high-energy experiments at, say, the LHC
- We do this by Experiment, Theory, Computation and the confrontation of the three
JLab Central to Nuclear Science

Nature of Confinement

Quark-Gluon Structure
Of Nucleons and Nuclei

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

Precise few-nucleon calculations

Exotic mesons
and baryons

Tony Thomas
### JLab: 8 of 10 SC Milestones in Hadronic Physics

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones:</th>
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<tbody>
<tr>
<td>2008</td>
<td>Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s_{NN}} = 200$ GeV.</td>
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<td>2008</td>
<td>Extract accurate information on generalized parton distributions for parton momentum fractions, $x$, of 0.1 - 0.4 , and squared momentum change, $-t$, less than 0.5 GeV$^2$ in measurements of deeply virtual Compton scattering.</td>
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<td>2009</td>
<td>Complete the combined analysis of available data on single $\pi$, $\eta$, and $K$ photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.</td>
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<td>2010</td>
<td>Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, $Q^2$, of 3.5 GeV$^2$ and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 &lt; 1$ GeV$^2$.</td>
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<td>2010</td>
<td>Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via $(e,e'N)$ and $(e,e'NN)$ knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4\text{He}(e,e'p)^4\text{H}$ reaction.</td>
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<td>2011</td>
<td>Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV$^2$ for the proton and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)\text{ and } g_2(x, Q^2)$ for $x=0.2-0.6$, and $1 &lt; Q^2 &lt; 5$ GeV$^2$ for both protons and neutrons.</td>
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<tr>
<td>2012</td>
<td>Measure the electromagnetic excitations of low-lying baryon states ($&lt;2$ GeV) and their transition form factors over the range $Q^2 = 0.1 - 7$ GeV$^2$ and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.</td>
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<tr>
<td>2013</td>
<td>Measure flavor-identified $q$ and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.</td>
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<tr>
<td>2014</td>
<td>Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.</td>
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<td>2014</td>
<td>Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.</td>
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**Note:** M3, M7, M9 and M10 involve Theory in analysis.
QCD

- QCD is the theory of the strong interaction – hadronic physics
- QCD is a *Gauge Theory*, characterised by local symmetry – c.f. QED

<table>
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<tr>
<th>QED</th>
<th>QCD</th>
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<tr>
<td>Photon, $\gamma$</td>
<td>Gluons, $G$</td>
</tr>
<tr>
<td>Charged particles, e, $\mu$, u, d,...</td>
<td>Quarks: u, d, s, c, b, t</td>
</tr>
<tr>
<td>Photon is <em>neutral</em></td>
<td>Gluons carry <em>color charge</em></td>
</tr>
<tr>
<td>$\alpha_e \approx 1/137$</td>
<td>$\alpha_s \approx O(1)$</td>
</tr>
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</table>

*How do they give rise to protons, neutrons, nuclei?*
Jefferson Laboratory – 6 GeV

HOW CEBAF WORKS

Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electron beam from one straight section of the tunnel to the next for up to five orbits.

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 30 millionths of a second.

A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists.
Jefferson Lab Today

Hall A
Two high-resolution 4 GeV spectrometers

Hall B
Large acceptance spectrometer electron/photon beams

Hall C
7 GeV spectrometer, 1.8 GeV spectrometer, large installation experiments
CEBAF at 12 GeV

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

- EM Form Factors of Proton
- Pion Form Factor
- Generalized Parton Distributions
- Baryon Spectroscopy
- The search for Hybrids
Lattice QCD

At short distance QCD is asymptotically free (2004 Nobel Prize!). At long distances coupling becomes stronger – force between quark and anti-quark or the order of tonnes!

- Lattice QCD enables us to undertake ab initio computations of many of the low-energy properties of QCD
- Continuum Euclidean space time replaced by four-dimensional lattice – current typical sizes $28^3 \times 96$
- Computations dominated by inversion of large, sparse matrices.

Highly regular problem, with simple boundary conditions – very efficient use of massively parallel computers using data-parallel programming.
Why do we never see a free quark? One of the early successes of lattice QCD was the demonstration of confinement – the constant force between color-non-singlet objects at large distances.

Force between heavy quark-antiquark pair constant UKQCD (1994)
JLab and National Effort

- Jefferson Laboratory co-equal partner with BNL and FNAL in lattice QCD effort.

- **FNAL**
  - Weak matrix elements

- **BNL**
  - RHIC Physics

- **JLAB**
  - Hadronic Physics

SciDAC – R&D Vehicle

Lattice QCD at JLab will have major impact on DOE’s Nuclear Physics Program
How quarks and gluons form hadrons
Electric and Magnetic Form Factor

- Electric and Magnetic Form Factors encapsulate distribution of charge and current within a nucleon → fundamental measure of nucleon structure
- Core of Jefferson Laboratory Experimental Program
Proton EM Form Factors - II

- Lattice QCD computes the *isovector* form factor
- Hence obtain Dirac charge radius assuming dipole form
- Chiral extrapolation to the physical pion mass

\[
\langle r^2 \rangle_{\text{ch}}^{u-d} = a_0 - 2 \left( \frac{1 + 5g_A^2}{4\pi f_\pi^2} \right) \frac{1}{2} \log \left( \frac{m_\pi^2}{m_\pi^2 + \Lambda^2} \right)
\]

Leinweber, Thomas, Young, PRL86, 5011

*As the pion mass approaches the physical value, the size approaches the correct value*
What is role of heavier quarks?

- Can we measure the contribution of the heavier (s,c,t,b) quarks to hadron structure?
- Yes, in Parity-Violating Electron Scattering (PVES)
Strange-quark form factors

RDY et al., PRL97(2006)
SAMPLE, PVA4, HAPPEX, G0

new precision
HAPPEX PRL98,032301(2007)

Leinweber, RDY et al.,
PRL(2005,2006)

95% CL

$G_E^s$ vs $G_M^s$
Quark angular momentum (Ji’s sum rule)

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


Generalized Parton Distributions (GPDs)

*Measured in eg Deeply Virtual Compton Scattering*

GPDs: Different Regimes in Different Experiments

Form Factors
transverse quark distribution in Coordinate space

Structure Functions
longitudinal quark distribution in momentum space

GPDs
Fully-correlated quark distribution in both coordinate and momentum space
Origin of Nucleon Spin

- How is the spin of the proton distributed between valence quarks, sea quarks and antiquarks, gluons and orbital angular momentum
- Spin carried by quarks long measured in Deep Inelastic Scattering (DIS)
- GPDs allow us to measure (by experiment) or calculate (lattice QCD or QCD-inspired models)
Origin of Nucleon Spin

- JLab measurement of DVCS on Neutron
- Hermes Measurement of DVCS on Proton
How does the spin of the nucleon arise from quark spin, quark orbital angular momentum, and gluons?

Total Quark OAM negligible: that of individual flavors substantial.
Impact of CLAS Precision Data on Parton Distribution Functions

CLAS precision data more than doubled the data points in the DIS region from 30 years of high energy polarized structure function measurements.

The much improved control of higher twist (HT) effects achieved with these data allows to use them in global fits of the world data to extract PDFs.

At moderate $x_B=0.4$, the relative uncertainty of $x\Delta G$ is reduced by a factor 3 and of $\Delta s-\Delta s$ by a factor 2.

Conclude $|\Delta G| < 0.3$ at $Q^2 = 1$ GeV$^2$

The dashed lines include the CLAS data in the analysis (LSS’06).
Kinematics Coverage of the 12 GeV Upgrade

Upgraded JLab has unique capability to define the valence region overlap with other experiments unique to JLab

High $x_B$ only reachable with high luminosity

Upgraded JLab has unique capability to define the valence region
How quarks and gluons form hadrons and nuclei?

QCD is a complicated many-body theory
What are the effective low-energy degrees of freedom?
Hadron Spectroscopy

• Spectroscopy is classic tool for gleaning information about structure of theory

• Both experimental and *ab initio* N* and Exotic-meson programs aim at *discovering effective degrees of freedom of QCD*, and resolving competing low-energy models
  – HP2009 and HP2012 milestones
  – Excited Baryon Analysis Center (EBAC) at Jefferson Lab

• Spectroscopy of Exotic Mesons flagship component of CEBAF@12GeV

“Calculate the masses of strongly interacting particles and obtain a qualitative understanding…..”
Are states Missing, because our pictures are not expressed in correct degrees of freedom?

Do they just not couple to probes?

Capstick and Roberts,
PRD58 (1998) 074011
\[ \pi^- p \rightarrow X \]
\[ \pi^- p \rightarrow \pi^- p + \pi^0 n \]

Excited Baryon Analysis Center
Lattice QCD

Lattice "Symmetries"

Nucleon Mass Spectrum (Exp)

Basak et al., PRD76, 074504 (2007)

$m_\pi = 490\text{MeV}$
Exotics – I

- Exotic Mesons are those whose values of $J^{PC}$ are in accessible to quark model
  - Multi-quark states: $q ar{q} q ar{q}$
  - Hybrids with excitations of the flux-tube
- Study of hybrids: revealing gluonic and flux-tube degrees of freedom of QCD.
Lattice QCD: Hybrids and GlueX - I

- GlueX aims to photoproduce hybrid mesons in Hall D.
- Lattice QCD has a crucial role in both predicting the spectrum and in computing the production rates.

\[ \langle \gamma | M R \rangle \]

Important goal for LQCD
How nucleons bind together to form nuclei?

- Build an effective description of the interaction between nucleons
- Show how that description arises from QCD, via effective theory, Lattice QCD,
Elastic Scattering off $^3$He and $^4$He

- Measurement of the form factors of $^3$He and $^4$He up to the largest $Q^2$ possible (~3 GeV$^2$).
- Data precision/range is pivotal for the establishment of a standard hadronic (nucleon-meson) model for the description of the few-body nuclear systems, severely constraining impulse approximation, meson exchange currents, nucleon-nucleon potential etc.

![Graphs showing data for $^3$He and $^4$He](image)
* Currently, can investigate \textbf{Meson-Meson} system in lattice QCD

\[ I = 2\pi - \pi \text{ Scattering Length} \]

\[ m_\pi a_{\pi+\pi+} \]

NPLQCD, arXiv:0706.3026
Standard Model and Beyond
PVES - I

- Can Jefferson Lab help in the search for new physics beyond the Standard Model of particle and nuclear physics?
- Yes – precise measurements of low energy constants
QWEAK will constrain new physics to beyond 2 TeV

future Qweak with PVES Atomic and others

95% CL

Young, Carlini, Thomas, Roche, hep-ph/0704.2618

QWEAK will constrain new physics to beyond 2 TeV
Jefferson Lab’s Energy Recovered Linac / FEL

Search for Axions
Summary

- Exciting physics program at 6 GeV aimed at gleaning an understanding of the structure of nucleons are nuclei in terms of the fundamental quarks and gluons of QCD
- On track for the 12 GeV Upgrade, with next milestone (CD-3) later this year
- Great opportunities for the next generation of Experimentalists, Theorists and amalgams of the two