Scientific Overview

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S&T Review: JLab July 14th 2009
Overview

• Past 12 years have yielded outstanding science

• Remaining years of 6 GeV operation promise more

• 12 GeV Upgrade offers “high probability for discoveries that may lead to significant paradigm shifts”
  - top rated NP project in the NSAC Long Range Plan

• Strong Theory Group focused on support for program

• Innovative design for staging a future (M)EIC

• World leader in SRF and ERL technology

• Opportunities for scientific discovery at the FEL
  - plans for a future 4th generation light source
Users / Students

• Active Users: 1,300
  - Largest nuclear physics user base at any laboratory worldwide
• Produce \( \sim 30\% \) of US PhDs in Nuclear Physics annually

![PhD Production Graph]
JLab Central to Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement

Precise few-nucleon calculations

Correlations

n-radii: N ≠ Z

Hypernuclei
Hadrons in-medium
Effective NN (+ HN) force

Exotic mesons and baryons

...n-stars
Highlights of First Decade

• Discovery of unexpected behavior of $G_E^p$ - new result FY09

• Superb program of studies in parity violation
  - strangeness content of the nucleon – new result FY09
  - factor 5 increase in precision of Standard Model couplings

• Study of deformation of $\Delta$ and transition form factors of nucleon excited states

• Major new results for structure functions – new result FY09
  - Bjorken & DHG sum rule; $g_{1n}$; $|\Delta G|$; d/u ratio
Highlights of First 10 years – cont.

• New information on correlations in nuclei
  - role of the tensor force

• Studies of hypernuclei – better than 400keV resolution

• Exploration of duality, pQCD counting rules, color transparency

• Initial exploration of Generalized Parton Distributions (GPDs) – towards mapping of angular momentum in the proton
Highlights of Remaining 6 GeV Program

Structure of nuclear building blocks

• Precision measurements of electric and magnetic form factors and their quark flavor decompositions (OMB milestone)
• Understand nucleon excitation spectra, measuring transition form factors (OMB milestone)
• Determine nucleon structure at intermediate $x$; measure moments of unpolarized structure functions (OMB milestone)
• Develop tools for a program of “nuclear tomography” (OMB milestone)
Highlights of Remaining 6 GeV Program (cont.)

Structure of nuclei

• Explore deeply-lying shell structure, QCD basis of N-N force via hypernuclear experiments
• Compare properties of nucleons bound in nuclei with those of free nucleons (OMB milestone)
• Measure the neutron radius of Pb$^{208}$ providing essential information for a broad range of physics
• Explore underlying quark-gluon structure of light nuclei by measuring elastic form factors at high momentum transfer

Symmetry Tests

• Determine the weak charge of the proton
CEBAF at 12 GeV

- Add new hall
- Upgrade magnets and power supplies
- Add 5 cryomodules
- Enhance equipment in existing halls
- CHL-2
- 20 cryomodules
- Add arc
- A
- B
- C

Thomas Jefferson National Accelerator Facility
Operated by Jefferson Science Associates for the U.S. Department of Energy
Highlights of the 12 GeV Program

• Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

• Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

• Totally New View of Hadron (and Nuclear) Structure: GPDs
  ➢ Determination of the quark angular momentum
Highlights of the 12 GeV Program

- Exploration of QCD in the Nonperturbative Regime:
  - Existence and properties of exotic mesons

- New Paradigm for Nuclear Physics:
  Nuclear Structure in Terms of QCD
  - Spin and flavor dependent EMC Effect
  - Study quark propagation through nuclear matter

- Precision Tests of the Standard Model
  - Parity Violating DIS & Möller
## 12 GeV: Milestone Performance

<table>
<thead>
<tr>
<th>Level and Number</th>
<th>Milestone Description</th>
<th>Baseline</th>
<th>Projected</th>
<th>Actual</th>
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<td>1-1</td>
<td>CD-0 (Approve Mission Need)</td>
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<td>CD-1 (Approve Preliminary Baseline Range)</td>
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<td>CD-3 (Approve Start of Construction)</td>
<td>Sep-08</td>
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<td>CD-4A (Approve Accelerator Project Completion and Start of Operations)</td>
<td>Dec-14</td>
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<td>CD-4B (Approve Experimental Equipment Project Completion and Start of Operations)</td>
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<td>Design Review of Superconducting Magnets</td>
<td>Jul-08</td>
<td>May-08</td>
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<td>Design of Conventional Facilities Completed</td>
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<tr>
<td>2-06</td>
<td>Award First Superconducting Magnet Contract</td>
<td>Jul-09</td>
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<td>2-15</td>
<td>Ready for Equipment - CHL Addition (RFE)</td>
<td>Sep-10</td>
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<tr>
<td>2-16</td>
<td>Ready for Equipment - Hall-D (RFE)</td>
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<td>2-10</td>
<td>Start Hall-D Installation</td>
<td>Nov-10</td>
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<td>Klystron Mass Production Authorization</td>
<td>Jun-11</td>
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**Talk of C. Rode**
Scientific Highlights
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
Preliminary Result from Bonus Experiment
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JLab Data Rewrote the Text Book on $G_E^p$

- High Intensity
- High Duty Factor
- High Polarization

$\Rightarrow$ Revolutionized our knowledge

![Graph showing data points and curves representing proton densities.](image)
Further Measurements of $G_E^p$

- Perdrisat et al. E01-109 — increased range of $Q^2$ by 50% in FY08 (analysis nearing completion)
- 12 GeV and SHMS in Hall C will go to 14 GeV$^2$
Strangeness in the Nucleon

• Strangeness contribution is a vacuum polarization effect, analogous to Lamb shift in QED

\[ g_e = 2 \left( 1 + \frac{\alpha}{2\pi} - 0.328 \frac{\alpha^2}{\pi^2} + \ldots \right) \]

• It is a fundamental test of non-perturbative QCD
Experimental Determination

• Assuming charge symmetry:

\[
G_{E,M}^{u,p} = \left(3 - 4 \sin^2 \theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{Z,p}
\]
\[
G_{E,M}^{d,p} = \left(2 - 4 \sin^2 \theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}
\]
\[
G_{E,M}^{s,p} = \left(1 - 4 \sin^2 \theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}
\]

• Need three independent observables to extract individual quark contributions to form factors
PVA4 2009: $Q^2 = 0.22$ GeV$^2$

\[ G_M^s = -0.14 \pm 0.11 \pm 0.11 \mu_N ; \quad G_E^s = 0.050 \pm 0.038 \pm 0.019 \]

arXiv: 0903.2733v1
The G0 experiment at JLAB

- Forward and backward angle PV e-p elastic and e-d (quasielastic) in JLab Hall C

- superconducting toroidal magnet

- scattered particles detected in segmented scintillator arrays in spectrometer focal plane

- custom electronics count and process scattered particles at > 1 MHz

- forward angle data published 2005

- backward angle data: 2006-2007

\[ G_E^s, G_M^s \text{ and } G_A^e \text{ separated over range } Q^2 \sim 0.1 - 1.0 \text{ (GeV/c)}^2 \]
Form Factor Results

Using interpolation of G0 forward measurements

Global uncertainties

Some calculations:
Leinweber, et al. PRL 97 (2006) 022001
Leinweber, et al. PRL 94 (2005) 152001
Wang, et al arXiv:0807.0944 (Q^2 = 0.23 GeV^2)
Flavor Separated Form Factors
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- Tests of Physics Beyond the Standard Model
QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

With the upgraded CEBAF, a linearly polarized photon beam, and the GlueX detector, Jefferson Lab will be uniquely poised to:

- discover these states,
- map out their spectrum, and
- measure their properties
Search for hybrid $\pi_1(1600)$ meson

- Possible evidence of exotic meson (hybrid) $\pi_1(1600)$ in $\pi p \rightarrow (3\pi)p$
- Not confirmed in a re-analysis of a higher statistic sample

E852-Brookhaven

**Phys.Rev.Lett.102:102002,2009**

- Clear evidence of non-exotic $2^{++}$ state $a_2(1320)$
- No-evidence of exotic $1^- +$ state $\pi_1(1600)$
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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 of the EMC Effect](image)


E03-103 Preliminary Results

- Analysis for $^4$He and $^3$He nearly complete → paper draft in progress (thesis of C. Seely, MIT)

- $^3$He ratio has significant correction due to “proton excess”

- Data show significant EMC effect, although somewhat smaller than $^4$He

- Heavy target analysis in progress → A. Daniel (Houston) thesis
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

\[
\frac{dA}{A} = 3\% \rightarrow \frac{dR_n}{R_n} = 1\%
\]
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Q\text{weak} Apparatus – to be installed late CY09

- **Region I:** GEM Gas Electron Multiplier
- **Region II:** Horizontal drift chamber location
- **Region III:** Vertical Drift chambers
- **Quartz Cherenkov Bars** (insensitive to non-relativistic particles)
- **Lumi Monitors**
- **Collimator System**
- **QTOR Magnet**
- **Trigger Scintillator**

**Beam Parameters:**
- \( E_{\text{beam}} = 1.165 \text{ GeV} \)
- \( I_{\text{beam}} = 180 \mu \text{A} \)
- Polarization \( \sim 85\% \)
- Target = 2.5 KW
New Physics Limits
(if result consistent with Standard Model)

Q_{weak} constrains new physics to beyond 2 TeV

future Q_{weak}
with PVES
Atomic only

95% CL
Next Generation: \( Q_{\text{weak}} \) has real discovery potential!

**IF:** \( Q_{\text{weak}} \) takes central value of current PVES measurement

\[ 1.5 < \frac{\Lambda}{g} < 2.5 \text{ TeV} \]

\( Q_{\text{weak}} \) yields mass scale and coupling of new \( Z' \)

Young et al. (Dec 2006)
Qweak Radiative Corrections

Claim: Gorchtein & Horowitz: PRL March 2009
Radiative corrections big and large errors ⇒ Qweak problem!

Melnitchouk, Sibirtsev AT: under control!
JLab Energy Recovered Linac / FEL

E = 150 MeV
135 pC pulses up to 75 MHz
(20)/120/1 microJ/pulse in (UV)/IR/THz
250 nm – 14 microns, 0.1 – 5 THz

All sources are simultaneously produced for pump-probe studies

UV hardware 95% complete
Jefferson Lab Light Source Plans

Talk of G. Neil

• Immediate: Engage key users for scientific utilization of existing FEL, while extending our capability into the 100nm region using the 3rd harmonic of UV-FEL by increasing beam energy from 100 MeV to 150 MeV,

• Increase the machine energy to 600 MeV by recirculation. Install amplifier undulator and seed laser – JLamp AMPlifier
  • JLAMP - Reach 10nm in fundamental
  • Two soft X-ray user stations
  • Validate CSR physics limitations to recirculation.

Parallel objectives of the approach are developing the technology for both the source and user while performing cutting edge science with a world class photon beam.
JLAMP Performance

Average Brightness
Photons/sec/0.1%BW/mm²/mrad²

Photon Energy (eV)

1E-3 0.01 0.1 1 10 100 1000 10000

2nd Gen
3rd Gen
4th Gen

Infrared FELs
FLASH
JLAB-THZ
JLAB-UV FEL
JLAMP
XFEL
LCLS

Gwen Williams - file brt_1.bas
Long-term Landscape: ELIC

30-225 GeV p
30-100 GeV/A ions

Electron Cooling

Snake

Snake

3-9 GeV $e^+$ and $e^-$

BUT recently much work devoted to lower cost staging options
MEIC@JLab – an overview

Main Features

- Electron energy: 3-11 GeV
- Proton energy: 12-60 GeV
- Luminosity: few \( \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\)
- Polarized electrons and light ions
  - Longitudinal and transverse
- Limited R&D

Science highlights

- Transverse imaging of gluons and sea quarks
- Nucleon spin (quark/gluon orbital motion)
- Nuclei in QCD (quark/gluon structure)
- QCD vacuum in hadron structure and creation

Talk of G. Krafft
Impressive Physics Reach

EIC@JLab

\[ x \sim \frac{Q^2}{ys} \]

- Luminosity (s^{-1} cm^{-2})
- s (GeV^2)

- EW
- DIS
- SIDIS
- DIFF
- Saturation

10^32
10^33
10^34
10^35
10^36

10
100
1000
10000
100000

19 June 2009
MEIC Accelerator R&D

• Key R&D for MEIC are
  • electron cooling for delivering low emittance/ultra short ion bunches
  • Traveling focusing for suppressing space charge effect & boosting luminosity
  • Crab cavity required for colliding high repetition beams
  • Forming high intensity low energy ion beam
  • Beam-beam effect

• There are other less critical/challenging R&D topics but required by ZDR

<table>
<thead>
<tr>
<th>Level of R&amp;D</th>
<th>MEIC</th>
<th>ELIC</th>
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<tbody>
<tr>
<td>Nearly impossible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very challenging</td>
<td></td>
<td>Electron cooling</td>
</tr>
<tr>
<td>Challenging</td>
<td>Electron cooling</td>
<td>Crab crossing/crab cavity</td>
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<tr>
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<td>Traveling focusing</td>
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<tr>
<td>Likely</td>
<td>Crab crossing/crab cavity</td>
<td>High intensity low energy i beam</td>
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<tr>
<td>Know-how</td>
<td>Spin tracking</td>
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<tr>
<td></td>
<td>IP design/chromaticity</td>
<td>IP design/chromaticity</td>
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Talk of G. Krafft
Summary

• Jefferson Lab has a remarkable record of outstanding science

• It has a very strong program for the remaining 6 GeV operation

• The 12 GeV Upgrade is on track and will produce discovery class science

• There are maturing plans beyond 12 GeV

• JLab has a position of world leadership as the world’s pre-eminent electron scattering facility for the next 20+ years