Exploring the Nature of Matter
Jefferson Lab and its plans

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This talk was compiled from the work of many others. In particular I have liberally used several transparencies from talks presented by my colleagues at Jefferson Laboratory and others from whom they in turn have “borrowed”.

I have also made use of the Nuclear Science Advisory Committee (NSAC) long range plan from 2007.
The Talk

• Introduction
  – Electron as a Probe of Nuclei and Nucleons
  – Quarks, Partons and Gluons
  – Technologies of Jefferson Laboratory
  – 12 GeV Upgrade Project
• Hadron (Nuclear and Nucleon) Structure
• Precision Electroweak Measurements
• Hadron Spectroscopy
• A Future Machine?
• Conclusions
The Ultimate Constituents

MATTER

ATOM

NUCLEUS

electron

NUCLEUS

PROTON

QUARK

LEPTONS

electron
Electric charge \(-1\)
Responsible for electricity and chemical reactions

electron neutrino
Electric charge 0.
Rarely interacts with other matter.

QUARKS

up
Electric charge \(+2/3\)
Protons have 2 up quarks
Neutrons have 1 up quark

down
Electric charge \(-1/3\)
... and one down quark.
... and two down quarks.

electron neutrino

muon
A heavier relative of the electron.

muon neutrino
Created with muons when some particles decay.

tau neutrino
Not yet observed directly.

tau
Heavier still.

top
Heavier still, recently observed.

bottom
Heavier still.

ANTIMATTER

Each particle also has an antimatter counterpart ... sort of a mirror image.
Electron Scattering: 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:
  \[ \lambda \approx \frac{2\pi}{q} \quad (1 \text{ fm} \leftrightarrow 1 \text{ GeV/c}) \]

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

$\tilde{q} = \tilde{k}_1 - \tilde{k}_2 =$Momentum Transfer

$\omega = E_p - E_{p'} =$Energy Transfer

$Q^2 = -q^2 =$4-Momentum Transfer
Nuclear Charge Distributions
Electron Scattering: A picture
Nucleon Structure Functions

**FIG. 2**

![Graph showing nucleon structure functions](image-url)
A Surprise: The EMC Effect

Unexpected

Despite the high momentum transfers involved

the measured $F_2^N$ depends on the nucleus!!!!!!

Lots of post-data wisdom from theorists!!

Also from experimentalists (Arie Bodek)
Nucleon Nucleon Correlations

Experiment from Jefferson Lab
Graphics from CERN Courier
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
Spin, Current, and Beam Delivery @CEBAF

<table>
<thead>
<tr>
<th>Polarimeter</th>
<th>$I_{ave}$</th>
<th>$P_x$</th>
<th>$P_y$</th>
<th>$P_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Mott</td>
<td>2 $\mu$A</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hall A Compton</td>
<td>70 $\mu$A</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Hall A Moller</td>
<td>1 $\mu$A</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Hall B Moller</td>
<td>10 nA</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Hall C Moller</td>
<td>1 $\mu$A</td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Under development

- <0.5% Atomic Beam Polarimeter (Hall A)
- <1% Compton Polarimeter (Hall C)
Polarized Targets at JLab

Hall A: $^3$He

$G_E^n$, SSAs Transversity

Hall B: eg1

Dynamically polarized NH$_3$ ND$_3$,

$Q^2$ evolution of Nucleon Spin Structure, DVCS

Hall B: FROST

Frozen Spin Target, Butanol

“Missing” N* Search.

Hall C:

Dynamically polarized, NH$_3$ ND$_3$

$G_E^n$, SANE, $g_{1p}$, $g_{1d}$

HDIce from BNL under development: Polarized neutron target for N* expts.
12 GeV Upgrade

Enhanced capabilities in existing Halls

Add 5 cryomodules

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

CHL-2

New Hall

Maintain capability to deliver lower pass beam energies
**12 GeV Upgrade**

**Exciting new scientific opportunities – continue world leadership**

- Discover the spectrum and properties of exotic mesons in mass range 1.5-2.6 GeV in order to explore the physical origins of quark confinement

- Define the spin and flavor structure of the nucleon in the valence region, hence test theories of di-quarks, pQCD….

- Determine the orbital angular momentum carried by up and down quarks and explore potential of Generalized Parton Distributions for tomographic imaging

- Exploit the unique capabilities of CEBAF at 12 GeV to explore the structure of nuclei at the level of quarks and gluons – understand the EMC effect

- Probe potential new physics (beyond the Standard Model) through precise test of evolution of $\sin^2 \theta_W$ from Z-pole
Four Halls

Hall D - exploring origin of confinement by studying exotic mesons

Hall B - understanding nucleon structure via generalized parton distributions

Hall C - precision determination of valence quark properties in nucleons and nuclei

Hall A - short range correlations, form factors, hyper-nuclear physics, future new experiments
Charged Pion Electromagnetic Form Factor

Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

- It will occur earliest in the simplest systems
  → the pion form factor $F_\pi(Q^2)$ provides our best chance to determine the relevant distance scale experimentally

To measure $F_\pi(Q^2)$:

- At low $Q^2 (< 0.3 \text{ (GeV/c)}^2)$: use $\pi + e$ scattering \( \rightarrow R_{\text{rms}} = 0.66 \text{ fm} \)

- At higher $Q^2$: use $^1\text{H}(e,e'\pi^+)n$

  Scatter from a virtual pion in the proton and

  1) extrapolate to the pion pole
  \( \rightarrow \) large uncertainty

  2) use a realistic pion electroproduction model

In asymptotic region, $F_\pi \rightarrow 8\pi\alpha_s \int\pi^2 Q^{-2}$
Super BigBite Spectrometer

BNL | INFN | NSF | D0 / SMU

BigCal
ITEP (HERA-B)

Dubna (COMPAS)
ITEP (HERA-B)

48D48

1 - 2 Gauss

10 - 20 Gauss

+/- 25 mrad
12 GeV in Hall A: Scientific Plans

GEP-15 Experiment (approved by August PAC32):

Goal: Measure $F_2/F_1$ on proton up to $Q^2 = 15$ GeV$^2$
Method: Recoil Polarization on elastic ep scattering
Expected Result: Relative accuracy $\sim 3$

Physics Impact:
- Study spin flip part of the hadron current
- Constrain Generalized Parton Distributions at high $t$
- Critical test of Form Factor models and reaction dynamics

Requires a new spectrometer

Other relevant physics experiments
(same detectors as $G_E^p$, different configurations):
- $G_E^n$ to 7 GeV$^2$ (double present knowledge)
- Nucleon Spin structure via Deep Inclusive and Semi-Inclusive Deep Inelastic Scattering
- $J/\Psi$ photo-production
Measuring High-x Structure Functions

REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers

12 GeV will access the regime ($x > 0.3$), where valence quarks dominate.
Hall B: The **CEBAF Large Acceptance Spectrometer (CLAS)**

Maximum luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$

Present-day **CLAS**
CLAS12 Central Detector

Solénoïde 5 T: Saclay?

Light guides TOF IN2P3/Glasgow

Central Tracker: Si JLab MM Saclay

Neutron counters IN2P3/INFN

(All subsystems under R&D or conceptual phase)
Generalized Parton Distributions (GPDs)


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions
Deep Inelastic and Deep Exclusive Scattering

\[ M = \gamma, \gamma^*, \pi, \eta, \rho, \omega, K, \ldots \]

\[ M = \pi, \eta, \rho, \omega, K, \ldots \]
Tests of the Handbag Dominance

- To study the combined spatial and momentum distributions, need to measure GPDs
  - But must demonstrate that the conditions for factorization apply!
- 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: $\sigma_L >> \sigma_T$
- Factorization theorems for meson electroproduction have been proven rigorously only for longitudinal photons [Collins, Frankfurt, Strikman, 1997]

\[
2\pi \frac{d\sigma}{dt d\varphi} = \frac{d\sigma_T}{dt} + \varepsilon \left( \frac{d\sigma_L}{dt} \right) + \sqrt{2\varepsilon (1 + \varepsilon)} \frac{d\sigma_{LT}}{dt} \cos\varphi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos2\varphi
\]
Electron Scattering: A picture
Parity Violating Asymmetries

\[ A_{PV} \sim 8 \times 10^{-5} Q^2 \quad \rightarrow \quad 0.1 \text{ to } 100 \text{ ppm} \]

SLAC E122: parity-violating deep inelastic scattering

20 GeV longitudinally polarized electrons

precision monitors

liquid Deuterium

integarting detector

asymmetry \sim 10^{-4}
error \sim 10^{-5}

C.Y. Prescott et al. 1978

- Steady progress in technology
- part per billion systematic control
- 1% normalization control
- JLab now takes the lead
  - New results from HAPPEX
  - Photocathodes
  - Polarimetry
  - Targets
  - Diagnostics
  - Counting Electronics
Extraction of $Q^p_{\text{weak}}$

The $Q_{\text{weak}}$ experiment measures the parity-violating analyzing power $A_z$

$$A_z = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \simeq -3 \times 10^{-7}$$

$$A_z \xrightarrow{Q^2 \to 0} \frac{-G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 Q^p_{\text{weak}} + Q^4 B(Q^2) \right]$$

Contains $G^{\gamma E,M}$ and $G^{Z E,M}$, Extracted using global fit of existing PVES experiments!

$Q^p_{\text{weak}} = 1 - 4\sin^2 \theta_W \sim 0.072$ (at tree level)

- $Q^p_{\text{weak}}$ is a well-defined experimental observable
- $Q^p_{\text{weak}}$ has a definite prediction in the electroweak Standard Model
Weak Couplings

Isoscalar weak charge

Isovector weak charge

All Data & Fits Plotted at 1 σ

Weak Couplings

Standard Model Prediction

Q-weak expected precision

HAPPEX: H, He
G⁰: H,
PVA4: H
SAMPLE: H, D
Møller & Deep Inelastic Scattering Parity Violation

Layout in Hall A

- Dedicated Møller Experiment with toroids
- SoLID general purpose deep inelastic parity violating experiment with solenoid
  - Semi-Inclusive Program?
$\sin^2 \theta_w$
PREX: $^{208}\text{Pb}$ Radius Experiment

Low $Q^2$ elastic e-nucleus scattering

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

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

Measure a Parity Violating Asymmetry

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

• Fundamental check of Nuclear Theory
• Input to Atomic PV Expts
• Neutron Star Structure
QCD and confinement

Asymptotic Freedom

Small Distance
High Energy

Perturbative QCD

High Energy Scattering

Gluon Jets Observed

Strong QCD

Confinement

Large Distance
Low Energy

Gluonic Degrees of Freedom
Missing

Spectroscopy
Hybrid mesons and mass predictions

- Transverse phonon modes
- Ground state

1 GeV mass difference

Hybrid mesons

Normal mesons

1-+ 1.9 GeV
2+- 2.1 GeV
0+- 2.3 GeV

Lattice

Lowest mass expected to be $\pi_1(1^{-+})$ at 1.9±0.2 GeV

Hybrid mesons and mass predictions

For $J^{pc} = 1^{-+}$

- $\pi_1(1^{-+})$
- $b_0(0^{-})$
- $b_2(2^{-})$

Mass predictions:

- $1^{-+}$: 1.9 GeV
- $2^{-+}$: 2.1 GeV
- $0^{-+}$: 2.3 GeV

For $J^{pc} = 1^{-+}$
Note that tagger is 80 m upstream of detector.
GlueX uses Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization.

Electrons in

Photons out

Spectrometer

Diamond crystal

Good "acceptance" up to $M \sim 2.5$ GeV

12 GeV electrons

Coherent spectrum

Incoherent &

40% polarization in peak

0.1% resolution

Tagged photon energy (GeV)

37
Finding the Exotic Wave

\[ \gamma \rightarrow V(\text{ector Meson}) \quad S = 1 \]

(Double-blind M. C. exercise)

An exotic wave \( (J^{PC} = 1^{-+}) \) was generated at level of 2.5 % with 7 other waves. Events were smeared, accepted, passed to PWA fitter.

\[ X(\text{exotic}) \rightarrow \rho \pi \rightarrow 3\pi \]

Mass

Input: 1600 MeV
Output: 1598 +/- 3 MeV

Width

Input: 170 MeV
Output: 173 +/- 11 MeV

Statistics shown here correspond to a few days of running.
Electron Ion Collider

• **Recommended as a generic capability** by:
  – NSAC Long Range Report
  – IUPAP WG9 Working Group on world-wide nuclear facilities

• **Candidate Facilities with different key characteristics**
  – LHeC at CERN
  – eRHIC at Brookhaven National Laboratory
  – ELIC – EElectron Ion Collider at Jlab
  – MANUEL at FAIR-GSI
  – Plus several new ideas!!!!

• **Natural Extension of Jlab nuclear physics agenda**

• **Issues**
  – Physics Case(s) not yet broadly accepted
  – Cost scale is thought to be large

• **Jefferson Lab and BNL: Joint EIC Advisory Committee reports to Laboratory Directors**
ELectron Ion Collider

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

3-9 GeV e^+ and e^-
Medium Energy Electron Ion Collider

Map the spin and 3D quark-gluon structure of protons
Discover the role of gluons in atomic nuclei
Understand the creation of the quark-gluon matter around us

MEIC = EIC@JLab
1 low-energy IR  (s ~ 200)
3 medium-energy IRs  (s < 2600)

ELIC = high-energy EIC@JLab  
(s = 11000)
(limited by JLab site)
Potential Physics Program Elements

- **Inclusive DIS**
  - **Unpolarized**: EMC effect, gluons in nuclei
  - **Polarized**: $\Delta G, \Delta q$

- **Semi-Inclusive DIS**
  - **Unpolarized**: flavor decomposition of sea, strangeness
  - **Polarized**: orbital angular momentum in TMDs, flavor separation of $\Delta q$

- **Exclusive (GPDs: transverse spatial distributions, orbital angular momentum)**
  - **Diffractive**: gluons from DVCS and $J/\psi$; DVCS on nuclei
  - **Non-diffractive**: sea quarks from light mesons
MEIC Exclusive Process Kinematics

- Electrons scattering angles are large compared with fixed-target kinematics.
- Large $e-p$ momentum asymmetry would require $e/\pi$ discrimination at large angles in order to reach $Q^2 \sim 10 \text{ GeV}^2$ (ensuring factorization).
- Small-angle coverage only needed for symmetric collisions and photoproduction.
EIC Working Group/Initiative at Jefferson Lab

• Coordinators
  – UGBOD Chair - Zein-Eddine Meziani
  – Jefferson Lab AD for Accelerators - Andrew Hutton
  – Jefferson Lab AD for Physics - Larry Cardman

• Goals
  • Physics/Detectors
  • Explore the case for a high luminosity \((10^{34} -- 10^{35} \text{ cm}^{-2} \text{ sec}^{-1})\), High Polarization (80% e, 70%p) collider with moderate energy reach.
  • Delineate those physics goals which can be achieved, and enumerate those which are not addressed. Concentrate on key experiments, the real physics drivers.
  • Explore at least one concept study and propose solutions for high luminosity.

• Machine
  • A concept for a machine with high luminosity, high polarization and moderate energy has been developed. The machine is somewhat novel:
  • Validate the existing conceptual design of the machine.
  • Develop ideas and an R&D program which will address any deficiencies.

• Report
  • Write a white paper which documents the physics case and which describes the machine and detectors.

• Timescale
  • To be maximally useful, the report should be available by the beginning of summer 2010. It would then permit a rational discussion of the potential for such a machine.
Exploring the Nature of Matter
JLAMP Spares

• JLAMP Follows
Jefferson Lab Free Electron Laser
JLAMP
JLAMP Layout
Spares Follow
Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab) is one of the premier facilities for nuclear and hadronic physics in the world. With high luminosity and high polarization continuous wave electron beams, the 6 GeV physics program has produced exciting results during the past decade. Currently the laboratory is executing an upgrade of the accelerator from 6 GeV to 12 GeV: this project was recommended as the top priority in the most recent US nuclear physics long-range plan. The upgrade, which also includes changes to the experimental facilities, will open new avenues of investigation. Beyond this upgrade Jefferson Lab is preparing the case for a future Electron Ion Collider.
Electron Scattering

- **1950:** Does the proton have finite size and structure?
  - Elastic electron-proton scattering
    - the proton is not a point-like particle but has finite size
      - charge and current distribution in the proton, $G_E/G_M$
  - Nobel prize 1961- R. Hofstadter

- **1960-1980:** What is the internal structure of the proton?
  - Deeply inelastic scattering
    - discover quarks in ‘scaling’ of structure functions
      - quark longitudinal momentum distribution
      - quark helicity distribution
  - Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor