Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration
University of Richmond

- Jefferson Lab’s Mission
- What we know.
- What we don’t know.
- What we measure.
- Experiments with CLAS12
- Concluding Remarks

"The Periodic Table"
What is the Mission of Jefferson Lab?

- Basic research into the quark nature of the atomic nucleus.
- Map the geography of the transition from proton-neutron picture of nuclei to one based on quarks and gluons.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
- Test the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.
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One of the seven Millenium Prize Problems from the Clay Mathematics Institute.
What Do We Know?

- The Universe is made of quarks and leptons and the force carriers.

- The atomic nucleus is made of protons and neutrons bound by the strong force.

- The quarks are confined inside the protons and neutrons.

- Protons and neutrons are NOT confined.
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---

**Table: FERMIONS**

<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2</th>
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</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c^2</td>
</tr>
<tr>
<td>(\nu_L) lightest neutrino*</td>
<td>((0-2)\times10^{-9})</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
</tr>
<tr>
<td>(\nu_M) middle neutrino*</td>
<td>((0.009-2)\times10^{-9})</td>
</tr>
<tr>
<td>(\mu) muon</td>
<td>0.106</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quarks</th>
<th>spin = 1/2</th>
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</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Approx. Mass GeV/c^2</td>
</tr>
<tr>
<td>u up</td>
<td>0.002</td>
</tr>
<tr>
<td>d down</td>
<td>0.005</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
</tr>
</tbody>
</table>

---

**Notes Used in Symphony #5**

![Graph showing notes used in Symphony #5](image)
What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.
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The hadronic model uses a phenomenological force fitted to data at low energy. This ‘strong’ force is the residual force between quarks.
We have a working theory of strong interactions: quantum chromodynamics or QCD (B. Abbott, et al., Phys. Rev. Lett., 86, 1707 (2001)).

The coherent hadronic model (the standard model of nuclear physics) works too (L.C. Alexa, et al., Phys. Rev. Lett., 82, 1374 (1999)).
How Well Do We Know It?

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What Don’t We Know?

- Matter comes in pairs of quarks or triplets.
- We are made mostly of the triplets (protons and neutrons).
- More than 99% of our mass is in nucleons.
- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
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- A quiz: How much does the proton weigh?

### Fermions

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
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</thead>
<tbody>
<tr>
<td>$\nu_L$ lightest neutrino*</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
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<td>$(0.009-2) \times 10^{-9}$</td>
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</tr>
<tr>
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<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$ heaviest neutrino*</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.777</td>
<td>-1</td>
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</table>

### Matter constituents

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.005</td>
<td>$-1/3$</td>
</tr>
<tr>
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<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>$t$ top</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.2</td>
<td>$-1/3$</td>
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A quiz: How much does the proton weigh?

$$m_p = 2m_{up} + m_{down}$$
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m_p = 2m_{up} + m_{down} = 2(0.002 \text{ GeV}/c^2) + 0.005 \text{ GeV}/c^2
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m_p = 2m_{\text{up}} + m_{\text{down}} = 2(0.002 \text{ GeV}/c^2) + 0.005 \text{ GeV}/c^2
\]

\[
= 0.939 \text{ GeV}/c^2 \quad \text{OOOPS!!!??????}
\]

2. NEED TO FIGURE OUT QCD AT THE ENERGIES OF NUCLEI!!
What Do We Measure?

The Magnetic Form Factor of the Neutron ($G_n^M$)

Fundamental quantity related to the distribution of magnetization/currents in the neutron. Needed to extract the distribution of quarks in the neutron.

Elastic form factors ($G_n^M$, $G_n^E$, $G_p^M$, and $G_p^E$) provide key constraints on theory and the structure of hadrons.

Part of a broad effort to understand how nucleons are 'constructed from the quarks and gluons of QCD'.

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- Part of a broad effort to understand how nucleons are ‘constructed from the quarks and gluons of QCD’.*

What is a Form Factor?

- Start with the cross section.

\[
\frac{d\sigma}{d\Omega} = \frac{\text{scattered flux/solid angle}}{\text{incident flux/surface area}}
\]

For elastic scattering use the Rutherford cross section.

\[
\frac{d\sigma}{d\Omega} = \frac{Z^2 \alpha^2 (\hbar c)^2}{4E^2 \sin^2 (\theta/2)} \left(1 - \beta^2 \sin^2 \theta/2\right) (\text{Mott cross section})
\]

Where \(Q^2\) is the 4-momentum transfer.

THE FORM FACTOR!
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- Get the cross section for elastic scattering by point particles with spin.

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- What happens when the beam is electrons and the target is not a point?

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THE FORM FACTOR!
Why Should You Care?

- The chain of reason.

\[
\frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow_{QCD, \text{Constituent quarks}}
\]

Experiment \hspace{1cm} Comparison \hspace{1cm} Theory

The form factors are the meeting ground between theory and experiment.

The Fourier transform of the form factors are related to the charge and current distributions within the neutron.
Why Should You Care Even More?

- The old picture of the neutron (and proton).

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How Do We Measure $G_n^M$ on a Neutron? (Step 1)

- Start at your local mile-long, high-precision, 12-GeV electron accelerator.
- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.
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How Do CEBAF Do That?

Accelerate your electrons to high energy.

What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each hall beam buckets are about 2 picoseconds long and arrive every 2 nanoseconds.
How Do We Measure $G^n_M$ on a Neutron? (Step 2)

- Add one 45-ton, $80$-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).

- CLAS covers a large fraction of the total solid angle at forward angles.

- Has about 62,000 detecting elements in about 40 layers.
Add one 45-ton, $80-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
How Do We Measure $G_M^n$ on a Neutron? (Step 2a)

- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.
- Scatter electrons off protons and deuterons (proton+neutron).
A Simulated CLAS12 Event - Drift Chamber close-up
A Simulated CLAS12 Event - Drift Chamber close-up
A Real CLAS12 Event - Building the Drift Chambers
A Real CLAS12 Event - Building the Drift Chambers
A Simulated CLAS12 Event - Calorimeter close-up
A Simulated CLAS12 Event - Calorimeter close-up

U-plane

V-plane

W-plane

Fiber Light Guides (front)

Fiber Light Guides (rear)

PMT's

Scintillator bars

Lead sheets

155 cm

Jerry Gilfoyle

Hunting for Quarks

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A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Summary

Drift chambers

Time-of-Flight

Calorimeters

electron

proton

192 cm
A Simulated CLAS12 Event - Cherenkov close-up

Cherenkov
Counter will go here.
A Simulated CLAS12 Event - Cherenkov close-up

Calorimeters

Cherenkov Light

Electron

Mirrors
A Simulated CLAS12 Event - Cherenkov close-up

Cherenkov
Light
Electron Calorimeters
Mirrors

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Simulated CLAS12 Events

Forward Detector

Central Detector

EC/PCAL
DC
HTCC
Solenoid
FTOF
Simulated CLAS12 Events

Forward Detector

Central Detector

EC/PCAL
DC
HTCC
Solenoid
FTOF
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
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Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Putting It All Together - 1

Overview

DC

Solenoid

CTOF

SVT

Beamline

HTCC

Torus

FTOF

PCAL/EC

LTCC

Click on boxes for info
Where’s my target?

Use a dual target cell with liquid hydrogen and deuterium.

How bad do the protons mess things up? They help!

The ratio is less vulnerable to corrections like acceptance, efficiencies, etc.

Use the dual target to perform in situ detector calibrations.

\[
R = \frac{\frac{d\sigma}{d\Omega}(D(e, e' n))}{\frac{d\sigma}{d\Omega}(D(e, e' p))} = a(Q^2) \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta}{2}\right) + \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta}{2}\right)
\]
How Do We Measure $G_M^n$ on a Neutron? (Step 4)

- Quasi-elastic event selection: Apply a maximum $\theta_{pq}$ cut to eliminate inelastic events plus a cut on $W^2$ (J. Lachniet thesis).

- Use the $ep \rightarrow e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.
How Do We Measure $G_M^n$ on a Neutron? (Step 5)

Analyzing the data - CLAS12 computing requirements.

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<tr>
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<td>7,938</td>
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</table>

We’ll collect 5-10 TByte/day!

Intel Many-Integrated CoProcessor computer
Anticipated Results

\[ \frac{G^p_n}{\mu_n G^D} \]

\( Q^2 \) (GeV\(^2\))

Red - J.Lachniet et al.
Green - Previous World Data
Black - CLAS12 anticipated
Blue - Hall A anticipated (with systematic uncertainties)

Guidal et al.
Cloet et al.
Miller

Anticipated
Statistical uncertainties only
By measuring all four EEFFs we have an opportunity to unravel the contributions of the $u$ and $d$ quarks.


$$ F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n $$

$$ F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p $$

- $u$ and $d$ are different.
- AND different from the proton and neutron form factors.
- Evidence of di-quarks, $s$ quark influence, ...?
Concluding Remarks

- JLab is a laboratory to test and expand our understanding of quark and nuclear matter, QCD, and the Standard Model.
- We continue the quest to unravel the nature of matter at greater and greater depths.
- Lots of new and exciting results are coming out.
- A bright future lies ahead in the 12 GeV Era.
Concluding Remarks

Additional Slides
What’s going on now?

Alignment and commissioning of the silicon vertex tracker (SVT).
Check alignment with Type 1 cosmic ray tracks

Type 1 tracks.
Check alignment with Type1 cosmic ray tracks

Type 1 tracks.
Students from Richmond (and one from Surrey) visit JLab

West Beam Arc

CLAS12 detector
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A CLAS Event

- Electromagnetic Calorimeters
- Cerenkov Counters
- Drift Chambers
- Scintillators
How Do We Measure $G_M^n$ on a Neutron? (Step 3)

- Where's my target?
  
  Use a dual target cell with liquid hydrogen and deuterium.

- How bad do the protons mess things up? They help!

$$R = \frac{d\sigma}{d\Omega}(D(e, e'n)) = \frac{d\sigma}{d\Omega}(D(e, e'p)) = a(Q^2) \frac{\sigma^n_1 + \tau \sigma^n_2}{1+\tau} + 2\tau G^n_M^2 \tan^2(\frac{\theta}{2})$$

$$= \frac{\sigma^n_1 + \tau \sigma^n_2}{1+\tau} + 2\tau G^n_M^2 \tan^2(\frac{\theta}{2})$$

- The ratio is less vulnerable to corrections like acceptance, efficiencies, etc.

- Use the dual target to perform *in situ* detector calibrations.
Results - Overlaps and Final Average

Overlapping measurements of $G_M^n$ scaled by the dipole are consistent.
Results - Comparison with Existing Data

\[ \frac{G_M^n}{\mu_n G_D} \]

- **CLAS**
- **Lung**
- **Kubon**
- **Anklin**
- **Arnold**
- **Xu**
- **Anderson**

Green band - Diehl
Solid - Miller
Dashed - Guidal

Systematic Uncertainty
Results - Comparison with Existing Data

The figure shows a comparison of the data from various experiments with theoretical predictions. The graph plots the ratio $G_M^n/\mu_G^n$ against $Q^2(\text{GeV}^2)$, where $Q^2$ is the square of the four-momentum transfer.

- **CLAS** results are represented by red squares.
- **Kubon** data are marked with open circles.
- **Anklin** data are indicated by upward triangles.
- **Lung** results are shown with black circles.
- **Bartel** data are represented by open squares.
- **Arnold** results are marked with diamonds.
- **Xu** data are indicated by upward triangles.
- **Anderson** results are shown with inverted triangles.
- **Green band - Diehl** is marked with a green shaded area.
- **Solid - Miller** is represented by a solid line.
- **Dashed - Guidal** is shown with a dashed line.

The graph also includes a shaded area representing the systematic uncertainty.
The electron beam energy at JLab (CEBAF) has been doubled from 6 GeV to 12 GeV.

Halls A, B and C will be upgraded to accommodate the new physics opportunities.

A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.