Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration

University of Richmond

- JLab Mission
- What we know and don’t know.
- The Neutron Magnetic Form Factor
- Experiments with CLAS
- More JLab Highlights
- Concluding Remarks

\(G_M^n\) Co-conspirators:

Jeff Lachniet       Will Brooks
Mike Vineyard      Brian Quinn
Kristen Greenholt (UG) Rusty Burrell (UG)
What is the Mission of Jefferson Lab?

- Pursue 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.
- Provide a testing ground for the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
What Do We Know?

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

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Force Carriers spin = 0, 1, 2, ...</th>
<th>Strong (color) spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass GeV/c^2</td>
<td>Electric charge</td>
</tr>
<tr>
<td>γ photons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W^-</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>W^+</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>Z^0</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

- 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.
What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.

- The hadronic model uses a phenomenological force fitted to data at low energy. This ‘strong’ force is the residual force between quarks.
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How Well Do We Know It?

- 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)).
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What Don’t We Know?


2. NEED TO FIGURE OUT QCD AT THE ENERGIES OF NUCLEI!!
The Magnetic Form Factor of the Neutron ($G^n_{M}$)

- Fundamental quantity related to the distribution of charge and magnetization/currents in the proton and neutron (the nucleons).
- Part of a broad effort to understand how nucleons are ‘constructed from the quarks and gluons of QCD’.*
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors ($G^m_{M}$, $G^E_{n}$, $G^p_{M}$, and $G^p_{E}$) provide key constraints on generalized parton distributions (GPDs) which promise to give us a three-dimensional picture of hadrons.
- Fundamental challenge for lattice 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.
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- Get the cross section for elastic scattering by point particles with spin.

\[ \frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2(hc)^2}{4E^2\sin^4(\theta/2)} \left(1 - \beta^2\sin^2\frac{\theta}{2}\right) \] (Mott cross section)
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- What happens when the beam is electrons and the target is not a point?

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where \(Q^2\) is the 4-momentum transfer.
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THE FORM FACTOR!
Why Should You Care?

- The chain of reason.

\[ \frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \]

\( QCD, \) Constituent quarks

Experiment Comparison 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?

- Some kinematic definitions
  \((\theta_{pq}, \phi_{pq}, b)\).


\[
\rho(b) = \int_{0}^{\infty} dQ \frac{Q}{2\pi} J_0(Qb) \frac{G_E(Q^2) + \tau G_M Q^2}{1 + \tau}
\]

\[
\tau = \frac{Q^2}{4M_N^2}
\]
How Do We Measure $G^n_M$ on a Neutron? (Step 1)

- Start at your local mile-long, high-precision, 6-GeV electron accelerator.
- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.
- Electrons do up to five laps, are extracted, and sent to one of three experimental halls.
- All three halls can run simultaneously.
How Do We Measure $G^n_M$ on a Neutron? (Step 2)

- Add one 45-ton, $50$-million radiation detector: the CEBAF large Acceptance Spectrometer (CLAS).
- CLAS covers a large fraction of the total solid angle.
- Has about 35,000 detecting elements in about 40 layers.
How Do We Measure $G^n_M$ on a Neutron? (Step 2)

- Drift chambers map the trajectory of the collision. A toroidal magnetic field bends the trajectory 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.
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!

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e, e'n))}{\frac{d\sigma}{d\Omega}(D(e, e'p))} = a(Q^2) \frac{G_E^n/Q_{1+n}^2 + \tau G_M^n/Q_{1+n}^2}{G_E^p/Q_{1+n}^2 + \tau G_M^p/Q_{1+n}^2} + 2\tau G_M^n \tan^2(\frac{\theta}{2})$$

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

- The dual target enables us to perform in situ detection calibrations.
How Do We Measure $G^m_M$ 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.
Results - Overlaps and Final Averages

- Overlapping measurements of $G_M^n$ scaled by the dipole are consistent.

- Weighted-average $G_M^n / \mu_n G_D$ and systematic uncertainty $\frac{\delta G_M^n}{G_M^n} \times 100 (< 2.5\%)$. 
Results - Comparison with Existing Data and Theory

![Graph showing comparison of data points with existing data and theory](image-url)
Results - Comparison with Existing Data and Theory

![Graph showing comparison of data and theory](image)

- **Solid** - Lomon
- **Dotted** - Miller
- **Dashed** - Guidal
- **CLAS Preliminary**
- **Lung**
- **Anklin**
- **Xu**
- **Arnold**
- **Kubon**
- **Anderson**

Legend:

- **CLAS Preliminary**
- **Bartel**

Data and theory comparison with various symbols representing different datasets and theoretical models.
More Jefferson Lab Highlights

Ratio of charge and magnetization of the proton ($G_E^p/G_M^p$).

Short range correlations in nuclei.

Fraction of nucleon momentum carried by struck quark.


Towards a 3-dimensional picture of hadrons.

Where is the nucleon spin?.

S. Stepanyan et al. (CLAS), Phys. Rev. Lett. 87 (2001) 182002


Azimuthal angle around the 3-momentum transfer $\vec{q}$. 
Life on the Frontiers of Knowledge
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 with the JLab 12-GeV Upgrade.