Understanding The Nature of Normal Matter

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#GHOSeminar
University of Central Arkansas
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Enough About Me... Onto the Physics!

- The Structure of Matter – A Sense of Size
- Electron Scattering Experiments
- Nucleon Structure:
  - Electromagnetic Form Factors
  - Structure Functions
  - The Future through Tensor Polarization
The Structure of Matter

A sense of scale: http://htwins.net/scale
Electron Scattering

Elastic Scattering ($x \geq 2$)

Quasi-Elastic Scattering (QE) ($x \sim 1$)

Deep Inelastic Scattering (DIS) ($x < 0.7$)

Target

Detector

$e^+ e^- \rightarrow e^+ e^-$

$Q^2 = 4EE' \sin^2 \frac{\theta}{2}$

$\lambda \propto \frac{1}{\sqrt{Q^2}}$

Higher $Q^2 \rightarrow$ Better Resolution

$x = \frac{Q^2}{2mv}$ → Scaled Momentum Fraction of Scattered Particle

Probes Nuclear Effects

Probes Nucleon Effects

Probes Quark Effects

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Electron Scattering at Jefferson Lab

- Fixed target electron accelerator
- Recently completed 12 GeV upgrade – First new physics in 3 years!
- World leader in polarized beam and polarized targets
- Mission includes: “To deliver discovery-caliber research by exploring the atomic nucleus and its fundamental constituents, including precise tests of their interactions”
Electron Scattering – Measuring Structure

Scattering electrons from nuclei (consisting of protons and neutrons)
We measure the cross section, which can be thought of as normalized counts \( (N = \mathcal{L}t\sigma) \)

\[
\sigma = \sigma_{\text{Mott}} \left( \frac{Q^2}{4M^2} G_M^2(Q^2) + \epsilon G_E^2(Q^2) \right)
\]

Scattering from a point-like nucleon
Deviation from a point-like nucleon

With polarized spins, can also measure asymmetries

\[
A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}
\]
Electromagnetic Form Factors

Scatter electrons from a proton or a neutron

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{Q^2}{4M^2} G_M^2(Q^2) + \epsilon G_E^2(Q^2) \right] \]

Scattering from a point particle

Deviation due to magnetic moment distribution

Deviation due to charge distribution

At \( Q^2 = 0 \),

- \( G_M^p \rightarrow \mu_p \)
- \( G_E^p \rightarrow 1 \)
- \( G_M^n \rightarrow \mu_n \)
- \( G_E^n \rightarrow 0 \)

Higher \( Q^2 \) → Better Resolution

Changes with \( Q^2 \) indicate substructure
Proton Form Factors

- Free proton targets available – $^1$H
- Protons are charged, so normal spectrometers can isolate them
- Counting number of particles detected gives the cross section
- Since two unknowns ($G_E^p$ and $G_M^p$), take two measurements to solve for them
- Relatively easy measurements
Proton Form Factors – World Data

- For ease, we compare data to electric and magnetic dipoles

- If dipole-like, then $\frac{G_P}{G_D} = 1$

Proton Form Factors – World Data

Proton Form Factors – World Data

Electric Form Factor / Dipole

Fourier Transform (Momentum → Position)


Neutron Form Factors

Neutron electric form factor is much smaller than proton’s

No free neutron target is available
- Requires small-nuclei targets, such as $^2$H or $^3$He

Neutrons, being neutral, cannot be directly detected using standard spectrometers

Neutron Form Factor, $G_E^n$
Measurement
Neutron Form Factor, $G_E^n$ Measurement
Neutron Form Factor, $G_E^n$
Measurement

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Neutron Form Factor, $G_E^n$
Measurement
Neutron Form Factor, $G_E^n$ Measurement
Neutron Form Factor, $G_E^n$

Measurement

Polarized $^3\text{He}$ Target

- Optically pumped Rb and K vapor used to polarize $^3\text{He}$ via spin exchange (SEOP)
- NMR and EPR used to measure $P_t$
- N present in cell to absorb photons from spin-exchange
  
  \[ D_N = 2.4 \pm 0.3\% \text{ at } Q^2 = 0.5 \]
  \[ 2.8 \pm 1.2\% \text{ at } Q^2 = 1.0 \]

- Achieved $P_t$ of $51.4 \pm 0.4 \pm 2.8\%$
- Details in Y. Zhang, Ph.D. Thesis, Rutgers, 2013

\[ A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \]
Neutron Form Factor, $G_E^n$

Measurement

Right HRS

- Detected scattered electrons from $^3$He(e,e'\') and $^3$He(e,e')
- Detector package included VDCs, trigger scintillators, gas Cherenkov, and lead-glass calorimeters
Neutron Form Factors – World Data

Neutron Form Factors – World Data

$G_E^n$ vs $Q^2 [GeV^2]$

- Herberg
- Ostrick
- Madey
- Seimetz
- Warren
- Becker
- Bemuth
- Schiavilla & Sick
- Lung
- this measurement
- E02-013
- Galster fit
- Kelly’s fit

Fourier Transform

$\rho(b) [fm^2]$

V. Sulkowsky, G. Jin, E. Long, et al, PRL (in prep.)
Electromagnetic Form Factors

Constituents of nucleons are charged particles

\[ \rho(b) \text{ [fm}^{-2}] \]

\[ b \text{ [fm]} \]

Proton

Neutron

\[ \rho(b) \text{ [fm}^{-2}] \]

\[ b \text{ [fm]} \]
Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left( \frac{2}{Mc^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \right) \]

Scattering from a point-like nucleon

Gives insight to proton substructure

Deviation from a point-like nucleon


Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M^2 c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{v} F_2(x, Q^2) \right] \]

Gives insight to proton substructure

3 Valence Quarks


Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{v} F_2(x, Q^2) \right] \]

Gives insight to proton substructure

3 Interacting Quarks


Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \right] \]

Gives insight to proton substructure

3 Interacting Quarks

With Sea Quarks


Higher \( Q^2 \) → Better Resolution
If no change with \( Q^2 \), no substructure

Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \right] \]

Derives from magnetic interaction

For spin ½ particles,

\[ \chi = \frac{F_1(x)}{F_2(x)} = \frac{1}{2} \]

\[ \frac{2 x F_1(x)}{F_2(x)} = 1 \]

Structure Functions - Unpolarized
Structure Functions - Unpolarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{y} F_2(x, Q^2) \right] \]

From \( F_1 \) and \( F_2 \) we learned that

- Nucleons are made up of three valence point-like particles
- These three particles are spin-\( \frac{1}{2} \)
- These particles interact with a “quark sea”

* From \( F_1 \) and \( F_2 \), we know they’re in there, but not where they are
Structure Functions - Polarized

Structure functions describe deviations from point-like structure

\[ \sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{v} F_2(x, Q^2) \right] \]

\[ \sigma = \frac{\alpha^2 E'}{Q^4 E} L_{\mu\nu} W^{\mu\nu} \]

\[ W^{\mu\nu} = -\alpha F_1 + \beta F_2 + i\gamma g_1 + i\delta g_2 \]

Scattering on Unpolarized Nucleons

Scattering on Polarized Nucleons (spin up or down)
Using a polarized target, we can gain access to more information.

\[ \Delta \sigma = \sigma_{++} - \sigma_{+-} \]

\[ \Delta \sigma \propto \frac{1}{2} \sum_i e_i^2 (q_i^+(x) - q_i^-(x)) \equiv g_1(x) \]

Tells us where valence quarks with a certain spin are located.
Structure Functions - Polarized

- Ratio of $\frac{g_1}{F_1}$ gives information on where valence quarks are.
- Difference in proton (uud) and neutron (udd) can separate information of a particular flavor of quark.

\[ \alpha \frac{g_1^p}{F_1^p} - \beta \frac{g_1^n}{F_1^n} = \frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} \]

\[ -\beta \frac{g_1^p}{F_1^p} + \alpha \frac{g_1^n}{F_1^n} = \frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} \]

Structure Functions - Polarized

Using a polarized target, we can gain access to more information.

\[ \Delta \sigma \propto \frac{1}{2} \sum_i e_i^2 (q_i^+ (x) - q_i^- (x)) \equiv g_1 (x) \]

Gives information on quark spin.

With \( F_1 \), gives information on quarks of a particular flavor.

* Sum of valence quark spin ≠ nucleon spin.
\[ W^{\mu\nu} = -\alpha F_1 + \beta F_2 + i\gamma g_1 + i\delta g_2 \]

**Structure Functions - Polarized**

- No simple interpretation for \( g_2 \)
- High \( Q^2 \) → Test of lattice QCD
- High \( Q^2 \) → Test of \( \chi PT \)
- Can provide information on polarizability, which might be causing the proton radius problem

\[ g_2(x, Q^2) = g_{ww}^{ww}(x, Q^2) + \bar{g}_2(x, Q^2) \]

\[ g_{ww}^{ww}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(x, Q^2) \]

- Leading twist-2 term
- Entirely dependent on \( g_1 \)

\[ \bar{g}_2(x, Q^2) = \int_x^1 \frac{\partial}{\partial y} \left[ \frac{m_q}{M} h_T(y, Q^2) + \zeta(y, Q^2) \right] \frac{dy}{y} \]

- \( h_T \) → Quark transverse polarization distribution
- \( \zeta \) → Quark-gluon interactions
Structure Functions - Polarized

* Sum of valence quark spin ≠ nucleon spin
The Tensor Polarized Future of Nucleon Structure
Tensor Structure Functions

For tensor polarization, need spin-1 particles

Protons and neutrons are spin-$\frac{1}{2}$ particles, but a system of two gives a $\frac{1}{2} + \frac{1}{2} = \text{spin-}1$ system

We can tensor polarize deuterons, which are made up of one neutron and one proton

Vector $P_z = p_+ - p_-$

Tensor $P_{zz} = (p_+ + p_-) - 2p_0$
Dynamic Nuclear Polarization (DNP) Tensor Structure Functions

- Start with simple case: Protons with spin-½
- Start with solid material (ammonia, LiD, butanol, plastic, etc.)
- Drop the temperature (1 K)
- Insert in large (5+ T) magnetic field
  - Now you have polarized electrons!
- Flood with millimeter wave radiation to transfer polarization to protons
- Build-up proton polarization and measure with NMR!
Tensor Structure Functions

- Dynamic Nuclear Polarization of ND$_3$
- Goal: $P_{zz} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$

"Brute Force" Tensor Polarization

\[ A = 2 \cdot (4 - 3P^3)^{1/2} \]
Tensor Structure Functions

- Dynamic Nuclear Polarization of ND$_3$
- Goal: $P_{ZZ} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$

"Hole Burning" Tensor Enhancement

\[ 0 \leftrightarrow -1 = c(N_0 - N_+), \quad 0 \leftrightarrow +1 = c(N_+ - N_0) \]

\[ k \cdot mV \]

D Keller, HiX Workshop (2014)

UVA Tensor Enhancement on Butanol (2014)

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Tensor Structure Functions

Structure functions describe deviations from point-like structure

$$\sigma = \sigma_{\text{Mott}} \left[ \frac{2}{M c^2} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \right]$$

$$W_{\mu\nu} = -\alpha F_1 + \beta F_2$$

$$+ i \gamma g_1 + i \delta g_2$$

$$- \varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4$$

Scattering on Unpolarized Targets

Scattering on Vector Polarized Targets (Up or Down)

Scattering on Tensor-Polarized Targets ((Up and Down) or 0)
Tensor Structure Functions

\( b_1 \rightarrow \text{Leading twist} \)

\[ b_1(x) = \frac{q^0(x) - q^1(x)}{2} \]

\( b_1 \) is the measure of quark distributions when the nucleus is in a particular spin state

**Looks at nuclear effects at the resolution of quarks!**

If there are no nuclear effects, then \( b_1 \) vanishes.

Even with D-state admixture, it’s expected to be vanishingly small

\[ b_1 = 0 \]

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Khan & Hoodbhoy, PRC 44 1219 (1991)
All conventional models predict small or vanishing values of $b_1$ in contrast with the HERMES data.

Any measurement of a $b_1 < 0$ indicates exotic physics.

Close-Kumano Sum Rule
Tensor Structure Functions

\[ \int b_1(x)dx = 0 \]
- Related to the electric quadrupole structure
- **Fails in any model with an unpolarized sea**

\[ b_1 = \frac{1}{36} \delta_T w[5\{u_v + d_v\}] + 4\alpha_\bar{q}[2\bar{u} + 2\bar{d} + s + \bar{s}] \]

- Looked at difference between unpolarized (\(\alpha_{\bar{q}} = 0\)) and polarized (\(\alpha_{\bar{q}} \neq 0\)) antiquarks in the sea
- Found \(\alpha_{\bar{q}} = 3.20 \pm 0.212\) improved \(\chi^2\), indicating **significant tensor polarization in antiquark distributions**

S Kumano, PRD 82 017501 (2010)
Close-Kumano Sum Rule
Tensor Structure Functions

\[ \chi^2 / \text{dof} = 1.57 \]

\[ \chi^2 / \text{dof} = 2.83 \]

S Kumano, PRD 82 017501 (2010)
6-Quark, Hidden Color Tensor Structure Functions

- Deuteron wave function can be expressed as
  \[ |6q\rangle = \sqrt{\frac{1}{9}} |NN\rangle + \sqrt{\frac{4}{45}} |\Delta\Delta\rangle + \sqrt{\frac{4}{5}} |CC\rangle \]

- Early hidden color calculations gave small results, but author noted “as experimental techniques have improved dramatically, the meaning of small has changed.”

- Even though experimental upper limit of \( P_{6q} < 1.5\% \), a much smaller value (0.15%) can have a significant effect on \( b_1 \)

G Miller, PRC 89 045203 (2014)
6-Quark, Hidden Color
Tensor Structure Functions

- Pionic effects alone would violate Close-Kumano Sum Rule
  \[ \int b_1(x)dx = 0 \]
6-Quark, Hidden Color Tensor Structure Functions

- 6-quark, hidden color states predict large negative $b_1$ at large $x$

Blue = Central
Others = ± 0.1R

G Miller, PRC 89 045203 (2014)
6-Quark, Hidden Color Tensor Structure Functions

- First theory to reproduce anomalous HERMES result
- $b_1^{\pi} + b_1^{6q}$ predictions made for upcoming JLab $b_1$ measurement

G Miller, PRC 89 045203 (2014)
Tensor Structure Functions

Measured by ratio method

\[
\frac{N_{Pol}}{N_u} - 1 = f \frac{1}{2} A_{zz} P_{zz}
\]

\[
A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right)
\]

\[
b_1 = -\frac{3F_1}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right) = -\frac{3}{2} F_1 A_{zz}
\]
Tensor Structure Functions

Using Hall C
Tensor Structure Functions

All conventional models predict small or vanishing values of $b_1$ in contrast with the HERMES data.

Any measurement of a $b_1<0$ indicates exotic physics.
Tensor Structure Functions – JLab

Measuring $b_1$ will give insight into

- Exotic effects in tensor-polarized systems
- Close-Kumano Sum Rule \[1\]
- Hidden color from 6-quark configuration \[2\]
- OAM and spin crisis \[3\]
- Pionic effects \[2,4\]
- Polarization of the quark sea \[4\]

**Approved** JLab Experiment E12-13-011


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Quasi-Elastic Tensor Structure

Repeat same experiment, only look at $A_{zz}$ in the quasi-elastic region

Can give insight to short range deuteron structure

$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right)$$

$$A_{zz} \propto \frac{1}{2} \frac{D^2 - SD}{S^2 + D^2}$$

Quasi-Elastic Tensor Structure

Repeat same experiment, only look at $A_{zz}$ in the quasi-elastic region

Can give insight to short range correlations

Quasi-Elastic Tensor Structure

SRCs & pn dominance\textsuperscript{[3]}
Differentiate light cone and VN models\textsuperscript{[1,2]}
Better understanding of S/D\textsuperscript{[4]}
Final state interaction models\textsuperscript{[5]}

JLab LOI12-14-002 Encouraged for full proposal

\textsuperscript{[1]} E. Long, \textit{et al}, JLab LOI12-14-002
\textsuperscript{[4]} L Frankfurt, M Strikman, Phys. Rept. 160, 235
\textsuperscript{[5]} W Cosyn, M Sargsian, arXiv:1407.1653
“The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range $pn$ correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program.”

-JLab PAC42 Theory Advisory Committee

Encouraged for full submission by PAC42

E. Long, et al, JLab LOI12-14-002
Summary

◦ A Sense of Scale
◦ Electromagnetic Form Factors
◦ Unpolarized Structure Functions
◦ Polarized Structure Functions
◦ Tensor Polarized Structure Functions
◦ Quasi-Elastic Tensor Structure/Short Range Correlations

Understanding The Nature of Normal Matter
Thank you