Jefferson Lab Hall A neutron spin structure program

Nilanga Liyanage

University of Virginia
Outline

• Introduction
• Neutron spin structure in the resonance region:
  • Jefferson lab Experiment 01-012 spin duality
• Neutron spin structure at high x with upgraded Jefferson lab.
  • Jefferson lab Experiment E12-06-112
• Conclusion
• Three $u$ and $d$ valence quarks
• Also gluons and a “sea” of $q, \bar{q}$ pairs
• Strong interaction between quarks
• Governed by QCD
• Mediated by gluons
• Gluons interact with other gluons: self coupling
Electro-magnetic force

\[ e^- + e^- + \frac{1}{137} \]

\[ q + q + \alpha_s \]

(Short distances)
- \( \alpha_s \to 0 \)
- Quarks are free (Asymptotic freedom)
- \( \Rightarrow \) pQCD applicable

(larger distances)
- Strong coupling between quarks
- Confinement important
- QCD has not been solved here

Understanding confinement in terms of QCD: an unresolved problem of particle physics
4-momentum transfer squared

\[ Q^2 = -q^2 = 4EE'\sin^2 \frac{\theta}{2} \]

Invariant mass squared

\[ W^2 = M^2 + 2M\nu - Q^2 \]

Bjorken variable

\[ x = \frac{Q^2}{2M\nu} \]
Resolution of the probe

\[ \lambda = \frac{h}{q} = \frac{h}{\sqrt{Q^2}} \]
Inclusive Electron Scattering

\[ e = (E, k) \quad e' = (E', k') \]

\[ q = (v, q) \]

\[ p = (M, 0) \]

4-momentum transfer squared

\[ Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2} \]

Invariant mass squared

\[ W^2 = M^2 + 2Mv - Q^2 \]

Bjorken variable

\[ x = \frac{Q^2}{2Mv} \]

Unpolarized case

\[
\frac{d^2 \sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \left[ \frac{1}{\nu} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2 \frac{\theta}{2} \right]
\]
Inclusive Electron Scattering

\[ e = (E, \vec{k}) \]
\[ e' = (E', \vec{k}') \]
\[ p = (M, \vec{0}) \]
\[ q = (\nu, \vec{q}) \]

4-momentum transfer squared
\[ Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2} \]

Invariant mass squared
\[ W^2 = M^2 + 2M\nu - Q^2 \]

Bjorken variable
\[ x = \frac{Q^2}{2M\nu} \]

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

Polarized case
\[
\frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\downarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{vEQ^2} \left[ (E + E' \cos \theta) g_1(x, Q^2) - 2M x g_2(x, Q^2) \right]
\]
Low $x$: sea region, large contribution from quark-antiquark pairs
High $x$: valence region:

- The three valence quarks dominate the wave function
- "Clean" - No "pollution" from sea quarks
- Constituent Quark Models are applicable
- Essential for understanding the valence structure of the nucleon
- Essential for connecting DIS with resonance and elastic regions
Structure functions in the parton model

- Partons are point-like non-interacting particles:

\[
F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) + q_i^\downarrow(x)] \\
F_{1p} = \frac{1}{2} \left[ \frac{4}{9} u(x) + \frac{1}{9} d(x) \right] \\
F_{1p} = \frac{1}{2} \left[ \frac{4}{9} (u(x)^\uparrow + u(x)^\downarrow) + \frac{1}{9} (d(x)^\uparrow + d(x)^\downarrow) \right]
\]

\[
g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) - q_i^\downarrow(x)] \\
g_{1p} = \frac{1}{2} \left[ \frac{4}{9} (u(x)^\uparrow - u(x)^\downarrow) + \frac{1}{9} (d(x)^\uparrow - d(x)^\downarrow) \right]
\]

Neglecting strange quarks and anti-quarks

\[
A_1 = \frac{g_1}{F_1}
\]
**Nucleon Structure at large $x_{Bj}$**

Neutron Wavefunction (Spin and Flavor Symmetric)

\[
\begin{aligned}
|n \uparrow\rangle &= \frac{1}{\sqrt{2}} |d \uparrow (ud)_{s=0}\rangle + \frac{1}{\sqrt{18}} |d \uparrow (ud)_{s=1}\rangle - \frac{1}{3} |d \downarrow (ud)_{s=1}\rangle \\
&\quad - \frac{1}{3} |u \uparrow (dd)_{s=1}\rangle - \frac{\sqrt{2}}{3} |u \downarrow (dd)_{s=1}\rangle
\end{aligned}
\]

<table>
<thead>
<tr>
<th>Nucleon Model</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6)</td>
<td>0</td>
<td>5/9</td>
</tr>
<tr>
<td>Valence Quark</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pQCD</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
• pQCD and SU(6) breaking quark models
  ➢ $A_1p, A_1n \to 1$ as $x \to 1$ and large $Q^2$
• But the mechanisms are very different
  • CQM - hyperfine interaction between quarks: symmetric configurations suppressed.
  • pQCD - at high $x$ quark carrying the much of the nucleon momentum has the same spin direction as the nucleon: HHC
Deep Inelastic Scattering

High $Q^2$ and $W>$2GeV: fine resolution $\rightarrow$ we see partons

Scaling $\rightarrow$ asymptotic freedom of the strong interaction
Scaling of $F_2$

Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

1990 Nobel Prize

J. I. Friedman, H. W. Kendall and R. E. Taylor
Low $Q^2$ and $W<2$ GeV: coarse resolution $\rightarrow$ we don't see partons.

The nucleon goes through different excited states: the resonances
DIS versus resonance:

two very different pictures of the nucleon.
Quark-hadron duality

- First observed by Bloom and Gilman in the 1970’s on $F_2$

- Scaling curve seen at high $Q^2$ is an accurate average over the resonance region at lower $Q^2$

- Global and Local duality are observed for $F_2$

*I. Niculescu et al., PRL 85 (2000) 1182*
World data

HERMES for $A_1^p$
A. Airapeian et al., PRL 90 (2003) 092002
Hall B (CLAS) EG1 experiment: proton and deuteron

Hatched bands are NLO PDF (GRSV) evolved to each Q2, TMC is included.
Test of “global” duality

Global duality appears to hold for $Q^2 > 1.7 \, \text{GeV}^2$ for both $g_1^p$ and $g_1^D$.

Hatched bands are NLO PDF (GRSV) evolved to each $Q^2$, TMC is included.

Including elastic

$1.08 < W < 2.0$

\[ < g_1(Q^2) > = \frac{\int_{x_l}^{x_h} g_1(x, Q^2) \, dx}{(x_h - x_l)} \]
HMS detects scattered electrons. 
Momentum settings: 4.7, 4.1 GeV/c
- $<Q^2> = 1.3 \text{ GeV}^2$, $0.8 < W < 2.0 \text{ GeV}$
- $I \sim 100\text{nA}$ for NH$_3$ and ND$_3$
- Beam Polarization ($P_B$) by Moller:
  - $P_B = 65.5 \pm 2.6 \%$ for $B_{\parallel}$
  - $P_B = 70.9 \pm 1.7 \%$ for $B_{\perp}$
- Beam charge asym. $< 0.1\%$
\[
\frac{\int_{x_l}^{x_h} g_1^{p} (NLO - PDF) \, dx}{\int_{x_l}^{x_h} g_1^{p} (resonance) \, dx} = 1.17 \pm 0.08
\]
Experiment E01-012
Spokespersons: N. Liyanage, J. P. Chen, S. Choi; PhD student: P. Solvignon

- Ran in Jan.-Feb. 2003

- Inclusive experiment:
  \[ ^3\text{He}(\vec{e}, e') X \]

- Measured polarized cross section differences

- Form \( g_1 \) and \( g_2 \)

⇒ Test of spin duality on the neutron (and \(^3\text{He}\))
Jefferson Lab Accelerator
Both HRS in symmetric configuration at 25° and 32°
- double the statistics
- control the systematics

Particle ID = Cerenkov + EM calorimeter
- π/e reduced by $10^4$
$^3$He as an effective neutron target

$^3$He as neutron target

- S state: $\sim 88\%$
- D state: $\sim 10\%$
- S' state: $\sim 1\%$

$P_n = 86\%$ and $P_p = -2.8\%$
The Polarized $^3$He Target

- Laser Optics
- 30W Diode Lasers (795nm)
- RF Drive Coil
- Oven
- EPR optics
- EPR coil
- Holding field Helmholtz Coil
- Pick-Up Coils
- RF Drive Coil
Unpolarized cross sections

Agreement between both HRS better than 2%
New $A_1$ results from Hall A experiment E01-012

$\langle Q^2 \rangle = 1 \text{ GeV}^2$

$\langle Q^2 \rangle = 1.7 \text{ GeV}^2$

$\langle Q^2 \rangle = 2.6 \text{ GeV}^2$

$\langle Q^2 \rangle = 3.6 \text{ GeV}^2$
New $A_1$ results from Hall A experiment E01-012

\[<Q^2> = 1 \text{ GeV}^2\]
\[<Q^2> = 1.7 \text{ GeV}^2\]
\[<Q^2> = 2.6 \text{ GeV}^2\]
\[<Q^2> = 3.6 \text{ GeV}^2\]
New $A_1$ results from Hall A experiment E01-012

$<Q^2> = 1$ GeV$^2$

$<Q^2> = 1.7$ GeV$^2$

$<Q^2> = 2.6$ GeV$^2$

$<Q^2> = 3.6$ GeV$^2$
New $A_1$ results from Hall A experiment E01-012

\begin{align*}
\langle Q^2 \rangle &= 1 \text{ GeV}^2 \\
\langle Q^2 \rangle &= 1.7 \text{ GeV}^2 \\
\langle Q^2 \rangle &= 2.6 \text{ GeV}^2 \\
\langle Q^2 \rangle &= 3.6 \text{ GeV}^2
\end{align*}
Test of Duality on Neutron and $^{3}$He

Used method defined by N. Bianchi, A. Fantoni and S. Liuti

on $g_1^p$  PRD 69 (2004) 014505

1. Get $g_1$ at constant $Q^2$
2. Define integration range in the resonance region in function of $W$
3. Integrate $g_1^{\text{res}}$ and $g_1^{\text{dis}}$ over the same $x$-range and at the same $Q^2$

\[
\tilde{\Gamma}_1^{\text{res}} = \int_{x_{\text{min}}}^{x_{\text{max}}} g_1^{\text{res}}(x, Q^2) \, dx
\]
\[
\tilde{\Gamma}_1^{\text{dis}} = \int_{x_{\text{min}}}^{x_{\text{max}}} g_1^{\text{dis}}(x, Q^2) \, dx
\]

If $\tilde{\Gamma}_1^{\text{res}} = \tilde{\Gamma}_1^{\text{dis}} \Rightarrow$ duality is verified
Test of Duality on Neutron and $^3$He

Global duality seems to work for all our $Q^2$
Bigbite Spectrometer for Hall A:
Recently commissioned for high $Q^2$ neutron electric form factor ($G_e^n$) measurement
Background under Control

- Open configuration of Bigbite: Background is a serious issue.
- Background levels in Bigbite extensively studied in Gen
Bigbite Spectrometer in Gen

- successfully used for Gen with pol. \(^3\text{He}\) (@ 50° and 1.1 m from target).
  - 76 msr over 40 cm of target.
  - 20 MHz/plane on MWDC.
  - \(~1\%\) momentum resolution
  - \(~5\) mm \(\gamma\)\(_\text{tg}\) resolution
Bigbite Performance at high Rates During Gen

Vertex reconstruction for the $^{12}\text{C}$ target

H elastic peak

<table>
<thead>
<tr>
<th>Entries</th>
<th>10006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.02493</td>
</tr>
<tr>
<td>RMS</td>
<td>0.08323</td>
</tr>
</tbody>
</table>
A new Experiment for upgraded Jefferson Lab: \( A_1^n \) in the high-\( x \) region using Bigbite spectrometer in hall A


Use first high energy beams of 6.6 GeV and 8.8 GeV electron beams for a precision measurement of \( A1n \) up to \( x \sim 0.72 \) in 550 h
Proposed Experiment

- $6.6 \text{ GeV}, 8.8 \text{ GeV}$ polarized electron beams: $10 \mu A, Pe = 0.8$
- Hall A polarized $^3\text{He}$ target: 30 cm of useful length.
- Bigbite Spectrometer @ 30°
- HRS-L @ 30°
Proposed Bigbite Configuration

- Located at 30° and 1.6 m from the target
- Detector package
  - 3 MWDC
  - Pre-shower
  - Shower
  - Scintillator plane
  - Gas Cerenkov - being designed for E06-014
- MWDC#1 to #3 distance doubled
- Detect electrons up to 3.2 Gev
The Polarized $^3$He Target

- This collaboration just completed a successful upgrade of the polarized $^3$He target for Gen
  - New hybrid technology: alkali mixture (Rb and K)
  - 100 W of laser power.
  - Pumping cell volume doubled.
    - ~55% polarization over the long run
    - no cell ruptures: a single cell for last six weeks
Kinematic Coverage

8.8 Gev beam Bigbite @ 30°

6.6 Gev beam Bigbite @ 30°
DIS

\[ \langle Q^2 \rangle = 1 \text{ GeV}^2 \]

\[ \langle Q^2 \rangle = 1.7 \text{ GeV}^2 \]

\[ \langle Q^2 \rangle = 2.6 \text{ GeV}^2 \]

\[ \langle Q^2 \rangle = 3.6 \text{ GeV}^2 \]

\( x \)
Projected data: DIS

- 8.8 GeV DIS Projected for BigBite: 350 hours
- 6.6 GeV DIS Projected for BigBite: 90 hours
- E99-117 Results
Summary

- Nucleon spin structure in the resonance region:
  - Three Jefferson lab experiments have provided precision data for neutron and proton spin structure functions in the resonance region:
    - For $Q^2 < 2 \text{ GeV}^2$, quark-hadron duality is violated in $\Delta(1232)$ and higher resonance regions.
    - Global duality for $Q^2 > 1.0 \text{ GeV}^2$.
  - Bigbite + pol. $^3\text{He}$ target: a powerful combination
    - $5 \times 10^{35}$ e-n luminosity with 50% polarization
    - 50 msr solid angle over 30 cm
    - A recently approved measurement for upgraded Jlab will provide most precise data for $A_1^n$ up to $x \sim 0.72$.
    - A crucial step in understanding valence nucleon structure
Virtual Photon Asymmetry

\[ h_\gamma = + \quad h_q = + \quad h_N = + \]

\[ h_\gamma = + \quad h_q = + \quad h_N = - \]

\[ \sigma_{1/2} \]

\[ \sigma_{3/2} \]

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1} \]
Bigbite Simulations

- A Complete Geant Simulation for the proposed setup
- Acceptance 50 msr averaged over 30 cm of target
- Momentum resolution ~ 1%
The Polarized $^3$He Target

- This collaboration just completed a successful upgrade of the pol $^3$He target for Gen
  - New hybrid technology: alkali mixture (Rb and K)
  - 100 W of laser power.
  - Pumping cell volume doubled.
    - ~55% polarization over the long run
    - no cell ruptures: a single cell for last six weeks
Theoretical Analysis

Using Operator Product Expansion (Rujula, Georgi, Politzer):

\[ M_n(Q^2) = \int_0^1 dx \ x^{n-2} F_2(x, Q^2) \]

\[ M_n(Q^2) = A_n^{(0)} + \frac{A_n^{(2)}}{Q^2} + \frac{A_n^{(4)}}{Q^4} + \ldots \]

- OPE of QCD moments of structure functions.
- Leading terms ⇒ free quark scattering
  ⇒ scaling
- \(1/Q^2\) terms ⇒ interactions between quarks and gluons
$\pi/e$ Ratio estimates for 8.8 GeV

Worst case $\pi/e$ ratio ~ 20
Can be handled with Shower + Pre-shower and Cerenkov

Calculated with a 2 GeV threshold on momentum