Proton and Deuteron Spin Structure from SLAC Experiment E155

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Inclusive Deep Inelastic Scattering

\[ \nu = E - E' \]
\[-Q^2 = (\nu, \vec{q}) \]
\[ \vec{q} = \vec{E} - \vec{E}' \]

- \( \theta \): scattering angle
- \( Q^2 \): 4-momentum transfer squared
- \( \nu \): energy transfer
- \( x = \frac{Q^2}{2M\nu} \): Bjorken scaling variable
Unpolarized Deep Inelastic Scattering

\[ \frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2(\theta/2)}{Q^4} \left[ \frac{F_2(x, Q^2)}{\nu} + \frac{2F_1(x, Q^2)}{M} \tan^2(\theta/2) \right] \]

\( F_1 \) and \( F_2 \) are the unpolarized structure functions.

In naive quark parton model \( F_1 \) is related to the spin averaged quark distribution functions:

\[ F_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x, Q^2) + q_i^\downarrow(x, Q^2)] \]

→ Up (down) arrow denotes spin aligned (anti-aligned) with nucleon spin

→ \( i \) is over the quark and antiquark

→ \( e_i \) is the corresponding charge
Polarized Deep Inelastic Scattering

\[ A_\parallel = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = f_k [g_1(x, Q^2)(E+E' \cos(\theta)) - \frac{Q^2}{\nu} g_2(x, Q^2)] \]

\[ A_\perp = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\downarrow\downarrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\downarrow\downarrow}} = f_k E' \sin(\theta) [g_1(x, Q^2) + \frac{2E}{\nu} g_2(x, Q^2)] \]

\( g_1 \) and \( g_2 \) are the polarized structure functions.

→ \( A_\parallel \) is primarily sensitive to \( g_1 \)

→ \( A_\perp \) is more sensitive to \( g_2 \)

→ \( f_k \) includes contribution from unpolarized structure functions
$g_1$ Structure Function

In QPM $g_1$ is related to the spin distribution functions:

$$g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 \Delta q_i$$

$$\Delta q_i = q_i^\uparrow(x, Q^2) - q_i^\downarrow(x, Q^2)$$

The index $i$ is over the quark and antiquark flavors and $e_i$ is the corresponding charge.

However, in pQCD $g_1$ is also sensitive to the polarized gluon distribution $\Delta G$:

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[ C_q \otimes \Delta q + C_G \otimes \Delta G \right]$$

where $C_{q,G}$ are the perturbative coefficients.
Virtual Photon-Nucleon
Asymmetries

\[ A_1(x, Q^2) = \frac{\sigma_T^{1/2} - \sigma_T^{3/2}}{\sigma_T^{1/2} + \sigma_T^{3/2}} = \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{F_1(x, Q^2)} \]

\[ \sigma_T^{1/2} \text{ and } \sigma_T^{3/2} \text{ are transverse virtual photoabsorption cross sections for final helicity states of } 1/2 \text{ and } 3/2 \]

\[ \rightarrow \sigma_T^{1/2} \sim \frac{1}{2} \Sigma_i e_i^2 q_i^\uparrow \text{ and } \sigma_T^{3/2} \sim \frac{1}{2} \Sigma_i e_i^2 q_i^\downarrow \]

\[ \rightarrow A_1 \approx g_1/F_1 \text{ for } \gamma^2 = Q^2/\nu^2 = 0 \text{ (high energy)} \]

\[ A_2(x, Q^2) = \frac{2\sigma_{TL}}{\sigma_T^{1/2} + \sigma_T^{3/2}} = \gamma \frac{g_1(x, Q^2) + g_2(x, Q^2)}{F_1(x, Q^2)} \]

\[ \rightarrow \sigma_{TL} \text{ is the transverse-longitudinal interference term.} \]
## Spin Structure Measurements

<table>
<thead>
<tr>
<th>Year</th>
<th>Exp.</th>
<th>Data</th>
<th>Target</th>
<th>Publications</th>
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</table>
| 1978 | E80  | $A^p_\parallel$ | Butanol    | PRL 37, 1258 (76)  
                               |       |             |                         | PRL 37, 1261 (76)  
                               |       |             |                         | PRL 41, 70 (78)  
                               |       |             |                         | PRL 45, 200 (80)  |
| 1983 | E130 | $A^p_\parallel$ | Butanol    | PRL 51, 1135 (83)  |
| 1988 | EMC  | $A^p_\parallel$ | NH$_3$     | PLB 206, 364 (88)  
                               |       |             |                         | NPB 328, 1 (89)  |
| 1991 | SMC  | $A^d_\parallel$ | Butanol    | PLB 302, 533 (93)  
                               |       |             |                         | PRL 71, 959 (93)  
                               |       |             |                         | PRD 54, 6620 (96)  
                               |       |             |                         | PLB 329, 399 (94)  
                               |       |             |                         | PLB 336, 125 (94)  |
| 1992 | E142 | $A^n_\parallel, A^n_\perp$ | $^3$He   | PRD 74, 346 (95)  
                               |       |             |                         | PRL 75, 25 (95)  
                               |       |             |                         | PLB 364, 61 (95)  |
                               |       |             |                         | PRL 76, 587 (96)  
                               |       |             |                         | PRL 78, 815 (97)  
                               |       |             |                         | PRB 357, 248 (95)  |
| 1994 | E143 | $A^p_\parallel, A^p_\perp, A^d_\parallel, A^d_\perp$ | $^{15}$NH$_3$, $^{15}$ND$_3$ | PRL 78, 815 (97)  
                               |       |             |                         | PRB 357, 248 (95)  |
| 1995 | SMC  | $A^d_\parallel$ | Butanol    | PRB 396, 338 (97)  |
| 1995 | HERMES | $A^n_\parallel$ | $^3$He   | PLB 404, 383 (97)  |
| 1995 | E154 | $A^n_\parallel, A^n_\perp$ | $^3$He | PRL 79, 26 (97)  
                               |       |             |                         | PLB 404, 377 (97)  
                               |       |             |                         | PLB 405, 180 (97)  |
| 1996 | HERMES | $A^p_\parallel$ | H$_2$ | HEP-EX 980715  |
| 1997 | E155 | $A^p_\parallel, A^p_\perp, A^d_\parallel, A^d_\perp$ | $^{15}$NH$_3$, LiD | PRL 78, 815 (97)  
                               |       |             |                         | PRB 357, 248 (95)  |
Physics Asymmetries

\[ A_{||}(or A_{\perp}) = C_1 \left( \frac{N_L - N_R}{N_L + N_R} \right) \frac{1}{f P_b P_t} + C_2 \right) + A_{RC} \]

- \( N_L \) and \( N_R \) are rates for L and R beam helicity, corrected for pair-symmetric contributions and electronics dead time.
- \( C_1 \) and \( C_2 \) are for nuclear corrections and/or target contamination corrections.
- \( f \) is the dilution factor (\( \approx 0.15 \) for \( \text{NH}_3 \), \( \approx 0.35-0.40 \) for \( \text{LiD} \))
- \( P_b, P_t \) are the beam and target polarizations
- \( A_{RC} \) radiative correction

Neutron Extraction

\[ g^m(x, Q^2) = \frac{2g^d(x, Q^2)}{1 - 1.5\omega_d} - g^p(x, Q^2) \]

- \( \omega_d = 0.05 \pm 0.01 \) = probability deuteron is in D-state
E155 Keys

- Decrease statistical uncertainties
  \[ \rightarrow \text{Collected } \approx 200 \text{ million deep inelastic events} \]

- Reduce systematic uncertainties

- Cover wide $x$ and $Q^2$ range in single experiment
  \[ \rightarrow \text{Use 48.3 GeV electron beam} \]
  \[ \rightarrow \text{Add third spectrometer} \]

- Improve precision on $Q^2$ dependence of $g_1$ to constrain $\Delta G$
Polarized Electron Beam

- Intense 48.3 GeV Beam

- Highly polarized: $P_b = 0.813 \pm 0.020$

- Beam polarization measured with two independent Møller detector systems

$$A = \frac{N_{e^{-}(\uparrow\uparrow)} - N_{e^{-}(\uparrow\downarrow)}}{N_{e^{-}(\uparrow\uparrow)} + N_{e^{-}(\uparrow\downarrow)}}$$

$$= -P_{\text{beam}}P_{\text{foil}} \frac{(7 + \cos^2\theta_{cm})\sin^2\theta_{cm}}{(3 + \cos^2\theta_{cm})^2}$$

→ Single arm system and double arm coincidence system agree within 1%

→ 20-50 μm thick target foils

- Helicity varied randomly from pulse to pulse (120 Hz)
Polarized Targets

- Solid cryogenic targets
- Dynamic nuclear polarization using microwaves

- $^{15}NH_3$ used for proton target
  \[ \rightarrow \text{Improved } \mu \text{wave power delivery } \rightarrow < P_t > \approx 80\% \]

- $^6$LiD used for deuteron target
  \[ \rightarrow \text{LiD } \approx 50\% \text{ improvement in dilution over } ^{15}ND_3 \]
  \[ \rightarrow \text{LiD 6 times as radiation resistant} \]
  \[ \rightarrow < P_t > \approx 20\% \]
E155 kinematic coverage by spectrometer
E155 $A_1$ proton

2 deg. spect.

5 deg. spect.

10 deg. spect.

Curves are E143 $A_1$ fit
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- E155 (preliminary)
- E143
- SMC

at $Q^2=5$ GeV$^2$

$g_1^p$

$10^{-2}$ $10^{-1}$ $1$

E155 systematic error
Preliminary

July 28 1998

$g_1$

-0.4

-0.2

0

0.2

$10^{-2}$ $10^{-1}$ 1

x

E155 (preliminary)
E143
SMC

at $Q^2 = 5$ GeV$^2$

E155 systematic error
E155 (preliminary) at $Q^2 = 5$ GeV$^2$
Global pQCD Fitting

- Use pQCD expansion for $g_1$:

$$
  g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[ C_q \otimes \Delta q + C_G \otimes \Delta G \right]
$$

→ $C_q$ contribution starts at order 1, $C_G$ at order $\alpha_S^1$

- Evolve $\Delta q$ and $\Delta G$ from initial $Q^2_0$ to $Q^2$ using NLO DGLAP equations.

- Parameterize non-perturbative inputs.

  $$
  EG : \quad \Delta f(x, Q^2_0) = A_f x^{\alpha_f} f(x, Q^2_0)
  $$

  where $f$ = valence $\Delta u_v$ and $\Delta d_v$, sea, gluons

- Factorization Scheme Dependence

  → Common schemes are $\overline{MS}$ and Adler-Bardeen

  → Ambiguity in definition of contributions

  $$
  \Delta \Sigma(AB) = \Delta \Sigma(\overline{MS}) + \frac{N_f}{2\pi} \alpha_s \Delta G
  $$

  $\alpha_s(Q^2) \Delta G(Q^2)$ is independent of $Q^2$ to $O(\alpha_S^2)$
E155 (preliminary)
E143
SMC
E154 NLO Fit
at $Q^2 = 5$ GeV$^2$

$g_1^p$

$10^{-2}$ $10^{-1}$ 1

E155 systematic error
$g_2(x, Q^2)$ Structure Function

- Wandzura-Wilczek $g_2$ expression (twist-2 only)
  \[ g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2) \]

- In general there are additional contributions.

\[
\begin{align*}
  g_2(x, Q^2) &= g_2^{WW}(x, Q^2) - \int_x^1 \frac{\partial}{\partial y} \left( \frac{m}{M} h_T(y, Q^2) + \xi(y, Q^2) \right) \frac{dy}{y} \\
  &= g_2^{WW}(x, Q^2) + \overline{g}_2(x, Q^2)
\end{align*}
\]

- $\overline{g}_2$ includes quark-gluon correlations ($\xi$) inside the nucleon

- Twist-2 term (quark transverse spin distribution $h_T$) in $\overline{g}_2$ suppressed by $\frac{m}{M} << 1$

- Burkhardt-Cottingham (BC) sum rule from virtual Compton scattering dispersion relations in $Q^2 \to \infty$ limit:
  \[ \int_0^1 g_2(x, Q^2) dx = 0 \]
Operator Product Expansion (OPE) For $g_1$ and $g_2$

OPE used in QCD to separate the physics into a perturbative piece (easily treated) and a non-perturbative piece (unknown matrix elements).

$$\Gamma_1^{(n)} = \int_0^1 x^n g_1(x, Q^2) dx = \frac{a_n}{2}, \quad n = 0, 2, 4, \ldots$$

$$\Gamma_2^{(n)} = \int_0^1 x^n g_2(x, Q^2) dx = \frac{1}{2} \frac{n}{n+1} (d_n - a_n)$$

$$n=2,4,\ldots$$

$a_n$ are the twist-2 and $d_n$ are the twist-3 matrix elements.

$$d_2 = \int_0^1 x^2[2g_1(x, Q^2) + 3g_2(x, Q^2)] dx$$

$$= 3 \int_0^1 x^2 g_2(x, Q^2) dx$$
Twist 3 Matrix Element $d_2$

**Proton**

- QCD Sum Rules
- World Data
- Bag Model
- Lattice

**Neutron**

PREDICTIONS and DATA
E155x

- An extension to E155 has been approved to precisely measure $g_2$.
- The experiment is planned for February and March 1999.
- The goal is to measure $g_2$ (and $A_2$) for the proton and deuteron over a wide range in $x$ and $Q^2$.
- Significant improvement in sensitivity to contributions beyond $g_2^{WW}$.
Expected $g_2^d$ results from E155X at 29GeV

- E155X $\delta d_2 = 0.0014$
- E155 $\delta d_2 = 0.007$
Expected $g_2^n$ results from E155X at 29 GeV

$\delta d_2 \approx 0.031$

E155X

E154
E155X sensitivity for $d_2$

![Graph showing sensitivity of E155X for $d_2$ with data points and predictions.](image)
Summary

- E155 has precision data on $g_1$ over a wide $x$ and $Q^2$ range for the proton and deuteron

- NLO analysis should yield improved constraints on gluon polarization

- Extension run will provide precision $g_2$ data on proton and deuteron

- More direct information on gluon polarization will have to come from RHIC, COMPASS, SLAC E156?, polarized HERA?