Spin structure functions of deuteron from COMPASS

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On behalf of the COMPASS collaboration

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \]

\[ \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \]

\textit{The Workshop ”Hadron Structure and Hadron Spectroscopy”, Prague}
August 1-3, 2005

\textsuperscript{a}on leave from JINR, Dubna

Prague, August 1-3, 2005
Overview

• Inclusive asymmetry $A_1^d$ and structure function $g_1^d$
• COMPASS experiment
• Asymmetry extraction procedure & results
• QCD analysis to world data
• Semi-inclusive asymmetries
• Summary and outlook
Spin structure functions of deuteron from COMPASS

Virtual photon-deuteron asymmetry

\[ A_{\gamma d} \equiv A_1 = \frac{1}{2} (\sigma_0 - \sigma_2) \]
\[ \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_0) \approx \frac{\sum_q e_q^2 (q^+ - q^-)}{\sum_q e_q^2 (q^+ + q^- + q^0)} \]

- Structure functions in QPM
  \[ F_1(x) = \frac{1}{3} \sum_q e_q^2 (q^+ + q^- + q^0) \]
  \[ g_1(x) = \frac{1}{2} \sum_q e_q^2 (q^+ - q^-) \]

- Measurement of \( A_1 \) gives access to structure functions
  \[ A_1 \approx \frac{g_1}{F_1} \]

- \( \mu \)-deuteron asymmetry is measured in experiment
  \[ A_{\mu d} = \frac{\sigma_{\uparrow \downarrow} - \sigma_{\uparrow \uparrow}}{\sigma_{\uparrow \downarrow} + \sigma_{\uparrow \uparrow}} \]

- Relation to \( A_1 \)
  \[ A_{\mu d} = D (A_1 + \eta A_2) \]

- \( |\eta A_2| \ll |A_1| \)

- \[ A_1 \approx \frac{A_{\mu d}}{D} \]
Spin structure functions of deuteron from COMPASS

- Beam: µ−beam
  - Energy: 160 GeV
  - Intensity: $2 \times 10^8 \mu$/spill
  - Polarization: −76%

- Target: Two 60 cm long target cells with opposite polarization
  - Target material $^6$LiD
    - Polarization: ~50%
    - Dilution factor: ~50%

- Spectrometer with 2 stages (SM1: 1Tm, SM2: 4.4 Tm)
- Electromagnetic & hadron calorimeters
- Particle identification: RICH & µF

Spectrometer

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Triggers

- Inclusive triggers ($\mu'$)
- Hadronic triggers
  - Semi-Inclusive triggers ($\mu'+2\text{MIP}$)
  - Calorimetric trigger (9MIP)

- Parallel analysis for inclusive and hadronic events
- Hadronic triggers are check with MC study for possible bias
Kinematic region

\[ Q^2 > 1 \text{GeV}^2 \]
\[ 0.004 < x < 0.03 \]
\[ 0.1 < y < 0.9 \]

- Data of 2002 + 2003
- \(34 \cdot 10^6\) events
- 71\% – data collected in 2003
Combining of data

- To cancel acceptance effects two sets of data with opposite target spin orientations are combined together
  - spin reversal every 8 h
  - polarization reversal few times per year

- To minimize influence of spectrometer instability data sets are split into pairs consecutively
2-nd order method for asymmetry extraction

\[ N_u = a_u \Phi n_u \bar{\sigma} (1 + f P_b P_u D A_1) \]
\[ N_d = a_d \Phi n_d \bar{\sigma} (1 - f P_b P_d D A_1) \]
\[ N'_u = a'_u \Phi' n_u \bar{\sigma} (1 - f P_b P'_u D A_1) \]
\[ N'_d = a'_d \Phi' n_d \bar{\sigma} (1 + f P_b P'_d D A_1) \]

\[
\frac{N_u N'_d}{N_d N'_u} = \frac{a_u a'_d}{a_d a'_u} \frac{1 + \langle \beta_u \rangle A_1}{1 - \langle \beta_d \rangle A_1} \frac{1 + \langle \beta'_d \rangle A_1}{1 - \langle \beta'_u \rangle A_1}
\]

, where \( \langle \beta_u \rangle = \frac{\sum_u f P_b P_u D}{N_u} \)

\[ \delta = \frac{N_u N'_d}{N_d N'_u} \]
\[ a = \frac{\delta}{\kappa} \langle \beta'_u \rangle \langle \beta_d \rangle - \langle \beta_u \rangle \langle \beta'_d \rangle \]
\[ b = -\frac{\delta}{\kappa} (\langle \beta'_u \rangle + \langle \beta_d \rangle) - (\langle \beta_u \rangle + \langle \beta'_d \rangle) \]
\[ c = \frac{\delta}{\kappa} - 1 \]

- 2-nd order equation:
  \[ a A_1^2 + b A_1 + c = 0 \]
  \[ A_1 = \frac{\pm \sqrt{b^2 - 4ac - b}}{2a} \]
- Stability in time: \( \kappa = \frac{a_u a'_d}{a_d a'_u} \approx 1 \)
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Target polarization

- After 5 days of build-up time: +0.53 and −0.50
- Average polarization over 2 years is 0.5
- Measurement by NMR coils with relative precision of 5%

Beam polarization

- MC simulation of the beam line
- Energy range: [140, 180] GeV
- Systematic uncertainty is 0.04
- Average polarization is 0.76

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Dilution Factor:

\[
f = \frac{\bar{\sigma}^{1\gamma}}{\bar{\sigma}} n_D \bar{\sigma}_D + \sum_A (n_A \bar{\sigma}_A)
\]

- Naive expectation \((f = 0.5)\)

\(^6\text{LiD} = (^4\text{He} + \text{D}) + \text{D}\)

- Packing factor \(= 0.55 \Rightarrow\) Fraction of polarized material. Nuclear effects. \((f \approx 0.42)\)

- Radiative corrections \((f \approx 0.36)\)
  - small \(x\): elastic scattering
  - high \(x\): different kinematic region
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  \(^6\)LiD = \(^4\)He + D + D

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Depolarization Factor

- it accounts for polarization transfer from $\mu$ to virtual photon

$$D \simeq \frac{y(2 - y)}{y^2 + 2(1 + R)(1 - y)}$$

$$R = \frac{\sigma_L}{\sigma_T}$$

- $x < 0.12$ – NMC parametrization
- $x > 0.12$ – SLAC parametrization

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### Main sources of systematic error

<table>
<thead>
<tr>
<th>Multiplicative error for $A_1$</th>
<th>Beam polariz.</th>
<th>4 – 5 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target polariz.</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Depolariz. fact.</td>
<td>4 – 5 %</td>
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<tr>
<td>Dilution. fact.</td>
<td>6%</td>
<td></td>
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<tr>
<td>Sum</td>
<td>$\delta A_1 \simeq 0.1 A_1$</td>
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<tr>
<th>Additive error for $A_1$</th>
<th>$A_2 \cdot \eta$</th>
<th>&lt; 0.005 \cdot \eta</th>
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<td>Rad. correct.</td>
<td>0.1 \cdot A^{RC}$, (A^{RC} &lt; 0.01)</td>
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<tr>
<td>$A_{false}$</td>
<td>$&lt; 0.5 \cdot \sigma_{stat}$</td>
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Results on Inclusive Asymmetry $A_1^d$

- Good agreement over the full range of $x$
- For $x < 0.03$ statistical error is reduced by factor of 2.5
- Results show no tendency toward negative values
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$$g_1^d = \frac{F_2^d}{2x(1 + R)} A_1^d$$

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- Integral over the range $0.004 < x < 0.03$
  - SMC: $(-5.3 \pm 2.3) \cdot 10^{-3}$
  - COMPASS: $(-0.3 \pm 1.0) \cdot 10^{-3}$
- Improved extrapolation of $g_1^d$ toward $x = 0$
- If compared to SMC no improvement in $\Gamma_1^d$
QCD analysis

- Measured structure functions $g_1^{p,d,n}$ (different $x, Q^2$)

$$g_1(x, Q^2) = \frac{1}{2} \langle e^2 \rangle \left[ C_q^S \otimes \Delta \Sigma + C_q^{NS} \otimes \Delta q^{NS} + 2n_f C G \otimes \Delta G \right]$$

- DGLAP equations ($Q^2$-dependence)

$$\frac{d}{dt} \Delta q^{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS}$$

$$\frac{d}{dt} \begin{pmatrix} \Delta \Sigma \\ \Delta G \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} P_{qq}^{S} & 2n_f P_{qG}^{S} \\ P_{Gq}^{S} & P_{GG}^{S} \end{pmatrix} \otimes \begin{pmatrix} \Delta \Sigma \\ \Delta G \end{pmatrix}, \quad t = \log \left( \frac{Q^2}{\Lambda^2} \right)$$

- Initial parametrization ($x$-dependence at fixed $Q^2$)

$$(\Delta \Sigma, \Delta q^{NS}, \Delta G) = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x)dx}$$

- Minimization routine

$$\chi^2 = \sum_{i=1}^N \left[ \frac{g_1^{\text{calc}}(x, Q^2) - g_1^{\text{exp}}(x, Q^2)}{\sigma_{\text{stat}}(x, Q^2)} \right]^2$$
Spin structure functions of deuteron from COMPASS

Results QCD fit

- Program “2” in SMC notation (D.Fasching, hep-ph/9610261)
- Numerical calculation in NLO ($\overline{MS}$ scheme)
- World data fit
Quark spin content (\(\Delta \Sigma\) in \(\overline{MS}\))
Quark spin content \((\Delta \Sigma\text{ in } \overline{\text{MS}})\)

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What is detected in final state?

**Inclusive DIS**

- Detected particle: $\mu, \mu'$
- $A_1 = \frac{\sum_q e_q^2 [\Delta q(x) + \Delta \bar{q}(x)]}{\sum_q e_q^2 [q(x) + \bar{q}(x)]}$
- only $\Delta q + \Delta \bar{q}$ can be measured

**Semi-Inclusive DIS**

- Detected particle: $\mu, \mu', h, ...$
- $A_1^h = \frac{\sum_q e_q^2 [\Delta q(x) \int D_q^h dz + \Delta \bar{q}(x) \int D_{\bar{q}}^h dz]}{\sum_q e_q^2 [q(x) \int D_q^h dz + \bar{q}(x) \int D_{\bar{q}}^h dz]}$
- $D_q^h \neq D_{\bar{q}}^h \Rightarrow$ quarks and anti-quarks separation
Asymmetries which we measure

\[ \vec{A}_1 = \{ A_1, A_1^{h+}, A_1^{h-}, A_1^{K+}, A_1^{K-}, A_1^{K_0} \} \]

Inclusive Asymmetry

\approx 90\% \text{ of hadrons are pions}

Secondary vertices produced by track coming from interaction point

90\% of hadrons are pions

Inclusive Threshold: \( p_K > 9 \text{ GeV} \)

RICH PID

Mass Spectrum

Zoom

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Agreement with previous experiments

Significant statistical improvement at low $x$
Spin structure functions of deuteron from COMPASS

- Agreement with previous experiments

- Significant statistical improvement at low $x$

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Summary

- Analysis of data of 2002 and 2003
- New measurement of $A_1^d$ and $g_1^d$ in DIS region ($Q^2 > 1 \text{ GeV}^2$, $0.004 < x < 0.7$)
  - Good agreement with results of previous experiments
  - Improvement in statistical precision factor 2.5 in region $x < 0.03$
  - Extrapolation improvement of $g_1^d$ toward $x = 0$
  - With QCD fit ($\overline{MS}$) decrease of error $\approx 2$ for $\Delta \Sigma$
- Hadron asymmetries $A_1^{h+}$ & $A_1^{h-}$ have been shown

Outlook

- Sizable improvement with 2004 data is expected (Calo trigger)
- Kaon asymmetries $A_1^{K+}$, $A_1^{K-}$, $A_1^{K_S}$ are coming
- Analysis of $A_1^d$ at low $x$ and low $Q^2$ is going