Spin Structure Functions in the Resonance Region

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- Introduction
- Formalism
- Experimental Setup
- Inclusive measurements on proton and neutron
- Exclusive measurements: single pion production
- Summary and Outlook
in 1989 the analysis of the EMC results showed that only a small fraction of the nucleon spin is carried by quarks

$$\Delta \Sigma = \Delta u + \Delta d + \Delta s \approx 0.2$$

since that, several measurements have been completed

- high $Q^2$ → CERN, SLAC, DESY
- $Q^2 = 0$ → Mainz, Bonn

and important results have been achieved

- extensive measurements of the nucleon spin structure functions performed in DIS
- the Bjorken sum rule has been verified at the 5% level
- the GDH integral for the proton has been measured at Mainz/Bonn: results for the proton are consistent with the sum rule prediction
Spin integrals and Sum rules

First Moment of $g_1(x,Q^2)$

$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2) dx$

Bjorken Sum Rule

$\Gamma_1^p - \Gamma_1^n \xrightarrow{Q^2 \to \infty} \frac{g_0}{6}$

Gerasimov–Drell–Hearn

$I_{GDH} = \frac{M^2}{8\alpha\pi^2} \int_{thr}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu} = -\frac{1}{4} \kappa^2$

the GDH sum rule constrains the slope of $\Gamma_1$ for $Q^2 \to 0$

because of this constraint, $\Gamma_1$ is expected to show a dramatic change from $Q^2 = 0$ to $Q^2 \to \infty$
A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude to the nucleon structure function $G_1 (→ g_1(Q^2/2Mν,Q^2)=Mν G_1(ν,Q^2))$


$S_1(0,Q^2)=4\int_{Q^2/2M}^{∞} dν \frac{G_1(ν,Q^2)}{ν}$

- GDH sum rule and Chiral Perturbation Theory
  $- \frac{κ^2}{M^2} + cQ^2 + O(Q^4)$

- Lattice?

- Bjorken Sum rule and Operator Product Expansion
  $\sim \sum_{κ=2,4,...} \frac{μ_κ(Q^2)}{Q^{κ-2}}$

the left side is a calculable quantity

the right side is a measurable quantity
Asymmetries and Structure Functions

\[ \frac{d\sigma}{dE'd\Omega} = \Gamma_v \left[ \sigma_T + \varepsilon \sigma_L + P_e P_t \left( \sqrt{1 - \varepsilon^2} A_1 \sigma_T \cos \psi + \sqrt{2 \varepsilon (1 - \varepsilon)} A_2 \sigma_T \sin \psi \right) \right] \]

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \quad A_2 = \frac{\sigma_{LT'}}{\sigma_T} \]

the structure functions \( A_1 \) and \( A_2 \) can be extracted by varying the direction of the nucleon polarization

\[ \mathbf{A}^\parallel = D(A_1 + \eta A_2) \]

\[ \mathbf{A}^\perp = d(A_1 + \zeta A_2) \]

where \( D, \eta, d, \xi \) are function of \( Q^2, W, E_0, R \)

the structure functions \( g_1 \) and \( g_2 \) are linear combination of \( A_1 \) and \( A_2 \)

\[ g_1(x,Q^2) = \frac{Q^2}{Q^2 + 4M^2x^2} \left( A_1 + \frac{2Mx}{\sqrt{Q^2}} A_2 \right) F_1(x,Q^2) \]

\[ g_2(x,Q^2) = \frac{Q^2}{Q^2 + 4M^2x^2} \left( \frac{\sqrt{Q^2}}{2Mx} A_2 - A_1 \right) F_1(x,Q^2) \]
the helicity amplitudes provide information on the structure of the excited states

- their $Q^2$ dependence is determined by the spatial structure of the excited state

- polarization measurements are necessary to extract the helicity amplitudes

$$\sigma_T = \sigma_{1/2} + \sigma_{3/2} = |A_{1/2}|^2 + |A_{3/2}|^2$$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \rightarrow |A_{1/2}|^2 - |A_{3/2}|^2$$

$$A_2 = \frac{\sigma_{LT'}}{\sigma_T} \rightarrow C_{1/2}^* A_{1/2}$$
Helicity Structure of Baryonic Resonances

\( \mathbf{P}_{33}(1232) \)

In the assumption of \( \mathbf{M}_{1+} \) dominance

\[
\mathbf{A}_1 \approx -\frac{1}{2} + 3 \frac{\text{Re}(\mathbf{E}_{1+}^\ast \mathbf{M}_{1+})}{|\mathbf{M}_{1+}|^2}
\]

\( \mathbf{P}_{11}(1440) - \mathbf{S}_{11}(1535) \)

\[ \mathbf{A}_1 = 1 \]

\( \mathbf{D}_{13}(1520) - \mathbf{F}_{15}(1680) \)

NRQM predicts

\[
\mathbf{A}_1 = \frac{1 - \left[\frac{\alpha^2}{\alpha^2 - 1}\right]^2}{1 + \left[\frac{\alpha^2}{\alpha^2 - 1}\right]^2}
\]

\[
\text{as } Q^2 \to 0 \quad \mathbf{A}_1 \to -1
\]

\[
\text{as } Q^2 \to 0^+ \quad \mathbf{A}_1 \to +1
\]
Double Polarization Experiments at JLab

Hall A → E94–010
\vec{e}^3\text{He} \rightarrow e' X

→ E91–011
\vec{e} p \rightarrow e' \pi^0 \vec{p}

Hall B → E91–023
\vec{e} p \rightarrow e' X

→ E93–009
\vec{e} D \rightarrow e' X

→ E93–036/E94–003
\vec{e} p \rightarrow e' \pi^+ n
\vec{e} p \rightarrow e' \pi^0 p
\vec{e} D \rightarrow e' \pi^- pp
Hall A: E94–010 setup

- **Moller Polarimeter**
- **Drift Chambers**
- **Cerenkov**
- **Scintillators**
- **Shower Counter Pb-glass**
- **Preshower**
- **To Beam Dump**
- **Laser hut**
- **BPM**
- **BCM**
- **Beam Polarization: 70%**
- **Beam Current: 15 microA**

**Hall A: E94–010 setup**

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**BARYONS 2002, Jefferson Lab, March 3–8 2002**
Hall B experimental setup

- large kinematical coverage
- detection of charged and neutral particles
- multi-particle final states
$A_1 + \eta A_2$ for proton and deuteron

JLab/CLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>$0.4 &lt; Q^2 &lt; 0.6 \text{ GeV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_3$</td>
<td>1232</td>
</tr>
<tr>
<td>$d_{13}/s_{11}$</td>
<td>1520-35</td>
</tr>
<tr>
<td>$s_{11}/f_{15}$</td>
<td>1650-80</td>
</tr>
</tbody>
</table>

$e p \rightarrow e' X$

$e d \rightarrow e' X$

PRELIMINARY
$g_1(x)$ for the proton

**JLab/CLAS**

![Graph showing data points and curves representing different models for $g_1(x)$, with annotations for Q$^2$=0.91 GeV$^2$, A$_1$+ηA$_2$ parameterization, Gehrmann and Stirling (Q$^2$=1.0), and Edelmann et al. (Q$^2$=1.0).](image)
$g_1(x)$ for the proton

strong $Q^2$ dependence

evident resonance structures

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$g_1$ for the proton

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PRELIMINARY
First moment of $g_1$ for the proton

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\[ \Gamma_{1P} \]

$Q^2(\text{GeV}^2)$

- pQCD DIS
- GDH
- Ji-\(\chi\)Pt
- Soffer-Teryaev
- Burkert-Ioffe

CLAS

CLAS+DIS

SLAC

PRELIMINARY

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GDH Integral for the Proton

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$g_1$ and $g_2$ on $^3$He

JLab/Hall A

$g_1(x)$ & $g_2(x)$

- $0.10$ GeV$^2$
- $0.28$ GeV$^2$
- $0.46$ GeV$^2$
- $0.64$ GeV$^2$
- $0.82$ GeV$^2$
- $1.0$ GeV$^2$
GDH Integral on the Neutron

JLab/Hall A

GDH Integral on the Neutron (W<2GeV)
GDH Integral on the neutron (W<2GeV)
GDH Integral on the neutron (W<30GeV)
Drechsel et al. [PRD63 (2001) 114010]
GDH sum rule on the neutron (Q^2=0)
$\Gamma_1$ for the neutron
Bjorken Integral

Jlab CLAS – Hall A

\[ \frac{\Gamma_{P} - \Gamma_{n}}{\Gamma_{n}} \]

\[ Q^2 \text{ (GeV}^2) \]

- Jlab/CLAS - Hall A
- SLAC
- Bjorken sum rule evolution at \( O(\alpha_s^3) \)
- GDH
- Ji-\( \gamma \)PT
- Burkert-Ioffe
- Soffer-Teryaev
Double Spin Asymmetry in $\vec{e}p \rightarrow e'\pi^+n$

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**Graphs**

- **MAID 2000**
- **AO**
- **AO res. Only**
- **AO - $F_{15}$ (+40%)**

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*BARYONS 2002, Jefferson Lab, March 3-8 2002*
Double Spin Asymmetry in $ep \rightarrow e'\pi^0p$

Ph.D. student: Angela Biselli – RPI

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$Q^2=0.5-0.9 \text{ GeV}^2$

$Q^2=0.9-1.5 \text{ GeV}^2$
Proton polarization in $\vec{e}p \rightarrow e'\pi^0\vec{p}$

$Q^2=1 \text{ GeV}^2$
$W=1.232 \text{ GeV}$

$\theta_{\text{cm}} = 11 - 33^\circ$

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Double Spin Asymmetry in $\vec{e}\vec{n} \rightarrow e'\pi^-p$

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Ph.D. student: M. Bektasoglu
ODU

PRELIMINARY
Upcoming experiments and future plans

Hall A
E94–101 → $A_1^n$ at large $x$
E97–103 → $g_2^n$ – higher twist effects
E97–110 → GDH Sum Rule and Spin Structure of the Neutron with Nearly Real Photons
E01–012 → Duality in Spin Structure Functions

Hall B/CLAS
EG2000 → new data taking period completed in April 2001
both proton (NH$_3$) and deuteron (ND$_3$) data
inclusive and exclusive reactions
broad energy range → 1.6 – 5.7 GeV
improved $Q^2$ range → 0.05 – 3 GeV$^2$

Hall C
E01–006 → Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances
Summary

- A broad physics program to study the spin structure of the nucleon and of baryon resonances is in progress at Jefferson Lab

- Inclusive measurements on proton, deuteron and helium-3 have been completed
  - first high precision measurements of the proton and neutron spin structure functions in the resonance region
  - the structure function $g_1$ both for proton and $^3$He is deeply affected by resonance contribution
  - $\Gamma_1$ integral and Generalized GDH Integral have been measured for the proton and neutron in a large $Q^2$ range from 0.15 to 2 GeV$^2$
  - $\Gamma_1^p$ shows a strong $Q^2$ variation with zero crossing around 0.25 GeV$^2$, while $\Gamma_1^n$ remains negative with a smooth transition to the high $Q^2$ region
  - Bjorken integral obtained combining the CLAS and Hall A measurement for 0.15 to 1 GeV$^2$ shows a clear rise in $Q^2$

- Exclusive measurements in $\pi^+$, $\pi^0$ on the proton and $\pi^-$ on the deuteron have been performed
  - sensitivity to resonance contribution
  - new tool to study the helicity structure of individual excited states

- NEW DATA COMING...