An Overview of Longitudinal Spin Structure Measurements from JLab

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Jefferson Lab is currently one of the facilities leading the investigation of the spin structure of the nucleon. Over the past 15 years, several high precision measurements have been completed, extending our knowledge of the polarized structure functions $g_1$ and $g_2$ down to $Q^2 = 0.02 \text{ GeV}^2$. In particular, the low-$Q^2$ range ($\leq 0.1 \text{ GeV}^2$) from these data allows us to make a benchmark-check of Chiral Perturbation theory ($\chi$PT). Previous results for the moments of the spin structure functions in this region have shown mixed agreement. For $\Gamma_1$, the first moment of $g_1$, we find good consistency between data and theory. However, we have seen a surprisingly large discrepancy with $\chi$PT calculations for the $\delta_{LT}$ spin polarizability on the neutron, which is significantly less sensitive to the $\Delta$-resonance contribution. These proceedings will discuss the recent experimental effort at low $Q^2$ from Jefferson Lab, including a discussion of preliminary results on the neutron. The new results on the neutron still show a sizeable discrepancy between data and theory. However, new calculations show improved agreement with data for some observables. In addition, new proton data for $g_2$ is also expected to help resolve the disagreement for $\delta_{LT}$.

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1. Introduction

The experimental technique of particle scattering has been widely used in nuclear and particle physics to unveil the internal structure of nuclei and nucleons. In particular, doubly-polarized electron scattering off of the nucleon provides a powerful tool to understand the strong interaction. Lepton scattering is an ideal and clean way to access the structure of the nucleon due to our understanding of the electromagnetic interaction, which is described by Quantum Electrodynamics (QED). In addition, polarization degrees of freedom provide stringent constraints on theory. On the other hand, the nucleon’s dynamics and internal structure are governed by the strong interaction and is described by the gauge theory known as Quantum Chromodynamics (QCD). Unlike QED, QCD is generally non-perturbative except at small distance scales, i.e., in high energy reactions. In the high energy region, predictions from perturbative QCD (pQCD) have been verified by comparison with experimental results from facilities such as SLAC, CERN and DESY. However, at low energies in the domain of non-perturbative QCD, calculations become difficult due to the complicated interactions of the quarks and gluons in the nucleon. Therefore low-energy effective field theories such as Chiral Perturbation Theory ($\chi$PT) or numerical methods (Lattice QCD) have been utilized to make predictions. In these proceedings, the experimental program at Jefferson Lab (JLab) that involves testing Chiral effective theories at low four-momentum transfers squared will be discussed.

2. Inclusive Electron Scattering

In the process of inclusive lepton-nucleon scattering only the scattered lepton is detected:

\[ l(p) + N(P) \rightarrow l(p') + X(P'), \]  

where a charged lepton \( l \), in our case an electron, scatters from a nucleon \( N \). The relevant kinematic variables are the incident and scattered electron four-momenta \( p^\mu = (E, \vec{k}) \) and \( p'^\mu = (E', \vec{k}') \) respectively and the nucleon four-momenta \( P^\mu = (E_t, \vec{P}) \). Since the target is at rest, \( P^\mu = (M, \vec{0}) \) in the laboratory system. The scattering angle is \( \theta \). The exchanged virtual photon carries four-momentum \( q^\mu = (p - p')^\mu = (\nu, \vec{q}) \) with energy \( \nu = \frac{P\cdot q}{M} = E - E' \) and momentum \( \vec{q} \) to the target. The differential cross section is a function of two Lorentz invariants and the scattering angle. Typically, the squared four-momentum transfer \( (Q^2) \) and the invariant mass of the residual hadronic system \( (W) \) are used:

\[ Q^2 \equiv -q^2 \simeq 2EE'(1 - \cos \theta) \]  

\[ W = \sqrt{(P + q)^2} = \sqrt{M^2 + 2M\nu - Q^2} \]

However, the Bjorken scaling variable \( x = Q^2 / 2M\nu \) is also used, which in the parton model represents the fraction of nucleon momentum carried by the struck quark.

The inclusive cross section for electron-nucleon scattering is proportional to the product of a leptonic and a hadronic tensor, \( L_{\mu\nu} \) and \( W^{\mu\nu} \), respectively. The leptonic tensor is calculable from
QED, and the hadronic tensor can be split into symmetric and antisymmetric parts. The internal
structure of the nucleon is described by four structure functions: \( F_1, F_2 \) and \( g_1, g_2 \), where the structure
functions \( g_1(x, Q^2) \) and \( g_2(x, Q^2) \) contain information on the spin structure of the nucleon.

3. Spin Structure of the Nucleon and Sum Rules

The internal structure of the nucleon is parametrized by structure functions; however, the avail-
able theoretical tools are unable to calculate them. Instead, theories are used to provide predictions
of the moments of the structure functions; in these proceedings, the \( n \)-th moments are used with
\( \Gamma_{1,2}^n = \int_0^1 x^{n-1} g_{1,2}^{N}(x, Q^2) \, dx \), where \( N \) is either the proton or neutron. In addition to the moments,
there are several dispersive sum rules that link the forward Compton scattering amplitudes to inte-
grals of the inclusive photoproduction cross sections. Sum rules utilize dispersion relations, which
relate the integral over the imaginary part of a quantity to its real part. When coupled with additional
hypotheses such as a low energy theorem, the integrals can often be related to a static property of the nucleon, e.g., its anomalous magnetic moment. The static properties are typically
well known, and hence, the confirmation of the sum rule provides a test of the theory and assump-
tions used in its derivation. Clearly, sum rules provide a useful testing ground to study the internal
degrees of freedom of the system.

There are several spin dependent sum rules. However in these proceedings, we will focus on
the Gerasimov-Drell-Hearn (GDH) sum rule \([1]\), the Bjorken sum rule \([2]\) and the forward spin
polarizabilities \([3, 4]\) at low- and intermediate-\( Q^2 \) values. Refs. \([4–6]\) provide detailed reviews on
the experimental and theoretical efforts in this field.

3.1 Generalized GDH and Bjorken Sum Rules

The Gerasimov-Drell-Hearn (GDH) sum rule relates a particle’s anomalous magnetic moment
\( \kappa \) to an energy-weighted integral over its photoabsorption cross section. The sum rule’s significance
is that it relates static properties of the particle’s ground state to dynamic properties of all its excited
states. It also divulges that a particle with a finite size and an excitation spectrum is required to
have a non-zero anomalous magnetic moment \([3]\). The sum rule for spin-\( \frac{1}{2} \) particles is

\[
\int_0^{\infty} \frac{d\nu}{\nu} \left[ \sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu) \right] = -2\pi^2 \alpha \frac{\kappa^2}{M^2}, \tag{3.1}
\]

where \( \nu_0 = m_\pi \left( 1 + \frac{m_\pi}{2M} \right) \approx 150 \text{ MeV} \) is the threshold energy for pion production. The anomalous
magnetic moment and mass of the target are \( \kappa \) and \( M \), respectively and \( \alpha \) is the electromagnetic
coupling constant. \( \sigma_{\frac{1}{2}} \) and \( \sigma_{\frac{3}{2}} \) are the photoabsorption cross-sections, where the sum of the photon
and target helicities in the center of mass system is \( 1/2 \) and \( 3/2 \). The GDH sum rule is also valid
for any target with definite spin-\( S \).

The GDH integral (left hand side of Eq. 3.1) was generalized \([7]\) to virtual photon absorption
\( (Q^2 > 0) \) by replacing the photoabsorption cross-sections with the electroproduction cross-sections.
Additional extensions have also been proposed \([3, 8]\). The extension of Ji and Osborne \([8]\) relates the integral to the forward virtual Compton scattering amplitude \( S_1(0, Q^2) \) to form a \( Q^2 \)-dependent
sum rule:

\[
\frac{8}{Q^2} \int_0^{\nu_0} g_1(x, Q^2) \, dx = S_1(0, Q^2), \tag{3.2}
\]
where \( x_0 = \frac{Q^2}{2M_0} \). This extension provides a relation that is constrained at the two ends of the \( Q^2 \) spectrum by well known sum rules: GDH at \( Q^2 = 0 \) and the Bjorken sum rule \([2]\) at large \( Q^2 \).

The Bjorken sum rule relates the integral over the isovector component of the \( g_1 \) structure function \((g_1^p - g_1^n)\) to the axial charge of the nucleon, \( g_A \). This sum rule is valid at infinite \( Q^2 \), but like the GDH sum rule, it has also been generalized to finite \( Q^2 \) via the Operator Product Expansion of pQCD:

\[
\Gamma_{p-n}^{n} (Q^2) = \int_0^1 \left[ g_1^n (x, Q^2) - g_1^p (x, Q^2) \right] dx
\]

\[
= \frac{g_A}{6} \left[ 1 - \frac{\alpha_s (Q^2)}{\pi} - 3.58 \frac{\alpha_s^2 (Q^2)}{\pi^2} - 20.21 \frac{\alpha_s^3 (Q^2)}{\pi^3} + \ldots \right] + \ldots , \quad (3.3)
\]

where \( \alpha_s (Q^2) \) is the coupling constant of the strong interaction. The expression in brackets represents the leading twist term and has a mild \( Q^2 \) dependence. There are also non-perturbative corrections known as higher twists to Eq. 3.3, which involve quark-gluon correlations. This sum rule has been pivotal in enhancing our knowledge of the nucleon spin structure, and the generalized sum rule has been measured and verified in polarized deep inelastic scattering (DIS) at CERN \([9]\), DESY \([10, 11]\) and SLAC \([12]\). Over the past decade, JLab experiments have increased the coverage at low and moderate \( Q^2 \) \([13–19]\).

Clearly, there is a close relationship between the Bjorken and generalized GDH integrals:

\[
I_{BGDH}^{p-n} (Q^2) = \frac{Q^2}{8} \times \Gamma_{p-n}^{n} (Q^2) . \quad (3.4)
\]

The extended GDH and Bjorken sum rules can be used to make comparisons between theoretical calculations and experimental data over the entire \( Q^2 \) range. At high \( Q^2 \), the Bjorken sum rule provides the prediction, whereas at intermediate and low \( Q^2 \) Lattice QCD and \( \chi \)PT provide the predictions, respectively, of the spin dependent Compton amplitude in Eq. 3.2. These comparisons also allow an important investigation of the transition between the non-perturbative and the perturbative regions of QCD.

### 3.2 Spin Polarizabilities

Higher moments of the polarized structure functions are connected to electromagnetic polarizabilities by sum rules that characterize the coherent response of the nucleon to photon absorption. The generalized spin polarizabilities characterize the response to virtual photons. Due to the higher power of \( x \) weighting, these integrals converge faster than the first moments, and therefore are less sensitive to the unmeasured low-\( x \) contributions. The expressions for the \( \gamma_0 \) and \( \delta_{LT} \) polarizabilities in terms of the structure functions are given by

\[
\gamma_0 (Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 (x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2 (x, Q^2) \right] dx , \quad (3.5)
\]

\[
\delta_{LT} (Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 (x, Q^2) + g_2 (x, Q^2) \right] dx . \quad (3.6)
\]
The derivation of the sum rules for the spin polarizabilities are discussed in [4].

For the longitudinal-transverse polarizability, \( \delta_{LT} \), the \( \Delta \)-resonance contribution of 1232 MeV is suppressed, since the transition is mostly transverse. Hence, based on this fact, \( \delta_{LT} \) is expected to provide a robust quantity to calculate within \( \chi \)PT.

In the next section, results on these sum rules from the Jefferson Lab low-\( Q^2 \) experiments will be discussed.

### 4. Experimental Measurements of Moments for \( Q^2 \approx 0.1 \) GeV\(^2\)

The results discussed below are from data taken with the JLab polarized electron beam with beam polarization near 85% and beam currents up to 15 \( \mu \)A, 0.01 \( \mu \)A, 0.1 \( \mu \)A for experimental halls: A, B and C, respectively. Hall B has a large acceptance spectrometer [20] known as CLAS for measurements over an extensive kinematic region. Hall A [21] and C have smaller acceptance spectrometers with high luminosity for higher precision measurements.

Polarized targets have been utilized in each of the halls. In Hall A, a gaseous \(^3\)He target is polarized by spin exchange optical pumping. The ground state of the \(^3\)He nucleus is predominantly in the S-state, where the two proton spins are anti-aligned due to the Pauli exclusion principle. Hence, polarized \(^3\)He can be utilized as an effective polarized neutron target. A high luminosity of \( 10^{30} \) s\(^{-1}\) cm\(^{-2}\) has been achieved with polarizations of beam on target over 60%. In these proceedings, the focus will be on the neutron results. However, results from \(^3\)He data have also been published [18]. In Hall B and C solid targets [22] made of polarized ammonia NH\(_3\) and ND\(_3\) are often employed. These targets are polarized via Dynamical Nuclear Polarization. The targets have reached polarized luminosities of \( 10^{34} \) s\(^{-1}\) cm\(^{-2}\) and \( 10^{35} \) s\(^{-1}\) cm\(^{-2}\) in Hall B and C, respectively with polarizations up to 90% for the proton and to 40% for the deuterated targets. Since light nuclear targets are required to study the neutron internal structure, the extraction of neutron information from both polarized deuteron and \(^3\)He provides a critical systematic check of our understanding of the nuclear effects involved. The target in Hall C has been exclusively used at moderate-\( Q^2 \) values (\( > 1 \) GeV\(^2\)), and hence, the results from these data [17] will not be discussed.

#### 4.1 Results on the First Moment of \( g_1 \)

In Figure 1, the measured results for the proton and Bjorken sum (isovector component) of the first moment of \( g_1 \) are presented. As can clearly be seen, the data cover a large range in \( Q^2 \) from 0.05 GeV\(^2\) up to 3 GeV\(^2\) including the region where \( \chi \)PT is expected to be valid. The data are gathered from experiments carried out at CERN [9], DESY [10, 11], JLab [13–17] and SLAC [12]. A comparison between the data and \( \chi \)PT calculations [23, 24] can be seen at low \( Q^2 \) in the figure. The slope at \( Q^2 = 0 \) is taken from the GDH sum rule, and hence, the \( \chi \)PT calculations provide the deviation from the slope. It is this deviation that can be checked between the experimental data and the predictions. A fit has been performed for the proton and Bjorken sum [16] with the form:

\[
\Gamma_{1N}^N = \frac{k_N^2}{8M^2} Q^2 + aQ^4 + bQ^6, \tag{4.1}
\]

where \( N \) is either the proton or neutron. For the proton and Bjorken sum, the determined numerical values for \( a \) from experiment and theory are listed in Table 1. The fits to the data indicate
Figure 1: Experimental results from CERN, DESY, JLab and SLAC on $\Gamma_1$ for the proton (left) and isovector component (right) in the low- and moderate-$Q^2$ regions. The theoretical curves and models are explained in the text.

<table>
<thead>
<tr>
<th>Nucleon Component</th>
<th>$a_{\text{exp}}$</th>
<th>$a_{\text{B}}$</th>
<th>$a_{\text{BM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>4.31 ± 0.31 ± 1.36</td>
<td>3.89</td>
<td></td>
</tr>
<tr>
<td>P–N</td>
<td>0.80 ± 0.07 ± 0.23</td>
<td>0.74</td>
<td>2.4</td>
</tr>
<tr>
<td>P+N</td>
<td>6.97 ± 0.96 ± 1.48</td>
<td>7.11</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Numerical values of $a$ from the $Q^2$-dependent fit compared to $\chi$PT calculations $a_{\text{B}}$ [23] and $a_{\text{BM}}$ [24].

the importance of the $Q^6$ term at $Q^2 < 0.1$ GeV$^2$. The data and $\chi$PT calculations are in good agreement for the proton up to $Q^2 \sim 0.08$ GeV$^2$; however, they agree over a much larger range up to 0.3 GeV$^2$ for the Bjorken sum. The data also agree very well with the two phenomenological model calculations [25, 26].

4.2 Results on Spin Polarizabilities

The data from Hall A and Hall B are shown in Fig. 2 for the spin polarizabilities in the low-$Q^2$ region. The left panel of the figure provides the isospin decomposition of the data from both Hall A and B for the $\gamma_0$ spin polarizability with the two independent $\chi$PT calculations [24, 27] indicated on the graph. In the right panel of Fig. 2, the neutron spin polarizabilities for $\gamma_0$ and $\delta_{LT}$ are shown. The light shaded band also includes the $\Delta$-resonance and vector meson contributions for the relativistic baryon $\chi$PT (RB$\chi$PT) calculation [24]. The data are also compared to the MAID model [3, 28], which shows very good agreement with the data over most of the $Q^2$ range. Surprisingly, there is little agreement between the available data and $\chi$PT calculations, except perhaps for $\gamma_0$ at the lowest-$Q^2$ point and the RB$\chi$PT band. The quantity $\delta_{LT}$ is most puzzling, since it is mostly insensitive to the $\Delta$-resonance contribution compared to the $\gamma_0$ polarizability. This disagreement has been referred to as the “$\delta_{LT}$ puzzle” and presents a real challenge to theorists, possibly
Figure 2: JLab data on the generalized spin polarizabilities at low $Q^2$. The isospin decomposition of $\gamma_0$ [16] from the combined Hall A and B data [13, 14] is shown on the left-hand side (top: $\gamma_{0^-}^p$, bottom: $\gamma_{0^+}^p$). The right-hand side of the figure shows the neutron spin polarizabilities $\gamma_0$ (top panel) and $\delta_{LT}$ (bottom panel) from the Hall A data.

indicating that the inclusion of the resonance contributions may not be the only issue. One of the major limitations of the available data was that the lowest $Q^2$ point might still be outside the region of $\chi PT$’s applicability. Since these data were published, recently completed experiments at JLab have obtained data for $Q^2$ down to approximately 0.02 GeV$^2$, where the data should be well within the $\chi$PT domain of validity.

5. Recent Experimental Progress and Preliminary Results

All the data discussed so far have covered the intermediate $Q^2$ region. However, a new set of high precision experiments has recently been completed at JLab with an emphasis on extending the data to lower $Q^2$ to make a bench-mark check of $\chi$PT predictions. This section will briefly discuss new $g_1$ measurements on the proton and deuteron from Hall B [29] and present the preliminary Hall A results on the neutron [30] from a polarized $^3$He target. A new measurement on the proton $\delta_{LT}$ polarizability [31] from Hall A was also presented at this conference by C. Gu and P. Zhu. The plan for all these measurements was to extend the measured-$Q^2$ range down to $\sim$ 0.02 GeV$^2$.

The main goal of the Hall B EG4 experiment [29] was to measure the $g_1$ structure function for both polarized NH$_3$ and ND$_3$ targets via doubly-polarized inclusive electron scattering at low $Q^2$. In Hall B, the target can only be polarized along the beam direction, which mostly provides access to $g_1$. On the other hand, the polarized ammonia target in Hall C can be polarized in directions along the beam and perpendicular (in the horizontal plane). Hence, the spokespersons for experiment E08-027 [31] decided to move the Hall C target into Hall A to measure the $g_2$ structure function, which provides the data necessary to determine the $\delta_{LT}$ polarizability for the proton between 0.02 GeV$^2$ and 0.16 GeV$^2$ when combined with the Hall B $g_1$ data.
For the EG4 experiment, the electron beam was polarized to about 80% with beam energies of 1–3 GeV. Since the cross section difference measurements require an uniform and high detection efficiency of electrons across the spectrometer acceptance, a new Cherenkov detector was installed in the CLAS spectrometer for detection of small angle scattering down to 6°. This experiment achieved good coverage of the resonance region for $0.015 < Q^2 < 0.5$ GeV$^2$. Currently, the data analysis is ongoing, and preliminary cross section differences were shown during the conference.

Hall A experiment E97-110 acquired data using the JLab longitudinally polarized electron beam, which was scattered on either a longitudinally or transversely (in-plane) polarized $^3$He target [21]. The doubly-polarized inclusive cross-section differences were measured. From these data, the polarized structure functions were extracted to form the integrals at $Q^2$ between 0.04 and 0.24 GeV$^2$. The experimental details and data analysis can be found in [30]. The experiment made a high precision measurement of the moments of the spin structure functions in a previously unmeasured region of kinematics to test $\chi$PT calculations. It also complements the data from the early Hall A experiment [14, 18].

For this experiment, the polarized $^3$He target was used as an effective neutron target. The neutron moments were extracted from the measured $^3$He quantities by using the technique described in [32]. The systematic uncertainty due to this extraction was determined to be 10% for $Q^2 \leq 0.1$ GeV$^2$ and 5% at higher $Q^2$. The deuteron data from EG4 will also provide an important systematic check of the neutron extraction. The parametrization in [33] was used to account for the unmeasured low-$x$ contribution for the generalized GDH integral.

In the top graph of Fig. 3, the preliminary results for the first moment $\Gamma_1^\gamma$, where the elastic contribution to the integral is excluded, are compared to theoretical calculations and earlier measurements [11–14]. The solid triangles show the preliminary data, and the inverted triangles indicate the results from a previous Hall A experiment [14]. The Hall B EG1b data are not shown for clarity. The error bars indicate the size of the total uncertainties with the statistical and systematic uncertainties added in quadrature. The data agree well with the earlier data and the two model calculations [25, 26] and indicate a smooth transition as $Q^2 \rightarrow 0$. Two calculations from $\chi$PT are also shown on the figure; the calculation with an estimate of the $\Delta$-resonance and vector meson contributions is represented by the shaded band. With the current uncertainties, the data show good agreement with the RB$\chi$PT calculation [24], and the three lowest-$Q^2$ points also agree well with the heavy baryon $\chi$PT (HB$\chi$PT) calculation [23].

The $\gamma_0$ and $\delta_{LT}$ polarizabilities for the neutron appear in the bottom-left and bottom-right panels of Fig. 3, respectively. The solid circles show the preliminary data, and the squares indicate the results from a previous Hall A experiment [14] between 0.1 GeV$^2$ and 0.26 GeV$^2$. The error bars on the data indicate the size of the statistical uncertainties, and the solid bands near zero show the size of the systematic uncertainties. The band on the negative side of the vertical axis is for the new data. The $\gamma_0$ data agree reasonably well with the earlier data and the MAID model [3, 28]. For $\delta_{LT}$, the data and the model agree extremely well with each other. The two available calculations from $\chi$PT [24, 27] are also shown in the graphs. The light-shaded band represents the calculation with an estimate of the $\Delta$-resonance and vector meson contributions. Within the current uncertainties, the $\gamma_0$ results show good agreement with the RB$\chi$PT calculation below 0.12 GeV$^2$. However, the HB$\chi$PT [27] calculation shows a large discrepancy, which might indicate the importance of the resonances for this observable. Preliminary results for the $\delta_{LT}$ polarizability show good agreement.
with the previously published data and a very significant discrepancy with the $\chi$PT calculations. However, recent theoretical progress [34] has been made that is not yet reflected in these graphs. For these preliminary data, we are in the process of significantly improving the largely dominant systematic uncertainties for the final results.

6. Summary

In these proceedings, we have discussed the data from Jefferson Lab experiments on the moments of the spin-dependent structure functions for the proton and neutron at low-$Q^2$ values, where $\chi$PT calculations are expected to be valid. In general, the comparison between the data and calculations have mixed agreement with the best agreement occurring for the Bjorken sum and for the

**Figure 3**: Preliminary neutron $\Gamma_n^i$ (top panel), $\gamma_n^i$ (bottom-left panel) and $\delta_{LT}$ (bottom-right panel) results. The theoretical curves and models are explained in the text.
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generalized GDH sum. For observables in which the $\Delta$-resonance contribution is highly suppressed such as $\delta_{LT}^{p}$, the discrepancy is rather significant and unexpected. Recent experimental endeavors have acquired data at lower $Q^2$ and on a transversely polarized proton target, providing data for $\delta_{LT}^{p}$, which might help resolve the disagreement between experiment and theory. Progress has also been made in theory calculations that appears to be bridging the gap between the data and earlier predictions.

References


[31] A. Camsonne, J. P. Chen and K. Slifer, JLab experiment E08-027.

