New Results on Nucleon Spin Structure

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October 28, 2005

Abstract

Recent precision spin structure data from Jefferson Lab have significantly advanced our knowledge of nucleon structure in the valence quark (high-$x$) region and improved our understanding of higher-twist effects, spin sum rules and quark-hadron duality. First, results of a precision measurement of the neutron spin asymmetry, $A_1^n$, in the high-$x$ region are discussed. The new data shows clearly, for the first time, that $A_1^n$ becomes positive at high $x$. They provide crucial input for the global fits to world data to extract polarized parton distribution functions. Preliminary results on $A_1^n$ and $A_1^d$ in the high-$x$ region have also become available. The up and down quark spin distributions in the nucleon were extracted. The results for $\Delta d/d$ disagree with the leading-order pQCD prediction assuming hadron helicity conservation. Then, results of a precision measurement of the $g_2^n$ structure function to study higher-twist effects are presented. The data show a clear deviation from the lead-twist contribution, indicating a significant higher-twist (twist-3 or higher) effect. The second moment of the spin structure functions and the twist-3 matrix element $d_2^n$ results were extracted at a high $Q^2$ of 5 GeV$^2$ from the measured $A_2^n$ in the high-$x$ region in combination with existing world data and compared with a Lattice QCD calculation. Results for $d_2^n$ at low-to-intermediate $Q^2$ from 0.1 to 0.9 GeV$^2$ were also extracted from the JLab data. In the same $Q^2$ range, the $Q^2$ dependence of the moments of the nucleon spin structure functions was measured, providing a unique bridge linking the quark-gluon picture of the nucleon and the coherent hadronic picture. Sum rules and generalized forward spin polarizabilities were extracted and compared with Chiral Perturbation Theory calculations and phenomenological models. Finally, preliminary results on the resonance spin structure functions in the $Q^2$ range from 1 to 4 GeV$^2$ were presented, which, in combination with DIS data, will enable a detailed study of the quark-hadron duality in spin structure functions.

1 Introduction and Motivation

Since the ‘spin crisis’[1], substantial efforts, both theoretical and experimental, have been devoted to understanding the nucleon’s spin puzzle. A new generation of experiments were carried out in the 1990s at SLAC, CERN and DESY. These experiments concluded that the quarks carry about 20 – 30% of the nucleon spin. The rest of the nucleon spin should come from the quark orbital angular momentum (OAM) and the gluon total angular momentum. The Bjorken sum rule[2], a fundamental sum rule of the spin structure function based on QCD, was verified to an accuracy of better than 10%. Attempts have been made to extract
the parton spin distributions from a global analysis of the polarized deep-inelastic-scattering
data. The uncertainties are much larger than those of the unpolarized parton distribution
due to the fact that the polarized data coverage in \(x\) and \(Q^2\) is much less extensive than that
of the unpolarized data.

Recently, the high polarized luminosity available at Jefferson Lab has allowed the study of
the nucleon spin structure with unprecedented precision, enabling us to access the valence
quark (high-\(x\)) region[3] and also to expand the study to the second spin structure function,
g_2[4]. Furthermore, the moments of the spin structure functions[5] were measured[6] and the
spin sum rules[6, 7], polarizabilities[6] and quark-hadron duality[8, 9] were studied.

1.1 Inclusive Polarized Electron-Nucleon Scattering

For inclusive polarized electron scattering off a polarized nucleon target, the cross section
depends on four structure functions, \(F_1(Q^2, x), F_2(Q^2, x), g_1(Q^2, x)\) and \(g_2(Q^2, x)\), where
\(F_1\) and \(F_2\) are the unpolarized structure functions and \(g_1\) and \(g_2\) the polarized structure
functions. In the quark-parton model, \(F_1\) or \(F_2\) gives the quark momentum distribution
and \(g_1\) the quark spin distribution. Another physics quantity of interest is the virtual
photon-nucleon asymmetry \(A_1\)

\[
A_1 = \frac{g_1 - (Q^2/\nu^2)g_2}{F_1} \approx \frac{g_1}{F_1}.
\]

1.2 Spin structure in the valence quark (high-\(x\)) region

The high-\(x\) region is of special interest, because this is where the valence quark contributions
are expected to dominate. With sea quark and explicit gluon contributions expected not to
be important, it is a clean region to test our understanding of nucleon structure. Relativistic
constituent quark models[10] should be applicable in this region and perturbative QCD[11]
can be used to make predictions in the large \(x\) limit.

To first approximation, the constituent quarks in the nucleon are described by SU(6)
wavefunctions. SU(6) symmetry leads to the following predictions[12]:

\[
A_1^p = 5/9; \quad A_1^n = 0; \quad \Delta u/u = 2/3; \quad \Delta d/d = -1/3.
\]

Relativistic Constituent Quark Models (RCQM) with broken SU(6) symmetry, e.g., the
hyperfine interaction model[10], lead to a dominance of a ‘diquark’ configuration with the
diquark spin \(S = 0\) at high \(x\). This implies that as \(x \to 1\):

\[
A_1^p \to 1; \quad A_1^n \to 1; \quad \Delta u/u \to 1; \quad \text{and} \quad \Delta d/d \to -1/3.
\]

In the RCQM, relativistic effects lead to non-zero quark orbital angular momentum and
reduce the valence quark contributions to the nucleon spin from \(1\) to \(0.6 - 0.75\).

Another approach is leading-order pQCD[11], which assumes the quark orbital angular
momentum to be negligible and leads to hadron helicity conservation. It yields:

\[
A_1^p \to 1; \quad A_1^n \to 1; \quad \Delta u/u \to 1; \quad \text{and} \quad \Delta d/d \to 1.
\]

Not only are the limiting values as \(x \to 1\) important, but also the behavior in the high-\(x\)
region. How \(A_1^n\) and \(A_1^p\) approach their limiting values when \(x\) approaches \(1\), is sensitive to
the dynamics in the valence quark region.
1.3 The $g_2$ structure function and the $d_2$ moment

$g_2$, unlike $g_1$ and $F_1$, can not be interpreted in the simple quark-parton model. To understand $g_2$ properly, it is best to start with the operator product expansion (OPE) method. In the OPE, neglecting quark masses, $g_2$ can be cleanly separated into a twist-2 and a higher twist term:

$$ g_2(x, Q^2) = g_2^{WW}(x, Q^2) + g_2^{HT}(x, Q^2). $$

(5)

The leading-twist term can be determined from $g_1$ as[13]

$$ g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(y, Q^2)}{y} dy, $$

(6)

and the higher-twist term arises from quark-gluon correlations. Therefore, $g_2$ provides a clean way to study higher-twist effects. In addition, at high $Q^2$, the $x^2$-weighted moment, $d_2$, is a twist-3 matrix element and is related to the color polarizabilities[14]:

$$ d_2 = \int_0^1 x^2 |g_2(x) - g_2^{WW}(x)| dx. $$

(7)

Predictions for $d_2$ exist from various models and lattice QCD.

1.4 Moments and sum rules of spin structure functions

Sum rules involving the spin structure of the nucleon offer an important opportunity to study QCD. In recent years the Bjorken sum rule at large $Q^2$ and the Gerasimov, Drell and Hearn (GDH) sum rule[15] at $Q^2 = 0$ have attracted large experimental and theoretical[16] efforts that have provided us with rich information. A generalized GDH sum rule[17] connects the GDH sum rule with the Bjorken sum rule and provides a clean way to test theories with experimental data over the entire $Q^2$ range. Spin sum rules relate the moments of the spin structure functions to the nucleon’s static properties (as in Bjorken or GDH sum rules) or real or virtual Compton amplitudes, which can be calculated theoretically (as in the generalized GDH sum rule or the forward spin polarizabilities). Refs. [5, 18] provide comprehensive reviews on this subject.

1.5 Quark-hadron duality in spin structure functions

Quark-hadron duality was first observed for the spin-independent structure function $F_2$. In 1970, Bloom and Gilman[19] noted the nucleon resonance data averaged follows the DIS scaling curve. Recent precision data[20] confirm quark-hadron duality in the unpolarized proton structure function. Efforts are ongoing to investigate quark-hadron duality in polarized structure functions[21]. It was predicted that in the high-x region at high enough $Q^2$, the resonances will have a similar behavior as the DIS. Results from HERMES[22] and CLAS[32] show the proton spin structure function $g_1^p$ approaching duality. The study of quark-hadron duality will aid in the study of the higher-twist effects and the high-x behavior in DIS.

2 Recent results from Jefferson Lab

The Thomas Jefferson National Accelerator Facility (Jefferson Lab, or JLab, formerly known as CEBAF - Continuous Electron Beam Accelerator Facility) is located in Newport News,
Virginia, USA. The accelerator produces a continuous-wave electron beam of energy up to 6 GeV. An energy upgrade to 12 GeV is planned in the next few years. The electron beam with a current of up to 180 μA is polarized up to 85% by illuminating a strained GaAs cathode with polarized laser light. The electron beam is deflected to three experimental halls (Halls A, B and C) where electron beam can be scattered off various nuclear targets. The scattered electrons and knocked out particles are detected in the halls with various spectrometer detector packages. The experiments reported here are from inclusive electron scattering where only the scattered electrons are detected. The neutron results presented here are from Hall A[24] where there are two High Resolution Spectrometers (HRS) with momentum up to 4 GeV/c. A polarized $^3$He target[25], with in-beam polarization of about 40%, provides an effective polarized neutron target. The polarized luminosity reached is $10^{36}$ s$^{-1}$ cm$^{-2}$. The detector package consists of vertical drift chambers (for momentum analysis and vertex reconstruction), scintillation counters (data acquisition trigger) and Čerenkov counters and lead-glass calorimeters (for particle identification (PID)). The π$^-$ were sorted from e$^-$ with an efficiency better than 99.9%. Both HRS spectrometers were used to double the statistics and constrain the systematic uncertainties by comparing the cross sections extracted using each HRS. The proton and deuterium results are from Hall B[26], where there is the CEBAF Large Acceptance Spectrometer (CLAS) and Hall C[27], where there are the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS). Polarized solid $NH_3$ and $ND_3$ targets[28] using dynamical nuclear polarization were used. Polarizations up to 70% for $NH_3$ and up to 30% for $ND_3$ were achieved.

2.1 Precision measurements of $A_1$ at high-\(x\)

In 2001, JLab experiment E99-117[3] was carried out in Hall A to measure $A_1^n$ with high precision in the \(x\) region from 0.33 to 0.61 ($Q^2$ from 2.7 to 4.8 GeV$^2$). Asymmetries from inclusive scattering of a highly polarized 5.7 GeV electron beam on a high pressure (> 10 atm) (both longitudinally and transversely) polarized $^3$He target were measured. Parallel and perpendicular asymmetries were extracted for $^3$He. After taking into account the beam and target polarizations and the dilution factor, they were combined to form $A_1^{3He}$. Using the most recent model[29], nuclear corrections were applied to extract $A_1^n$. The results on $A_1^n$ are shown in the left panel of Fig. 1.

The experiment greatly improved the precision of data in the high-\(x\) region, providing the first evidence that $A_1^n$ becomes positive at large \(x\), showing clear SU(6) symmetry breaking. The results are in good agreement with the LSS 2001 pQCD fit to previous world data[30] (solid curve) and the statistical model[31] (long-dashed curve). The trend of the data is consistent with the RCQM[10] predictions (the shaded band). The data disagree with the predictions from the leading-order pQCD models[11] (short-dashed and dash-dotted curves). These data provide crucial input for the global fits to the world data to extract the polarized parton distribution functions and the extractions of higher-twist effects.

In the leading-order approximation, the polarized quark distribution functions $\Delta u/u$ and $\Delta d/d$ were extracted from our neutron data combined with the world proton data. The results are shown in the right panel of Fig. 1, along with predictions from the RCQM (dot-dashed curves), leading-order pQCD (short-dashed curves), the LSS 2001 fits (solid curves) and the statistical model (long-dashed curves). The results agree well with RCQM predictions as well as the LSS 2001 fits and statistical model but $\Delta d/d$ is in significant disagreement with the predictions from leading-order pQCD models assuming hadron helicity.
conservation. This suggests that effects beyond leading-order pQCD, such as the quark orbital angular momentum, may play an important role in this kinematic region.

2.2 Measurements of $A_1^p$ and $A_1^d$ in the high $x$ region

Preliminary results of $A_1^p$ and $A_1^d$ from the Hall B $eg1$ experiment[32] have recently become available. The data cover the $Q^2$ range of 1.4 to 4.5 GeV$^2$ for $x$ from 0.2 to 0.6 with an invariant mass larger than 2 GeV. Data in the resonance region are also available. The precision of the data improved significantly over that of the existing world data.

2.3 Precision $g_2$ and $d_2$ measurements and higher twist effects

A precision measurement of $g_2^n$ from JLab Hall A E97-103[4] covered five different $Q^2$ values from 0.58 to 1.36 GeV$^2$ at $x \approx 0.2$. Results for $g_2^n$ are given in the left panel of Fig. 2. The light-shaded area in the plot gives the leading-twist contribution, obtained by fitting world data[34] and evolving to the $Q^2$ values of this experiment. The systematic errors are shown as the dark-shaded area near the horizontal axis.

The precision reached is more than an order of magnitude improvement over that of the best world data[33]. The difference of $g_2$ from the leading twist part ($g_2^{WW}$)[13] is due to higher-twist effects and is sensitive to quark-gluon correlations. The measured $g_2^n$ values are consistently higher than $g_2^{WW}$. For the first time, there is a clear indication that higher-twist effects become significantly positive at $Q^2$ below 1 GeV$^2$, while the bag model[35] and Chiral Soliton model[36, 37] predictions of higher-twist effects are negative or close to zero. The $g_1^n$ data obtained from the same experiment agree with the leading-twist calculations within
the uncertainties.

The second moment of the spin structure function $d_2$ is of special interest: at high $Q^2$, it is a twist-3 matrix element and can be calculated in lattice QCD. Experimentally, due to $x^2$ weighting, the contributions are dominated by the high-$x$ region and the problem of low-$x$ extrapolation is avoided. The Hall A experiment E99-117 also provide data on $A_2^\pi$ at high-$x$. The precision of the $A_2^\pi$ data is comparable to that of the best existing world data[33] at high $x$. Combining these results with the world data, the second moment $d_2^n$ was extracted at an average $Q^2$ of 5 GeV$^2$. Compared to the previously published result[33], the uncertainty on $d_2^n$ has been improved by about a factor of 2. The $d_2$ moment at high $Q^2$ has been calculated by Lattice QCD[38] and a number of theoretical models. While a negative or near-zero value was predicted by Lattice QCD and most models, the new result for $d_2^n$ is positive. Also shown in Fig. 2 are the low $Q^2$ (0.1-1 GeV$^2$) results of the inelastic part of $d_2^n$ from another Hall A experiment E94-010[6], which were compared with a Chiral Perturbation Theory calculation[39] and a model prediction[40]. Detail of the experiment E94-010 and comparison with ChPT and model will be discussed below.

2.4 Precision measurements of Moments and sum rules of spin structure functions

JLab E94-010[6] in Hall A measured the generalized GDH sum and the moments of the neutron spin structure functions $\Gamma_1$ and $\Gamma_2$ in the low to intermediate $Q^2$ range. The measurement of doubly-polarized inclusive cross sections was performed at five beam energies from 0.86 to 5.1 GeV at a scattering angle of 15.5°. Parallel and perpendicular cross-section differences were obtained, from which $g_1$, $g_2$, $\sigma_{PT}$ and $\sigma_{LT}$ for $^3$He were extracted. Interpolation to constant $Q^2$ values was performed and the GDH integrals were formed from pion threshold to $W^2 = 4$ GeV$^2$. Finally, nuclear corrections[41] were applied to extract the GDH integral for the neutron. The results are shown in the left-top panel of Fig. 3. The higher energy contributions (for $W^2$ from 4 to 1000 GeV$^2$) were estimated using the parameterization of Thomas and Bianchi[42].

These data show a smooth but dramatic change in the value of the generalized GDH sum from what was observed at high $Q^2$. While not unexpected from phenomenological models, these data illustrate the sensitivity to the transition from partonic to hadronic behavior. The measured values of the first moment of $g_1^n$ are shown in the left-middle panel of Fig. 3, along
with the world data from SLAC and HERMES. Also shown are Chiral Perturbation Theory calculations and several model predictions. These data provide a precision data base for a twist expansion analysis at the higher end of the $Q^2$ range, a check for Chiral Perturbation Theory (ChPT) calculations[39] at the low end of the $Q^2$ range, and establish an important benchmark against which one can compare future calculations (such as Lattice Gauge Theory calculations). The measured values of the first moment of $g_2^p$ are shown in the left-bottom panel of Fig. 3. These results indicate the first validation of the Burkhardt-Cottingham sum rule[43], $\Gamma_2 = 0$. Also shown in the right-bottom panel is the Bjorken sum[7], the first moment of $g_2^p - g_1^n$, which were extracted from the E94-010 neutron data and the CLAS proton and deuteron results.

Higher ($x^2$ weighted) moments of the spin structure functions are related to the generalized forward spin polarizabilities $\gamma_0$ and $\delta_{LT}[6]$. The right panels of Fig. 3 show the E94-010 results on $\gamma_0$ and $\delta_{LT}$, and the comparison with the ChPT calculations and MAID model[40] predictions. The relativistic baryon ChPT with resonance shows a good agreement with the data for $\gamma_0$ at $Q^2 = 0.1$ GeV$^2$. However, ChPT calculations deviate significantly from the data for $\delta_{LT}$, which was expected to be an excellent candidate to check Chiral dynamics of QCD since it was not sensitive to the dominating resonance ($\Delta$) contributions. This disagreement presents a real challenge to theorists.

New experiments[44, 45] will extend the generalized GDH sum measurements to very low $Q^2$ (down to $Q^2 = 0.01$ GeV$^2$), below the turn-around point predicted by calculations (at $Q^2 \approx 0.1$ GeV$^2$). ChPT calculations will be extensively tested at low $Q^2$ where they are expected to be applicable. Extrapolation to the real photon point provides an alternative way to test the original GDH sum rule. Data taking was completed for the neutron in Hall A in the summer of 2003. Analysis is underway. Data taking is planned in 2006 for the proton experiment in Hall B.

2.5 Preliminary results of spin structure functions for Quark-hadron duality study

JLab E01-012[8] ran successfully in early 2003 in Hall A. Asymmetries and cross sections were measured in the resonance region, for $Q^2$ range from 1 to 3.6 GeV$^2$, for inclusive scattering of polarized electrons on a longitudinally and transversely polarized $^3$He target. The spin structure function $g_1$ and virtual photon asymmetry $A_1$ were extracted. The preliminary results for $A_1^{^3\text{He}}$ are presented in Fig. 4. Work is ongoing to extract the neutron results. These results, combined with the DIS results[3], will provide a test of quark-hadron duality in the neutron spin structure functions.

Preliminary results have also become available from the JLab Hall C experiment E01-006 [9] on the proton spin structure in the resonance region. These data, combined with the world DIS data, will help study quark-hadron duality in the proton spin structure function.

3 summary

In summary, the high polarized luminosity available at JLab has provided us with high-precision data to study the nucleon spin structure in a wide kinematic range. They shed light on the valence quark structure and helped to understand quark-gluon correlations and study the transition between perturbative and non-perturbative regions of QCD.
Figure 3: Comparisons of JLab E94-010 neutron results and the Bjorken sum (proton-neutron) results, which are extracted from E94-010 and CLAS data, with world data, ChPT calculations and model calculations. The bands above the zero axes are the systematic uncertainties. The band below the zero axis on left-bottom panel shows the estimated uncertainties from low-$x$ extrapolation.
Figure 4: Results for $A_1^{^3He}$ from JLab Hall A E01-012. Also plotted are $^3$He DIS data from E99-117 and SLAC.

The work presented was supported in part by the U. S. Department of Energy (DOE) contract DE-AC05-84ER40150 Modification NO. M175, under which the Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility.

References

[27] http://www.jlab.org/HallC/