Latest Results on $g_1$ and $g_2$ at high $x$

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Abstract. Recent progress from Jefferson Lab has significantly improved our understanding of the nucleon spin structure in the high-$x$ region. Results of a precision measurement of the neutron spin asymmetry, $A_n^1$, in the high-$x$ (valence quark) region are discussed. The up and down quark spin distributions in the nucleon were extracted. $A_n^2$ was also measured in the same experiment. The results were used, in combination with existing data, to extract the second moment of the spin structure function $d_n^2$. Preliminary results on $A_p^1$ and $A_d^1$ in the high-$x$ region have also become available. Finally, the results of a precision measurement of the $g_2$ structure function to study higher twist effects will be presented.

Keywords: Spin Structure, high x, higher twist, JLab

PACS: 13.60.Hb

Introduction and Motivation

Recently, the high polarized luminosity available at Jefferson Lab (JLab) has allowed the study of the nucleon spin structure with an unprecedented precision, enabling us to access the hard-to-reach valence quark (high-$x$) region and also to expand the study to the second spin structure function, $g_2$.

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 [1] should be applicable in this region and perturbative QCD [2] can be used to make predictions in the large $x$ ($x \to 1$) limit. The spin asymmetry $A_n^1$ in the high-$x$ region was measured, with high precision, in JLab experiment E99-117. Polarized quark distributions were extracted. The spin asymmetries $A_p^1$ and $A_d^1$ in the high-$x$ region were measured in JLab eg1 experiment. The precision $g_2$ measurement from JLab E97-103, provides a clean access to higher twist effects and helps shed light on quark-gluon correlations.

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 $g_1$ gives the quark spin distribution. Another physics quantity of interest is the virtual photon-nucleon asymmetry $A_1$

$$A_1 = \frac{g_1 - (Q^2/v^2)g_2}{F_1} \approx \frac{g_1}{F_1}. \quad (1)$$
To first approximation, the constituent quarks in the nucleon are described by the SU(6) wavefunctions. SU(6) symmetry leads to the following predictions:

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

(2)

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

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

(3)

In the RCQM, relativistic effects take into account the quark orbital angular momentum and reduce the valence quark contributions to the nucleon spin from 1 to about \( 0.6 - 0.75 \).

Another approach is with leading-order pQCD [2], which assumes the quark orbital angular momentum to be negligible and leads to hadron helicity conservation. It yields the same limiting values for \( A_1^p \) and \( A_1^n \) as previously, but different limiting values for \( \Delta u/u \) and \( \Delta d/d \):

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

(4)

Not only are the limiting values at \( x \to 1 \) important, but also the behavior in the high-\( x \) region. How \( A_1^p \) and \( A_1^n \) approach their limiting values when \( x \) approaches 1, is sensitive to the dynamics in the valence quark region.

The structure function \( g_2 \), unlike \( g_1 \) and \( F_1 \), cannot be easily interpreted in the simple QPM. To understand \( g_2 \) properly, it is best to start with the operator product expansion method (OPE) [3]. In the OPE, neglecting quark masses, \( g_2 \) can be cleanly separated into a leading-twist (twist-2) and a higher-twist (twist-3 and higher) term:

\[ g_2(x, Q^2) = g_2^{WW}(x, Q^2) + g_2^{H.T.}(x, Q^2). \]  

(5)

The leading-twist term can be determined from \( g_1 \) as [4]

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

(6)

and the higher-twist term arises from the quark-gluon correlations. Therefore \( g_2 \) provides a clean way to study higher-twist effects. In addition, the \( x^2 \)-weighted moment is the twist-3 matrix element, which is related to the color polarizabilities [5]:

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

(7)

Predictions for \( d_2 \) exist from various models and lattice QCD.

**Recent results from Jefferson Lab**

In 2001, JLab experiment E99-117 [6] 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 \(^3\text{He}\) target were measured. Parallel and perpendicular asymmetries were extracted for \(^3\text{He}\). After taking into account the beam and target polarization and the dilution factor, they were combined to form \(A_{1}^{3\text{He}}\). Using the most recent model [7], 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 [8] (solid curve) and the statistical model [9] (long-dashed curve). The trend of the data is consistent with the RCQM predictions (the shaded band). The data disagree with the predictions from the leading-order pQCD models (short-dashed and dash-dotted curves).

\[
\begin{align*}
A_{1}^{n} \quad \Delta u/u \quad \Delta d/d \\
\text{This work}(^{3}\text{He}) & \quad \epsilon 142 & \quad \epsilon 154 & \quad \text{HERMES} \\
\text{LSS 2001} & \quad \text{RCQM} & \quad \text{Statistical} & \quad \text{LSS(HBS)}
\end{align*}
\]

Fig. 1: \(A_{1}^{n}\), \(\Delta u/u\) and \(\Delta d/d\) results compared with the world data and theoretical predictions.

Assuming that the strange sea quark contributions are negligible in the region \(x > 0.3\), 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 models but are in significant disagreement with the predictions from the 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.

\(A_{2}^{n}\) was also obtained from the same experiment. The precision of the \(A_{2}^{n}\) data is
comparable to that of the best existing world data [10] 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$^2$:

$$d_2^n = 0.0062 \pm 0.0028.$$  \hspace{1cm} (8)

Compared to the previously published result [10], 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 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.

Preliminary results of $A_1^p$ and $A_1^d$ from the Hall B eg1 experiment [11] 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. The precision of the data improved significantly over that of the existing world data.

A precision measurement of $g_2^n$ from JLab E97-103 [12] covered five different $Q^2$ values from 0.58 to 1.36 GeV$^2$ at $x \approx 0.2$. Results for $g_2^n$ as well as $g_1^n$ from E97-103 are given in Fig. 2. The light-shaded area in the two plots gives the leading-twist contribution to these two quantities, respectively, obtained by fitting world data and evolving to the $Q^2$ values of this experiment. The systematic errors are shown as the dark-shaded area at the horizontal axes.

$$\text{FIGURE 1.}$$ Fig. 1: results for $g_1^n$ (left) and $g_2^n$ (right) from E97103.

The precision reached is more than an order of magnitude improvement over that of the best world data. The difference of $g_2$ from the leading twist part ($g_2^{WW}$)\cite{4} is due to higher twist effects and is sensitive to quark-gluon correlations. The $g_2^{WW}$ values were obtained from a fit \cite{13} to the world high $Q^2$ data, then evolved to the $Q^2$ values of this experiment. 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 important at the level of precision of these data. The new $g_1^n$ data agree with the leading-twist calculations within the uncertainties.

In summary, the high polarized luminosity available at JLab, has provided high-precision data to study the nucleon spin structure in the high-$x$ region and higher twist effects, which shed light on the valence quark structure and help to understand quark-gluon correlations.
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.

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