THE SEARCH FOR HIGHER TWIST EFFECTS IN THE SPIN-STRUCTURE FUNCTIONS OF THE NEUTRON

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(FOR THE JEFFERSON LAB E97-103 COLLABORATION)

Jefferson Lab experiment E97-103 measured the spin structure function g_2^n from a Q^2 of 0.58 to 1.36 with a nearly constant x of 0.2. Combining this data with a fit to the world g_1^n data, the size of higher twist contributions to g_2^n can be extracted using the Wandzura-Wilczek relation. These higher twist contributions result from quark-gluon correlations and are expected to be larger as Q^2 decreases. This experiment was performed in Hall A with a longitudinally polarized electron beam and a high density polarized ^{3}He target. The physics motivation and an overview of the experiment will be presented.

1. Introduction

1.1. *The Spin Dependent Structure Functions*

A virtual photon exchange process in inclusive deep inelastic scattering can be characterized by the differential cross-section:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu} \tag{1}$$

where $\frac{d^2\sigma}{d\Omega dE'}$ is the differential cross-section, α is the fine structure constant, $L_{\mu\nu}$ is the lepton vertex and $W_{\mu\nu}$ is the nucleon vertex. While the lepton vertex can be calculated exactly using QED, the nucleon vertex uses structure functions to summarize the QCD structure of the nucleon.

The nucleon vertex can be seperated into spin-independent and spin-dependent parts. The spin-dependent parts, being the ones of interest to this experiment, can be written as follows:

$$W^A_{\mu\nu} = \frac{\epsilon_{\mu\nu\lambda\sigma}q^\lambda S^\sigma}{M\nu}g_1(x,Q^2) + \frac{\epsilon_{\mu\nu\lambda\sigma}q^\lambda\left(M\nu S^\sigma - q\cdot Sp^\sigma\right)}{M^2\nu^2}g_2(x,Q^2) \tag{2}$$

where M is the nucleon mass, S^μ is the nucleon polarization vector, p_μ is the ingoing nucleon momentum, q_μ is the ingoing electron momentum, ν is the energy transfer and Q^2 is the four-momentum transfer squared. $g_1(x,Q^2)$ and $g_2(x,Q^2)$ are the spin dependent structure functions of the nucleon, each depending only on x and Q^2.

These structure functions can be isolated by different combinations of the cross-section as shown in these equations:

$$\frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 EM\nu}\left[(E+E'\cos\theta)g_1(x,Q^2) - 2xMg_2(x,Q^2)\right] \quad (3)$$

$$\frac{d^2\sigma^{\downarrow\Leftarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Leftarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 EM\nu}E'\sin\theta\left[g_1(x,Q^2) - \frac{2xEM}{Q^2}g_2(x,Q^2)\right] \quad (4)$$

where the single line arrows, $\uparrow$ and $\downarrow$, refer to postive and negative beam helicity and the double line arrows, $\Uparrow$ and $\Downarrow$, refer to the target polarization being either pointing along the direction of positive beam helicity or opposing it. The $\Leftarrow$ symbol refers to a target polarization perpendicular to the beam.

1.2. *The Operator Product Expansion*

The nucleon vertex can also be written in terms of vector currents as shown here:

$$W_{\mu\nu}(q,p,S) = \frac{1}{4\pi}\int d^4\xi e^{iq\cdot\xi}\langle pS|\left[J_\mu(\xi), J_\nu(0)\right]|pS\rangle \quad (5)$$

In pQCD, the vector current terms $J_\mu(z)J_\nu(0)$ can be expanded in a power series in $\frac{1}{Q}$ (known as the operator product expansion). The moments of hadronic structure functions can be expressed as:

$$\int_1^{-1} x^{n-1}W(Q^2,x)dx = \frac{1}{4}\sum_{\tau=2}^{\infty}\bar{C}_n^\tau(Q^2,\mu^2)\bar{\mathcal{O}}_n^\tau(\mu^2)\left(\frac{1}{Q^2}\right)^{\frac{\tau}{2}-1} \quad (6)$$

where τ is the order of the twist.

If one applies this expansion to $g_1(x,Q^2)$ and $g_2(x,Q^2)$ and limits the expansion to the twist-2 and twist-3 operators then we get:

$$\int_0^1 x^n g_1(x,Q^2)dx = \frac{1}{4}\bar{\mathcal{O}}_n^{\{2\}} = \frac{1}{4}a_n \quad (7)$$

$$\int_0^1 x^n g_2(x,Q^2)dx = \frac{1}{4}\frac{n}{n+1}(\bar{\mathcal{O}}_n^{\{3\}} - \bar{\mathcal{O}}_n^{\{2\}}) = \frac{1}{4}\frac{n}{n+1}(d_n - a_n) \quad (8)$$

where n is the set of even integers starting at 2. Notice that g_1 does not contain the twist-3 operator and that the twist-2 term is the same in both g_1 and g_2. This is what allows E97-103 to extract the higher twist effects.

1.3. *The Wandzura-Wilczek Relation*

In their 1977 paper [5], Wandzura and Wilczek postulated if the twist-3 term is small ($\bar{\mathcal{O}}_n^{\{3\}} = 0$) then g_2 can be written :

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dx'}{x'} g_1(x', Q^2) \tag{9}$$

where g_2^{WW}, the leading twist part of $g_2(x, Q^2)$, is completely determined by the twist-2 part of $g_1(x, Q^2)$. Therefore, g_2 can be seperated into two functions:

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2) \tag{10}$$

where $\bar{g}_2(x, Q^2)$ is expected to be dominated by the twist-3 term [1] . The Wandzura-Wilczek relation, as it is known, presents a method of isolating higher twist contributions to $g_2(x, Q^2)$: measure $g_2(x, Q^2)$ precisely, use the world data on g_1 to calculate $g_2^{WW}(x, Q^2)$ and the difference will be from $\bar{g}_2(x, Q^2)$.

2. Measuring Spin Structure Functions

2.1. *Extracting spin structure functions*

To extract g_2 one measures the cross-section asymmetry with change in beam helicity or target polarization direction. There are two methods of analyzing the data taken in this method. The first is to measure the cross-section difference divided by the unpolarized cross-section, known as the raw asymmetry, which reduces to the following formulas:

$$A_\parallel = \frac{1}{fP_bP_t} \frac{(N/Q)^{\downarrow\Uparrow} - (N/Q)^{\uparrow\Uparrow}}{(N/Q)^{\downarrow\Uparrow} + (N/Q)^{\uparrow\Uparrow}} \tag{11}$$

$$A_\perp = \frac{1}{fP_bP_t} \frac{(N/Q)^{\downarrow\Leftarrow} - (N/Q)^{\uparrow\Leftarrow}}{(N/Q)^{\downarrow\Leftarrow} + (N/Q)^{\uparrow\Leftarrow}} \tag{12}$$

where $A_\parallel$ is the raw parallel asymmetry, $A_\perp$ is the raw perpendicular asymmetry, N is the number of electrons detected within the selected kinematic range, Q is the amount of charge delivered to the target with a particular helicity, f is the dilution factor of the target, P_b is the beam polarization and P_t is the target polarization. These raw asymmetries can then be used to calculate g_1 and g_2 by the following formulas:

$$g_1(x, Q^2) = \frac{F_1(x, Q^2)}{D'} \left[A_\parallel + A_\perp \tan\theta/2\right] \tag{13}$$

$$g_2(x,Q^2) = \frac{F_1(x,Q^2)}{D'}\frac{y}{2\sin\theta}\left[A_\perp\frac{E+E'\cos\theta}{E'} - A_\parallel\sin\theta\right] \tag{14}$$

$$D' = \frac{(1-\epsilon)(2-y)}{y(1+\epsilon R(x,Q^2))} \tag{15}$$

$$\epsilon = 1/[1+2(1+\nu^2/Q^2)\tan^2\theta/2] \tag{16}$$

$$y = \nu/E \tag{17}$$

Calculating $g_2(x,Q^2)$ in this manner requires knowledge of $R(x,Q^2)$ and $F_1(x,Q^2)$, both of which can be found in the literature.

The second method simply calculates the unnormalized cross-section featured in equations (3) and (4). This method requires detailed knowledge of the acceptance and detector inefficiencies, but does not depend on knowing $F_1(x,Q^2)$ or $R(x,Q^2)$. The two methods provide a good cross-check of systematic uncertainties.

2.2. *Radiative Corrections*

Radiative corrections are made to the measured asymmetries directly. Most of the error from radiative corrections will come from knowledge of the structure functions F_2, g_1, g_2 and R from the world data.

2.3. *Correcting for an effective neutron target*

Since there is no practical polarized neutron target, E97-103 uses a polarized ^{3}He as an effective neutron target. To extract the neutron asymmetries, a model including the S,S',D states and the pre-existing Δ (1232) components in ^{3}He ground state wavefunction has been used [2]. The formula derived from this model, for the leading twist part, is:

$$g_2 = \frac{1}{P_n(1+\frac{0.056}{P_n})}\left[g_2^{^3\mathrm{He}} - 2P_p g_2^p\left(1-\frac{0.014}{2P_p}\right)\right] \tag{18}$$

where P_n and P_p are the nucleon polarizations inside ^{3}He. g_2^p is from a calculation of $g_2^{p\ WW}$ using a fit to SLAC g_1^p data [4]. The data is calculated using values of $P_p = -0.028 \pm 0.004$ for the proton and $P_n = 0.86 \pm 0.02$ [3]. However, the extreme case of $P_n = 0.897$ [8] will also be used to study the uncertainty of the nuclear correction.

3. Running the experiment

E97-103 ran from August 1 to September 17th, 2001. In this time, we measured 5 kinematic points from $Q^2 = 0.58$ to $Q^2 = 1.36$ with $x = 0.2$. The

experiment used 10-12 microAmps of CW beam, at energies from 1.1 to 5.7 GeV and with polarizations of 70-80%. Two high-resolution spectrometers with standard electron detector packages measured the scattered electrons. Table 1 lists the specific kinematic settings.

Table 1. Kinematics for E97-103.

Q^2 (GeV/c)^2	x	W^2 (GeV/c)^2
0.579	0.17	3.82
0.956	0.20	4.43
0.796	0.18	4.83
1.138	0.20	5.57
1.358	0.21	6.03

The experiment used a polarized ^{3}He gas target. The ^{3}He gas is polarized by spin-exchange with optically polarized Rb. The target system consists of a glass cell which sits between two Helmholtz coils that provide a 25 Gauss field (another set of Helmholtz coils allows the target to be polarized in the perpendicular position). This glass cell has two chambers: one that is spherical and contains the rubidium vapor and the other which is cylindrical and is where the beam passes through. The cell is filled with roughly 8-10 atmospheres of ^{3}He at room temperature. The spherical chamber of the cell is placed in an oven 170 degrees and exposed to 90 watts of 795 nm circularly polarized laser light. It reached a maximum polarization of above 49% and an average polarization of 41%. Two target cells were used and both performed well.

4. Results

The statistical errors for each kinematic point are shown in Figure 4. The data are compared to a calculation of $g_2^n{}^{WW}$ from the E155 fit to g_1^n data [4] and two calculations of $g_2^n{}^{WW}$ using parton models evolved to our kinematics.

There have been two bag model calculations of g_2^n by X. Song [6] and M. Stratmann [7]. Both predict that the higher twist effects are large and that $g_2^n(x, Q^2)$ will be near zero or negative in our kinematic range. The achieved error bars will have the precision to make statements about g_2^n's relation to $g_2^n{}^{WW}$ and to the bag model predictions. The significance of the data will also depend on a meaningful value of $g_2^n{}^{WW}$ in this kinematic region, as the world g_1^n data is at higher Q^2. There are standard procedures for doing this that produce reasonable error bars for interpreting our data.

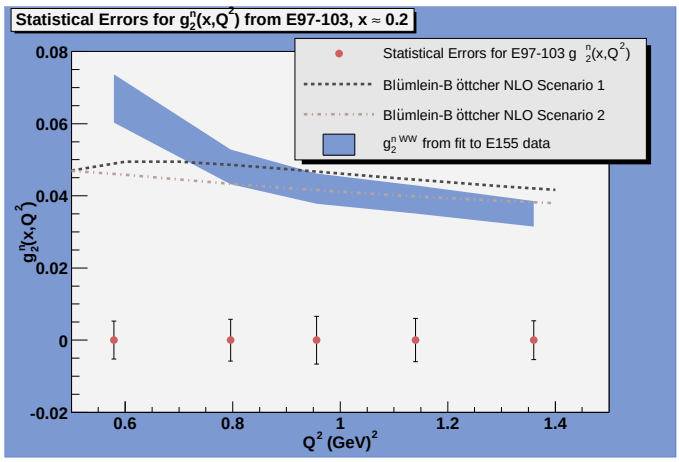

Figure 1. Statistical errors of E97-103. Presented with $g_2^{n\ WW}$ calculated using world data on g_1^n and two calculations of $g_2^{n\ WW}$ using two different parton models that are evolved down to our kinematics.

5. Summary

While the spin structure function g_1^n has been the focus of extensive experimental programs over the last decade there have been few dedicated experiments on g_2^n. While g_2^n doesn't have a simple quark-parton model interpretation, it contains important information about quark-gluon correlations in the nucleon. E97-103 measured g_2^n precisely at low Q^2 in a narrow x range. This data will provide information about the magnitude of higher twist effects in the spin structure functions and will be able to guide theorists in understanding the physics of the higher twist terms.

Acknowledgments

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