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Nucleon spin structure at Jefferson Lab

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Abstract. In the past decade an extensive experimental program to measure the spin structure of the nucleon has been carried out in the three halls at Jefferson Lab. Using a longitudinally polarized beam scattering off longitudinally or transversely polarized ^{3}He, NH_3 and ND_3 targets, the double spin asymmetries $A_{||}$ and $A_\perp$ were measured, providing data of impressively high precision that gives a better understanding of the structure of the nucleon in the deep inelastic scattering and the valence quarks regions. The virtual photon asymmetries $A_{1,2}$ and polarized structure functions $g_{1,2}$ were also extracted for the proton, neutron and deuteron over large kinematic ranges, allowing the extraction of first moments and the testing of sum rules and duality.

Keywords: Spin structure, Nucleon Spin
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INTRODUCTION

After the "spin crisis" in 1980, large experimental programs have been devoted to unraveling the spin structure of the nucleon. Inclusive inelastic scattering of polarized electrons off polarized nucleons is a powerful tool to study the polarized structure functions and their moments. For a longitudinally polarized beam the measured asymmetries are

$$A_{||} = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\downarrow\Uparrow}} \quad \text{and} \quad A_\perp = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}} \tag{1}$$

where $\sigma^{\uparrow\Uparrow}$ ($\sigma^{\uparrow\Downarrow}$) is the cross sections for beam and target polarization oriented parallel (antiparallel), and $\sigma^{\uparrow\Rightarrow}$ ($\sigma^{\downarrow\Rightarrow}$) is the cross section for a transversely polarized target with the electron spin aligned antiparallel (parallel) to the beam direction. The asymmetries $A_{||}$ and $A_\perp$ are related to the virtual photon asymmetries A_1 and A_2 by

$$\frac{A_{||}}{D} = A_1 + \eta A_2 \quad \text{and} \quad \frac{A_\perp}{d} = A_1 + \zeta A_2 \tag{2}$$

where $\eta = \varepsilon Q/(E - E'\varepsilon)$, $\zeta = \eta(1+\varepsilon)/(2\varepsilon)$, $D = (1 - E'\varepsilon/E)/(1+\varepsilon R)$, $d = D\sqrt{2\varepsilon/(1+\varepsilon)}$, $R = \sigma_L/\sigma_T$ is the ratio of longitudinal and transverse virtual photon-absorption cross sections, Q^2 is the squared 4-momentum transfer, and $\varepsilon = (1 + 2\frac{\vec{q}^2}{Q^2}\tan^2\frac{\theta_e}{2})^{-1}$ is the degree of transverse photon polarization. The asymmetry A_1 is related to the difference of virtual photo-absorption cross sections for total helicity between photon and nucleon of 1/2 and 3/2, while A_2 is related to the interference term between the transverse and longitudinal photon-nucleon amplitudes.

Given the virtual photon asymmetries, one can extract the spin structure function g_1 and g_2 using:

$$g_1(x,Q^2) = \frac{\tau}{1+\tau}(A_1 + \frac{1}{\sqrt{\tau}}A_2)F_1(x,Q^2) \quad \text{and} \quad g_2(x,Q^2) = \frac{\tau}{1+\tau}(-A_1 + \sqrt{\tau}A_2)F_1(x,Q^2) \tag{3}$$

where $\tau = \nu^2/Q^2$, ν is the energy transfer of the virtual photon, and F_1 is the unpolarized structure function. The spin structure function g_2 contains information about higher twists.

A quantity of particular interest is the first moment of g_1

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx. \tag{4}$$

At high Q^2, Γ_1^{p-n} is related to the spin carried by the quarks as stated by the Bjorken sum rule. For $Q^2 \to 0$ this quantity becomes $\frac{Q^2}{2M^2}I_{GDH}$, where I_{GDH} is the Gerasimov-Drell-Hearn sum rule and is equal to $-\kappa^2/4$, where κ is the nucleon anomalous magnetic moment.

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SELECTED RESULTS

The virtual photon asymmetry A_1 was measured in all three experimental Halls at Jefferson Lab in different kinematic ranges and for different nucleons. The Hall A experiment [1, 2] used the High Resolution Spectrometer (HRS) with a momentum resolution of 2x10^{-4} and a ^{3}He target, in which more than 87% of the spin is carried by the neutron, thereby providing an effective polarized neutron target. The target was oriented both longitudinally and transversely with respect to the direction of the beam, allowing the measurement of both $A_{||}$ and $A_{\perp}$. The result for A_1^n shows the first evidence of A_1^n becoming positive and large at high x, consistent with the relativistic constituent quark model (RCQM) predictions, the LSS 2001 perturbative quantum chromo-dynamics (PQCD) fit to previous data and a global NLO QCD analysis of deep inelastic scattering (DIS) data [1]. The Hall B experiment, known as the EG1 experiment [3, 4], used the CLAS detector, which gives a nearly 2π acceptance, achieving a kinematic coverage from 0.05 up to 5 GeV^2 in Q^2 and from 1.08 to 3 GeV in W. The targets were longitudinally polarized, solid, 1-cm-long, ammonia targets, $^{15}NH_3$ and $^{15}ND_3$, polarized up to 70% and 40% respectively via dynamic nuclear polarization [5]. Preliminary results are shown in Figure 1 for the virtual photon asymmetry A_1 for the proton (left) and deuterium (right) averaged in the deep inelastic region $Q^2 > 1$ GeV^2 and W >2 GeV. These preliminary results confirm the trend of A_1 to exceed the SU(6) limit at x=1 already found in [4]. At higher x, where the valence quarks are expected to dominate, data are most consistent with the hyperfine perturbed quark model [6], but also very close to other models that consider different scenarios of SU(6) symmetry breaking [7].

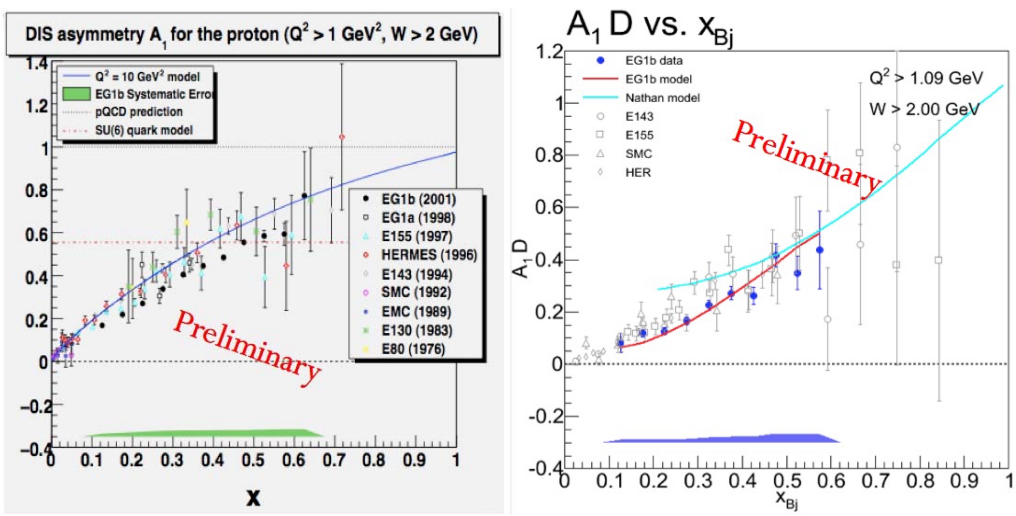

FIGURE 1. Virtual photon asymmetry A_1 vs. x for proton (left) and deuteron (right).

The structure function g_1 can be extracted from the virtual photon asymmetries using a parameterization of the world's data for the unpolarized structure function F_1. Figure 2 shows a sample of the results of the EG1 experiment for the deuterium polarized structure function g_1 for several Q^2 bins. Similar results were found for the proton. As can be seen at low Q^2 the $\Delta(1232)$ resonance drives the structure function towards negative values, due to dominance of the spin-3/2 amplitude. At higher Q^2, g_1 becomes positive everywhere.

The virtual photon asymmetry A_2 and the polarized structure function g_2 were measured both in Hall A [2] and Hall C [8] due to the ability of running there with a transversely polarized target. The RSS experiment in Hall C used the High Momentum Spectrometer and longitudinally and transversely polarized ammonia targets $^{15}NH_3$ and $^{15}ND_3$. The experiment focused on the resonance region $1.09 < W < 1.91$ GeV at an average Q^2 of 1.3 GeV^2. The structure function g_2 for the proton is clearly non-zero, providing strong evidence of higher-twist contributions as shown in Figure 3 [8].

The extensive kinematic range of these measurement allows the extraction of the first moments. Figure 4 shows the first moment of the structure function g_1 (see Eq. 4) for the proton using EG1 data. The world data parameterization was used to include the unmeasured part to the integral down to x =0.001. The low Q^2 data points are consistent with the I_{GDH} limit, and are in fairly good agreement with the phenomenological model by Burkert and Ioffe [9] that parameterizes the transition between the real photon point and the DIS regime using measured pion electro- and photo-production resonance amplitudes. The comparison of data at low Q^2 with the ChPT calculation of Ji (dashed

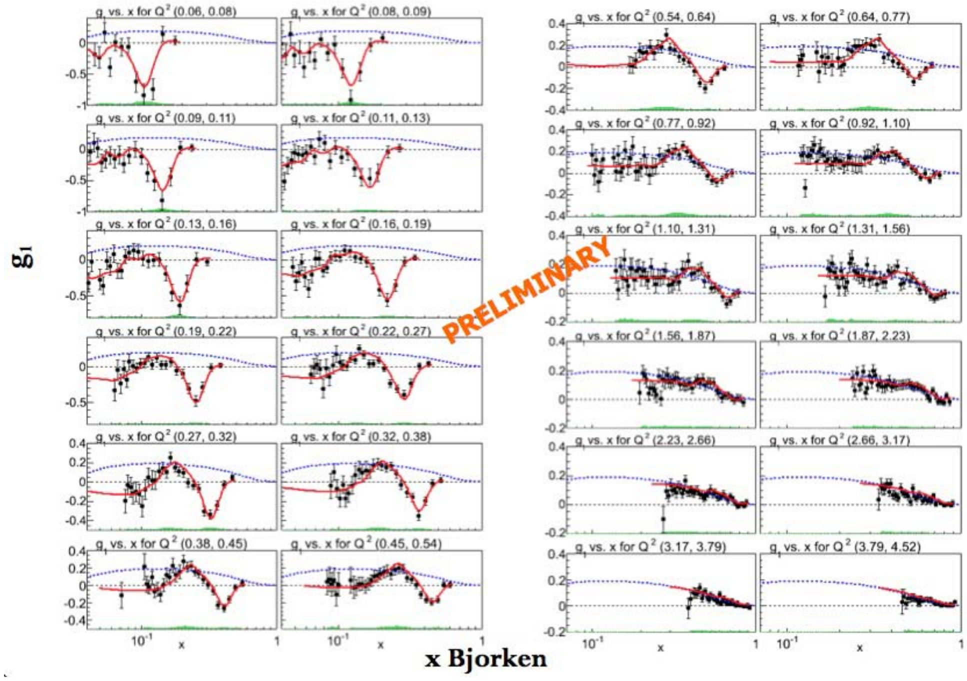

FIGURE 2. The structure function g_1 vs x for several Q^2 bins from 0.06 to 2.23 GeV^2.

curve) [10] shows a disagreement; however, this calculation is an expansion up to Q^4 and a fit of the data up to Q^8 shows agreement with Ji's Q^4 coefficient and a non negligible Q^6 term even at $Q^2 < 0.1\ \mathrm{GeV}^2$ [3]. The right panel of Figure 3 shows the first moment of the structure function g_1 for the neutron using Hall A data [11] including, the latest preliminary results at low Q^2, which are also in good agreement with the phenomenological model by Burkert and Ioffe.

The experimental program on the spin structure at Jefferson Lab has produced unprecedentedly precise measurements of the spin structure functions $A_{1,2}$, $g_{1,2}$, Γ_1 and related quantities for the proton, neutron and deuteron. New results are expected from more recent experiments such as the Hall B EG4 experiment and the Hall C SANE ex-

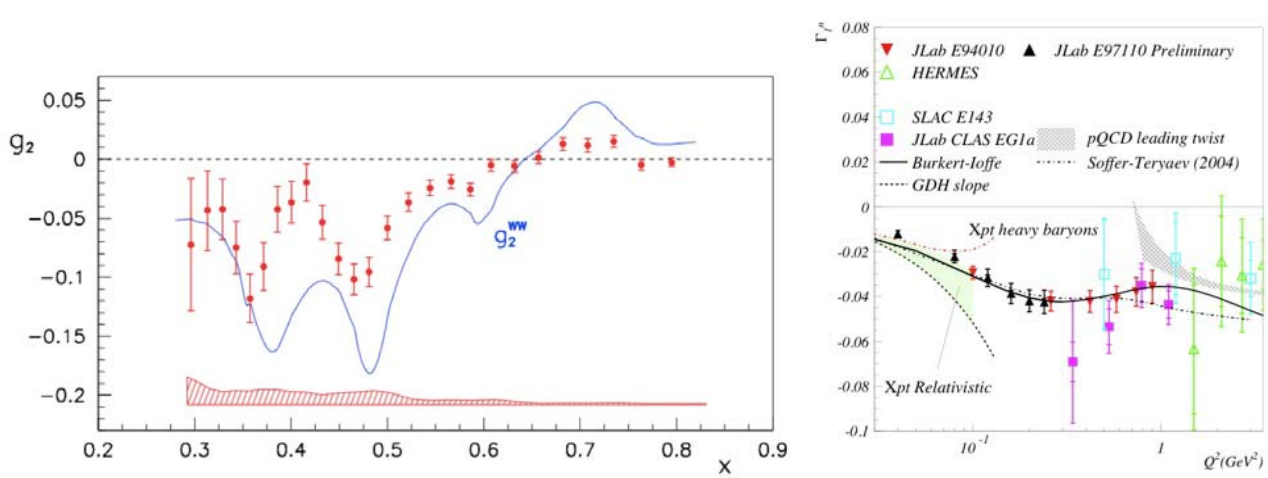

FIGURE 3. The structure function g_2 vs. x for proton (left) [8] and first moment of the structure function g_1 for the neutron using Hall A data [11] (right).

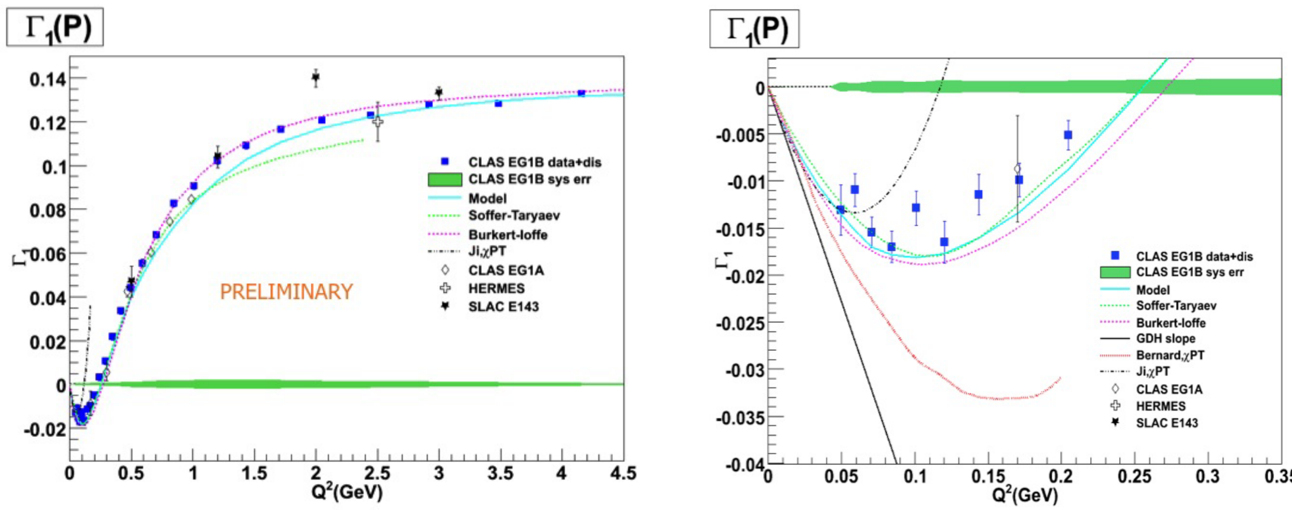

FIGURE 4. First moment of g_1 for the proton (Γ_1^p) vs Q^2. The left plot shows the full range in Q^2 while the right plot shows the lower Q^2 region. The figure shows the new preliminary data from EG1 (squares) and the previous EG1 (diamonds), HERMES (crosses) and SLAC E143 (stars) results. Phenomenological predictions (Burkert-Ioffe, Soffer-Teryaev, ChPT) and the GDH slope are also shown.

periment. The EG4 experiment, as a result of an additional Cherenkov counter placed at low angles, will extend the measurement of Γ_1 down to 0.015 GeV^2, allowing a better test of the ChPT calculations. The SANE experiment which uses the novel large solid angle electron telescope BETA detector will extract A_1 at high x, study the structure function g_1 and g_2 and twist 3 effects from their moments. In addition new experiments are planned for the 12 GeV upgrade of the accelerator. The higher energy and the improved detectors will increase the statistical precision of the current measurements, will extend the measurements to kinematic regions at the moment not accessible, such as high x, and will allow the extraction of fundamental quantities such as parton distribution functions.

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