Spin Structure Functions: A Window into the Structure of Hadrons

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Abstract. A large program of spin structure measurements is underway in Jefferson Lab’s Hall B. Of particular interest is the first moment of the spin structure function $g_1$, which goes through a rapid transition from the photon point ($Q^2 = 0$), where it is constrained by the Gerasimov-Drell-Hearn sum rule, to the deep inelastic limit where it is sensitive to the nucleon spin fraction carried by quarks. One can then study the transition from hadronic to quark degrees of freedom over the whole range of $Q^2$. It is also interesting to look for the onset of quark-hadron duality in spin structure functions. We use longitudinally polarized electrons with energies from 1.6 to 5.7 GeV incident upon polarized NH$_3$ and ND$_3$ targets to investigate proton and deuteron spin observables in and above the resonance region. We present the GDH and Bjorken integrals using the 1.6 and 5.7 GeV data and comment on the validity of local quark-hadron duality over the wide kinematical range ($0.05 \leq Q^2 \leq 4.5$ GeV$^2$ and $W < 3.2$ GeV) covered by this experiment.

Investigation of the structure of the nucleon using polarization observables continues to be of great interest to the hadronic physics community. At Jefferson Lab there is a comprehensive program of spin structure measurements underway in all three experimental halls. These experiments typically use longitudinally polarized electrons incident on longitudinally or transversely polarized targets to measure the spin structure functions $g_1$ and $g_2$, which are functions of the four-momentum transfer squared $Q^2$ and the quark momentum fraction $x = Q^2 / 2M\nu$, where $\nu$ is the energy of the virtual photon. Here we report on measurements in Hall B, collectively known as “EG1.”

There is particular interest in the first moment of $g_1$, $\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)dx$, which is constrained at low $Q^2$ by the Gerasimov-Drell-Hearn sum rule [1] and at high $Q^2$ by the Bjorken sum rule [2] and previous deep inelastic scattering (DIS) experiments. In our definition the upper limit of the integral does not include the elastic peak. Ji and Osborne [3] have shown that the GDH sum rule can be generalized to all $Q^2$ via

$$S_1(\nu = 0, Q^2) = \frac{8}{Q^2} \left[ \Gamma_1(Q^2) + \Gamma_1^{el}(Q^2) \right],$$

where $S_1(\nu, Q^2)$ is the spin-dependent virtual photon Compton amplitude. $S_1$ can be calculated in Chiral Perturbation Theory (χPT) at low $Q^2$ and with perturbative QCD (pQCD) at high $Q^2$. There is some hope that lattice QCD will one day be able to fill in the intermediate $Q^2$ range. In $\Gamma_1$ we have a calculable observable that spans the entire energy range from hadronic to partonic descriptions of the nucleon.
In the EG1 experiment we scatter longitudinally polarized electrons from longitudinally polarized proton (NH$_3$) and deuterium (ND$_3$) targets [4]. The beam was produced from a strained GaAs wafer and had an average polarization of 70% as measured by a Moller polarimeter. The proton polarization ranged from 70–90% and the deuteron polarization varied from 10–35%. Scattered electrons and other final state particles were detected in the Cebaf Large Acceptance Spectrometer (CLAS) in Hall B [5], which enabled us to take data over a wide kinematic range at one time.

All data (over 25 billion triggers) for EG1 have been taken in two runs, in 1998 (EG1a) and 2000–2001 (EG1b), with beam energies of 1.6, 2.4, 4.2 and 5.7 GeV. Inclusive results from the smaller EG1a data set have been published [6, 7]. The EG1b data set extends the kinematic coverage to both lower and higher $Q^2$ and higher $W$, and has significantly better statistical accuracy. Here we report on the analysis of the 1.6 and 5.7 GeV EG1b data. Our data include multi-particle final states, making it possible to investigate exclusive and semi-inclusive pion production, deeply virtual Compton scattering and other exclusive channels.

![Figure 1](image_url)

**Figure 1.** Preliminary data for $g_1(x, Q^2)$ taken with a beam energy of 1.6 GeV (left) and 5.7 GeV (right). The solid line is a parameterization of world data [8].

Preliminary results for the spin structure function $g_1(x, Q^2)$ at 1.6 and 5.7 GeV are shown in Figure 1. Similar data are available on the proton. At low momentum transfers the negative $\Delta(1232)$ resonance is quite prominent but it decreases steadily in strength as $Q^2$ increases. The higher mass resonances make a rapid transition from nearly zero to rather large positive values of $g_1$. The first moment of $g_1$ for the proton is shown in Figure 2. We see the integral turn over at low $Q^2$, consistent with the slope predicted by the GDH sum rule. In general the data are well described by a phenomenological model [9] which includes all resonances and a VMD-inspired transition to the DIS limit. After the 2.4 and 4.2 GeV data are analyzed, the intermediate $Q^2$ region will be covered with good precision.

$\Gamma_1$ at low $Q^2$ is especially interesting because $\chi$PT calculations should be valid there. The low $Q^2$ $\Gamma_1$ data are shown in more detail in the right-hand panel of Figure 2. Here one can see that the calculation of Ji et al. [13] is consistent with the data only at low $Q^2$. The fourth order (one-loop) $\chi$PT calculation by Bernard et al. [12] is also indicated; their calculation, which includes $\Delta$ and vector meson contributions, has large uncertainties which do include the data.
Figure 2. Preliminary results for $\Gamma_1$ for the entire range of $Q^2$ covered by EG1b (left) and for low $Q^2$ (right). The EG1a [7] and SLAC [10] data are shown as the solid red circles and green squares, respectively. The open blue circles represent the integral of the EG1b data over the measured kinematic region and the closed blue circles include an extrapolation over the unmeasured part of the $x$ spectrum using a model of world data. Phenomenological models by Burkert and Ioffe [9] and Soffer and Teryaev [11] are represented by solid and dashed lines, respectively. At low $Q^2$ $\chi$PT calculations from Bernard [12] and Ji [13] are shown as the pink and green lines, respectively. The dark shaded band indicates the systematical error.

Data have been taken in Hall A [14] and an experiment is planned for Hall B [15] to provide additional precise measurements in the low $Q^2$ region.

Another interesting topic that can be addressed with these data is that of duality. Bloom-Gilman duality [16] refers to the observation that nucleon resonances at low $Q^2$ average to the scaling curve measured in deep inelastic scattering. This phenomenon has recently been studied with high precision in the unpolarized $F_2$ structure function [17]. The presence of duality is related to the suppression of higher twist strength in structure function moments [18] and is therefore a tool for studying the structure of hadrons. We have looked for duality in the spin structure function $g_1$ and the results are shown in Figure 3. At low $Q^2$ the resonance data clearly do not average to the scaling curve represented by the solid line. This is to be expected since $g_1$ in the $\Delta(1232)$ resonance region is strongly negative at low $Q^2$ whereas the scaling curve is always positive. However, as $Q^2$ increases the influence of the $\Delta(1232)$ decreases and the data start to agree with the scaling curve. One can examine this effect quantitatively by taking the ratio of $g_1$, integrated over a given range in $W$, to the DIS scaling curve integrated over the same range. These ratios are shown in Figure 4 for the entire resonance region and for the first, second and third resonance regions individually. Duality holds when the ratio is 1, which is certainly not the case in the $\Delta(1232)$ region but is true down to fairly low $Q^2$ for the 2nd and third resonance region. Global duality in the entire resonance region seems to be valid above $Q^2 \approx 1.5$ GeV$^2$. The results for the deuteron are quite similar. The onset of duality in $g_1$ will be investigated in detail with the analysis of the 2.4 and 4.2 GeV data, which will greatly improve the precision of our data in the crucial intermediate $Q^2$ regime.

There are many other interesting topics that can be addressed with these data, including the behavior of $A_1$ at large $x$ $\Delta u/u$ and $\Delta d/d$ and higher twist effects. We will also extract
information about the spin structure of the neutron from the deuteron and proton data by working closely with theorists to understand nuclear and binding effects. Together with results from Halls A [19] and C [20] these new data should lead to an improved understanding of the spin structure of the nucleon in the transition to the scaling regime.

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