Neutron Spin Structure and the Extended GDH Sum Rule at Low Q^2

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I INTRODUCTION

Over the past several decades, the spin structure of the nucleon has been a topic of central interest in nuclear physics. The primary goal is to understand the origin of the nucleon spin in terms of its fundamental constituents, quarks and gluons. It is also reasonable to assume that at small Q^2, the quark-gluon picture will begin to fail and a hadron-like description will be needed. Understanding the transition from quark-like to hadron-like behavior is an important step in obtaining a complete description of the spin structure of the nucleon. In the recently completed Jefferson Lab experiment E94-010, spin-dependent cross sections for the reaction ${}^3\vec{H}e(\vec{e},e')$ were measured in the quasi-elastic, resonance, and into the deep-inelastic regions. Using these cross-sections, the extended Gerasimov-Drell-Hearn (GDH) sum was obtained as a function of Q^2 in the range 0.1-1.0 GeV^2. The Q^2 evolution of this sum rule allows us to study the spin structure of the neutron at low Q^2 in this transition region.

The Gerasimov-Drell-Hearn (GDH) sum rule [1] is derived at $Q^2 = 0$ using the low-energy theorem and dispersion relations for the forward Compton scattering amplitudes. It relates the integral of the spin dependent cross sections to the anomalous magnetic moment of the nucleon and is considered to be a theoretically solid prediction. The sum rule is expressed as follows,

$$\int_{\nu_{thr}}^{\infty} \left[\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right] \frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2 \tag{1}$$

where $\sigma_{1/2}$ and $\sigma_{3/2}$ are the spin-dependent cross sections for real photon absorption, with the total helicity of the photon-nucleon system indicated by the subscripts. The quantity κ is the anomalous magnetic moment of the nucleon and ν is the photon energy.

It is possible to extend the left-hand side of the GDH sum rule to the $Q^2 > 0$ region by replacing the real-photon cross sections with the corresponding transverse virtual photon cross sections, $\sigma^T_{1/2}$ and $\sigma^T_{3/2}$,

$$\int_{\nu_{thr}}^{\infty}\left[\sigma_{1/2}^{T}(\nu)-\sigma_{3/2}^{T}(\nu)\right]\frac{d\nu}{\nu}\equiv 2\int_{\nu_{thr}}^{\infty}\sigma^{TT}(\nu)\frac{d\nu}{\nu} \tag{2}$$

However, it is not possible to rigorously extend the right hand side of equation 1 in this case. At best, phenomenological models for the virtual photon cross sections can be used to predict the behavior of the integral, which must match the GDH sum rule prediction at $Q^2=0$.

Recently, Ji and Osborne [2] were able to obtain a sum rule that is valid at all Q^2 and which reduces to the GDH sum rule at the real photon point,

$$\int_{\nu_{el}}^{\infty}\frac{G_1(\nu,Q^2)}{\nu}d\nu=\frac{S_1(Q^2)}{4} \tag{3}$$

In the above expression, $G_1(\nu,Q^2)$ is one of the nucleon spin structure functions, and is measurable experimentally. The term $S_1(Q^2)$ is the forward virtual Compton scattering amplitude. At large and intermediate Q^2, twist expansions and lattice QCD can be used to calculate $S_1(Q^2)$, and at low Q^2, where hadronic degrees of freedom dominate, Chiral Perturbation Theory can be applied.

One remarkable feature of this extended sum rule is that as $Q^2\rightarrow\infty$, equation 3 reduces to the fundamental Bjorken sum rule [3] (for the case of proton minus neutron):

$$\int_{0}^{1}\left[g_1^p(x)-g_1^n(x)\right]dx=\frac{1}{6}g_A \tag{4}$$

where $g_1^{p,n}(x)$ are the proton and neutron deep-inelastic spin structure functions, and g_A is the axial coupling constant. It is important to note that Ji and Osbourne's extended GDH sum rule provides a theoretically rigorous tool for studying the spin structure of the nucleon that is valid from $Q^2=0$ to $Q^2=\infty$. It is particularly useful for studying the dynamics of the nucleon spin at low Q^2 where a clear theoretical picture does not exist.

II EXPERIMENT E94-010

In experiment E94-010, electrons with longitudinal polarization of 70% were scattered from ^{3}He which was either longitudinally or transversely polarized with respect to the incoming electron momentum. Data was collected at six different beam energies, $E_{beam}=0.86, 1.7, 2.6, 3.4, 4.3$, and 5.1 GeV, and the scattered electrons were detected (inclusively) in one of two magnetic spectrometers. The spectrometers were located on either side of the beam line at a scattering angle of $\theta=15.5°$. The experiment took place in Hall A at Jefferson Lab and the complete kinematic coverage is shown in Figure 1.

The ^{3}He nuclei were polarized by spin exchange collisions with atomically polarized Rubidium atoms in a two-chambered glass target cell. Rubidium was contained in the upper chamber and polarized by the technique of optical pumping. Laser

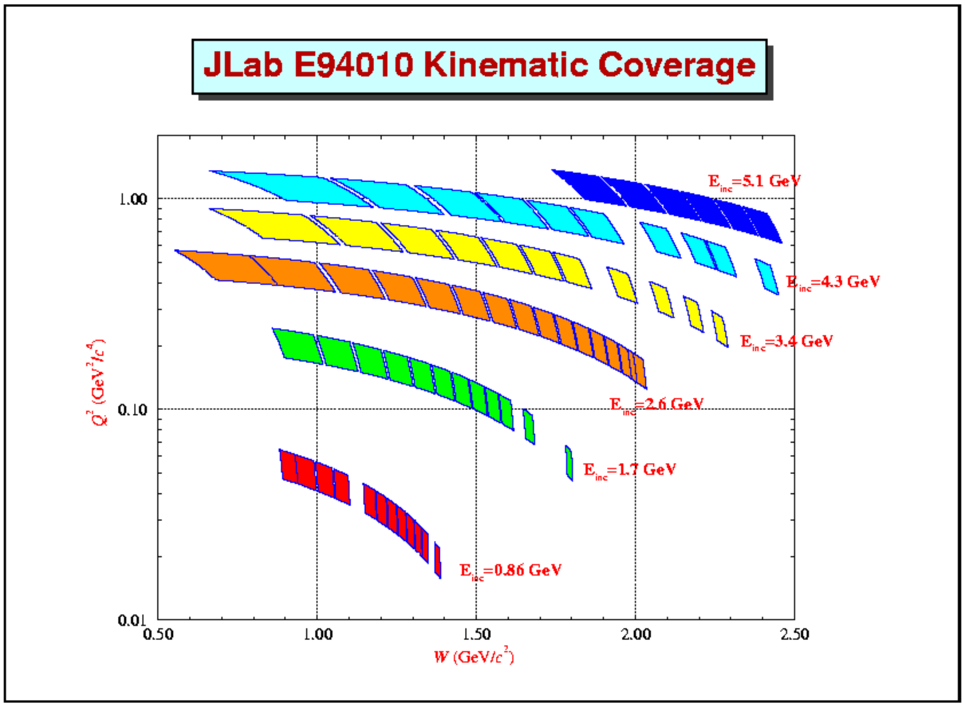

FIGURE 1. Kinematic coverage of experiment E94-010, where W is the invariant mass of the photon-nucleon system. Each box represents one kinematic point where data was collected.

light at a wavelength of $\lambda = 795$ nm was produced using 3 laser diode arrays with a total power output of roughly 100 Watts. The electron beam passed through the lower chamber which was 40 cm in length with thin end-windows ($\sim 120\mu$m) to minimize interactions between the beam and the glass. The target contained roughly 10 standard atmospheres of gaseous ^{3}He with an in-beam polarization of $30-40\%$. Target polarization was measured using two independent methods: NMR with adiabatic fast passage, and EPR (Electron Paramagnetic Resonance).

III PRELIMINARY RESULTS

The data analysis for this experiment is underway and the results presented here are preliminary. Differential cross sections were measured at each kinematic point for all possible combinations of beam and target polarization directions. The consistency of the data was checked by measuring the ^{3}He elastic cross section and asymmetry and comparing these to world data. Using the measured inelastic cross sections, the spin structure functions g_1 and g_2 were obtained for ^{3}He, as well as the virtual photon cross section difference σ^{TT} as defined in equation 2.

Data for $\sigma^{TT}(\nu)$ are shown in Figure 2. Notice the large negative value in the region of the delta resonance which will give a large negative contribution to the GDH integral.

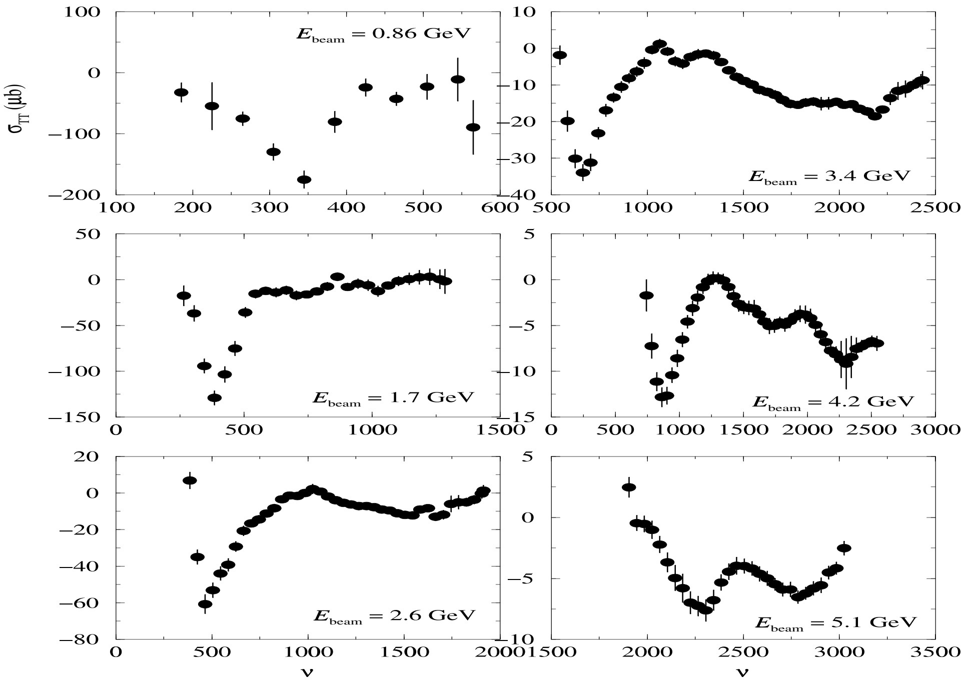

FIGURE 2. The cross section difference $\sigma^{TT} = [\sigma^T_{1/2} - \sigma^T_{3/2}]/2$ for ^{3}He is shown here versus the photon energy ν in MeV. The errors are statistical only. At all but the highest energy setting, the left-most dip is the delta resonance which is large and negative.

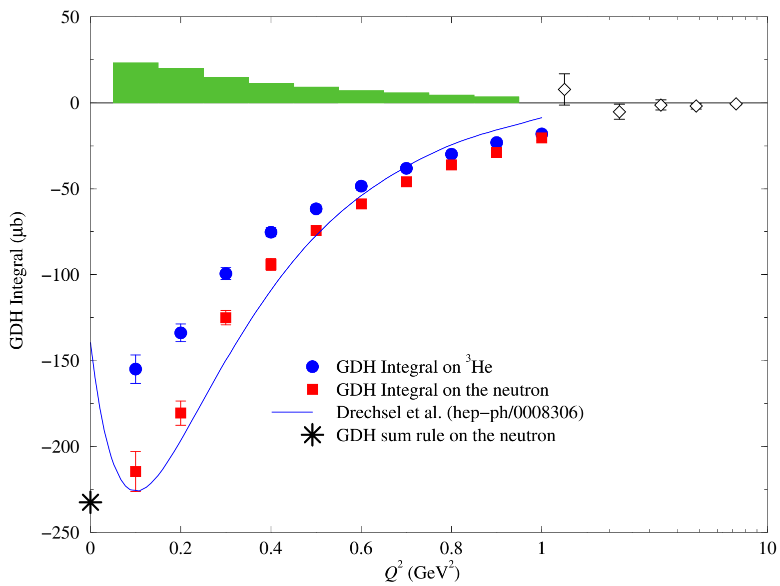

FIGURE 3. The GDH integral versus Q^2 for the neutron and ^{3}He as measured by E94-010. Error bars are statistical and the systematic error is indicated by the band. The high Q^2 HERMES data are shown by the diamonds and the Q^2 scale is logarithmic for that data only. The $Q^2 = 0$ value predicted by the GDH sum rule is shown by the asterisk, and the solid curve is the model of Drechsel *et al.*

A Extraction of Neutron Results from ^{3}He

In its ground state, the ^{3}He nucleus is primarily S-wave, with relatively small S' and D-wave components. J. Friar et al. [4] calculated that the effective neutron polarization in ^{3}He is 87% and the proton is about -3%, which means that ^{3}He behaves as an effective polarized neutron target. Recently, C. degli Atti and S. Scopetta [5] studied the extraction of the neutron asymmetries and the generalized GDH sum from a polarized ^{3}He target. Although in the resonance region at low Q^2, the extracted neutron spin structure function g_1 could differ significantly from g_1 for the free neutron, the extracted neutron GDH sum does not differ significantly from the free neutron GDH sum. This is largely because the dominant nuclear effect is Fermi motion, which is effectively averaged out in the integration.

To calculate the GDH sum at fixed Q^2, interpolations were made between the measured kinematic points. Figure 3 shows the GDH sum in equation 2 as a function of Q^2 for the neutron and ^{3}He in the measured region only. No extrapolation to the unmeasured high energy region was made. Also shown is a phenomenological model of Drechsel et al. [6] and the high-Q^2 Hermes data [7].

IV CONCLUSION AND FUTURE OUTLOOK

A first measurement was made of the spin dependent cross sections for the process $^3\vec{H}e(\vec{e}, e')$ in the region $0.1 < Q^2 < 1.0$ GeV^2. This data cover the quasi-elastic, resonance and into the deep-inelastic regions. The preliminary results indicate a large negative contribution from the delta region and, for the first time, we have observed the negative trend of the GDH sum towards the expected value at $Q^2 = 0$. Final results from this experiment are expected soon. A future Jefferson Lab experiment, E97-110 (Cates, Chen, Garibaldi *et al.*) will soon measure the cross sections for this process at scattering angles as low as 6° which will allow extraction of the GDH sum down to $Q^2 = 0.01$ GeV^2 with photon energies up to $\nu = 4.5$ GeV.

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