THE NEUTRON AND ^{3}HE SPIN STRUCTURE FUNCTIONS AND THE GENERALIZED GERASIMOV-DRELL-HEARN SUM RULE

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Abstract

We have measured spin-dependent $\overrightarrow{^3He}(\vec{e},e')$ longitudinal and transverse cross sections for the momentum transfer range $0.1 \leq Q^2 \leq 1.0$ GeV^2 using two High Resolution Spectrometers located in Hall A at Jefferson Lab [1].

A longitudinally polarized beam (P≃70%) of 0.86 to 5.1 GeV electrons was scattered off a high-pressure longitudinally or transversely polarized ^{3}He target (P≃35%). The measurement allowed for extraction of the ^{3}He polarized structure functions, g_1 and g_2, and the evaluation of the Q^2 evolution of the generalized Gerasimov-Drell-Hearn (GDH) sum rule for both ^{3}He and the neutron.

The GDH sum rule when compared to the theoretical calculations provides important insights on the nucleon spin structure in a transition region from the perturbative to low energy regimes of QCD.

1 Introduction

For many years, the spin structure of the nucleon has been a topic of central importance in nuclear physics. One of the still unresolved issues is the transition from quark-gluon description at high energies to the low energy regime where the hadronic degrees of freedom are important. At the two opposite kinematic extremes we have two fundamental sum rules: the Bjorken sum rule [2] at high Q^2 and the Gerasimov-Drell-Hearn (GDH) sum rule [3, 4] at $Q^2 = 0$. Studies of the evolution of the GDH sum rule are crucial to the understanding of the link between the two sum rules and the transition region from perturbative to non-perturbative regimes of QCD.

More than 30 years ago Gerasimov [3] and independently Drell and Hearn [4] derived a very powerful sum rule that relates the integral of the spin dependent cross section to the anomalous magnetic moment of a nucleon:

$$\int_{\nu_0}^{\infty} \frac{d\nu}{\nu} \left[\sigma^T_{1/2}(\nu) - \sigma^T_{3/2}(\nu)\right] = -\frac{2\pi^2\alpha\kappa^2}{M_N^2} \tag{1}$$

where $\sigma^T_{1/2}$ and $\sigma^T_{3/2}$ are spin dependent cross sections for the absorption of real photons, ν is the photon energy, ν_0 the pion photoproduction threshold, α the fine structure constant, κ is the anomalous magnetic moment of the nucleon and M_N is nucleon's mass. The superscript T stands for transverse (i.e. real) photons and the subscripts 1/2 and 3/2 denote the total photon-nucleon system helicity. The sum rule is valid for real photons

(Q^2=0) and is derived on the basis of three very general assumptions: a) analicity of the forward Compton scattering amplitude (dispersion relations), b) unitarity (the optical theorem) and c) relativity and gauge invariance (the low energy theorem). Thus it is considered to be a theoretically solid prediction.

Recently, Ji and Osborne [5] have shown how to extend the GDH sum rule for any Q^2 ($Q^2 \geq 0$, i.e virtual and real photons). The generalized GDH sum rule reads:

$$\int_{\nu_0}^{\infty} \frac{d\nu}{\nu}\, G_1(\nu, Q^2) = S_1(Q^2) \tag{2}$$

where $S_1(Q^2)$ is the forward Compton scattering amplitude and, $G_1(\nu, Q^2)$ is the spin-dependent structure function $(G_1(\nu, Q^2) \equiv \frac{M_N}{\nu} g_1(\nu, Q^2))$. In the limit of $Q^2 = 0$ the extended GDH sum rule becomes the original sum rule. At the opposite end of spectrum, in the Bjorken limit $Q^2, \nu \to \infty$, while $x = Q^2/(2\nu M_N)$ is finite, the extended GDH sum rule becomes the fundamental Bjorken sum rule [2]

$$\int_0^1 dx\ \left(g_1^p(x) - g_1^n(x)\right) = \frac{1}{6}\frac{g_A}{g_V} \tag{3}$$

Thus we have this very interesting sum rule that links deep inelastic region phenomena to low energy nuclear physics. It is important to note that the extended GDH sum rule provides a rigorous tool for studying the spin structure of the nucleon that is valid in the entire Q^2 regime $(0 \leq Q^2 \leq \infty)$.

2 JLab E94-010 Experiment

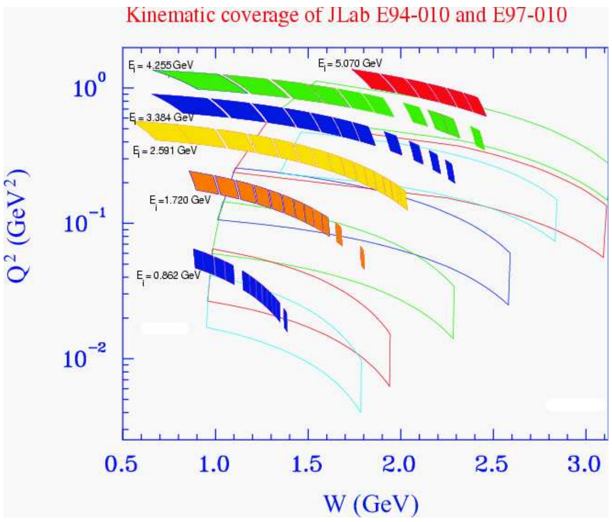

Figure 1: Kinematical coverage of E94-010 (filled bands) and E97-110 (open bands) experiments

Experiment E94-010 was conducted in Jefferson Lab Hall A [1]. A longitudinally polarized electron beam was scattered off the ^{3}He target which was polarized either longitudinally or transversely with respect to the incoming electron momentum. Data were collected at six beam energies E_{beam} = 0.86, 1.72, 2.59, 3.39, 4.24 and 5.07 GeV and the kinematical coverage is shown in Fig. 1 (solid bands). The scattered electrons were detected in either one of the two high resolution magnetic spectrometers ($\Delta p/p \simeq 10^{-4}$) located on either side of the beam line at a scattering angle of $\theta = 15.5°$. Detector packages consisted of a set of wire chambers for tracking, two planes of scintillators for triggering, and a set of pre-shower, shower and Cerenkov detector for particle identification (π rejection inefficiency at the few $\times 10^{-4}$ level).

The beam polarization ($\simeq 70\%$) was determined by Mott and Møller polarimeters to a precision of 3%. In order to minimize systematic errors, the beam helicity was flipped with a frequency of either 1 or 30 Hz. The current was limited to 10-15 μA in order to minimize the target depolarization and was measured at the percent level. A precision of 10^{-3} was achieved in the determination of the beam energy.

At the core of the Jefferson Lab neutron spin structure program is the polarized ^{3}He target. It consists of a 40 cm glass cylinder filled with 12 atm of gaseous ^{3}He connected to a spherical glass chamber filled with a small amount of Rubidium vapor. The Rb atoms are polarized by the standard optical pumping technique. The ^{3}He nuclei are then polarized by spin-exchange collisions with the polarized Rb atoms. During the experiment, the target polarization was about 35%. Two independent methods are used to determine and monitor the polarization with the accuracy better than 4%: NMR with adiabatic fast passage and EPR (Electron Paramagnetic Resonance).

In its ground state, the ^{3}He nucleus is primarily S-wave, where only the neutron contributes to the nucleus spin. The ground state also contains a small admixtures of S' and D-wave components, thus the two protons also contribute a small amount to the total nucleus spin. This can be corrected for by using the effective neutron ($\approx 87\%$) and proton (3%) polarizations within the ^{3}He nucleus [6]. A convolution model due to degli Atti and Scopetta [7] which takes into account nuclear effects such as Fermi motion and binding can be used to extract neutron quantities in the DIS regime. The model can also be used for low Q^2 integrated quantities (such as sum rules) because the nuclear effects are averaged during the integration.

3 Preliminary Results

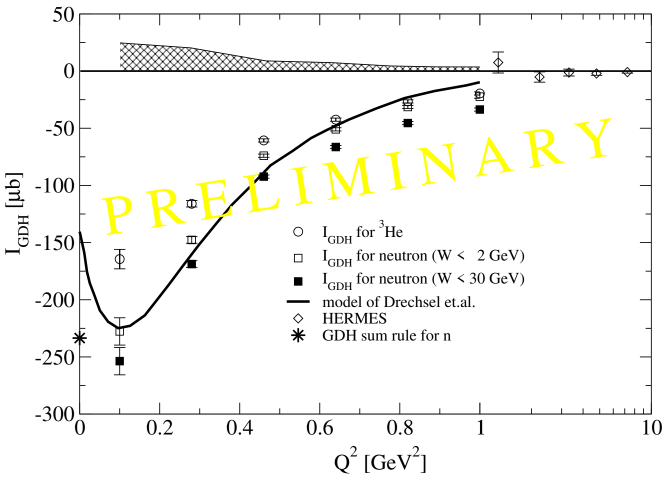

Figure 2: Our results for the extended GDH integral. See text for explanation

The data analysis for this experiment is under way and the results presented here are still preliminary. We have measured the inclusive polarized differential cross sections $\sigma^{\uparrow\Uparrow}$,$\sigma^{\downarrow\Uparrow}$, $\sigma^{\uparrow\Rightarrow}$ and $\sigma^{\downarrow\Rightarrow}$, where the first arrow denotes the beam and the second one the target polarization. Measurement of the ^{3}He elastic cross section provided a consistency check. The spin structure functions $g_{1,2}^{^3He}$ and the cross sections $\sigma^T_{1/2}$ and $\sigma^T_{3/2}$ were determined using our measured inelastic cross sections. Interpolation between the data at various energies allowed us to get $\sigma^T_{1/2,3/2}$ at fixed Q^2 in order to evaluate the GDH integral

$$I_{GDH}(Q^2) = \int_{\nu_0}^{\infty} \frac{d\nu}{\nu} \left[\sigma^T_{1/2}(\nu, Q^2) - \sigma^T_{3/2}(\nu, Q^2)\right]$$

Fig. 2 shows our preliminary results for the GDH integral $\mathrm{I}_{GDH}(Q^2)$ for ^{3}He (open circles) and neutron (squares). Open squares denote I_{GDH} integrated from pion threshold (ν_0) up to ν corresponding to $W = 2$ GeV. The error bars are statistical only and the band above the horizontal axis gives the systematic errors. To account for the unmeasured portion of I_{GDH} for $2 \leq W \leq 30GeV$ we made an estimate of the missing contribution based on a parameterization of Bianchi and Thomas [8] and the resulting I_{GDH} is plotted as solid squares. Also shown are the calculations of Drechsel, Kamalov and Tiator based on the phenomenological model MAID [9] (to be compared with open squares). The value of the GDH sum rule $I_{GDH}(Q^2 = 0) = -232.8\ \mu b$ for the neutron is plotted as a star. For comparison, data from the HERMES collaboration [10] taken at high Q^2 (1.28 GeV$^2 \leq Q^2 \leq 7.25$ GeV^2 are plotted as open diamonds (note logarithmic Q^2 scale).

4 Summary and Outlook

The neutron spin structure studies are one of the major experimental efforts at Jefferson Lab. The results presented here are the first measurement of the generalized GDH integral $I_{GDH}(Q^2)$ for the neutron at low Q^2. Our data demonstrates the large sensitivity of the GDH integral I_{GDH} to the transition from the partonic (high Q^2) to hadronic (low Q^2) degrees of freedom. The present experiment will soon be complemented and extended with the measurement of the I_{GDH} with nearly real photons. The region below $Q^2 = 0.2$ GeV^2 is of special importance, since it is there, where the Chiral Perturbation Theory is expected to be valid. Moreover, by measuring the $I_{GDH}(Q^2)$ slope at very low Q^2, one could extrapolate the value of $I_{GDH}(Q^2)$ down to $Q^2 = 0$, thus testing the fundamental GDH sum rule for real photons. Jefferson Lab Hall A experiment E97-110 [11], expected to take data next year, will measure the I_{GDH} at very low Q^2 ($0.01 \leq Q^2 \leq 0.5$ GeV^2) (see open bands in Fig. 1 for the kinematical coverage).

References

[1] B. Anderson, Basic Instrumentation for the Hall A at Jefferson Lab, to be published in Nucl. Inst. Methods.

[2] J. Bjorken, Phys. Rev. **148**, 1467 (1966).

[3] S. Gerasimov, Yad. Fiz. **2**, 598 (1965).

[4] S. Drell and A. Hearn, Phys. Rev. Lett. **16**, 908 (1966).

[5] X. Ji and J. Osborne, J. Phys. **G 16**, 127 (2001).

[6] J. Friar *et. al.* , Phys. Rev. **C 42**, 2310 (1990).

[7] C. Ciofi degli Atti and S. Scopetta, Phys. Lett. **B 44**, 223 (1997).

[8] N. Bianchi and E. Thomas, Phys. Lett. **B 450**, 439 (1999).

[9] D. Drechsel, S. S. Kamalov, and L. Tiator, Phys. Rev. **D63**, 114010 (2001).

[10] HERMES Collaboration, Phys. Lett. **B 72**, 531 (1998).

[11] J. Chen, A. Deur, and F. Garibaldi, JLAB E97-110.