Neutron (^3He) Spin Structure Functions at Low Q^2

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Abstract. Experiment E97-110 was performed at the Thomas Jefferson National Accelerator Facility to provide a precise measurement of the ^3He spin structure functions at low Q^2 from 0.02 to 0.3 $[\text{GeV}/c]^2$. A longitudinally-polarized electron beam was scattered from a longitudinally or transversely polarized ^3He target. From these data, we have extracted moments of the neutron and ^3He spin structure functions at very low momentum transfers. These data allow us to make a benchmark check of Chiral Perturbation Theory calculations in a region where they are expected to be valid. In these proceedings, the experimental details are discussed and preliminary results on the first moments of the $g_1(x, Q^2)$ and $g_2(x, Q^2)$ structure functions are presented.

Keywords: neutron, spin structure, chiral perturbation theory

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INTRODUCTION

The study of nucleon spin structure has been an active field over the past thirty years, both experimentally and theoretically [1, 2, 3]. A principle goal of this work is to test our understanding of Quantum Chromodynamics (QCD); the leading gauge theory that describes nucleons and their interactions. In the high energy region, where the quarks are asymptotically free, the use of perturbative QCD has shown good agreement with the experimental observables. However, in the low energy region theoretical calculations are difficult to obtain due to the complex interactions between the quarks and gluons. In this non-perturbative region, low-energy effective field theories such as Chiral Perturbation Theory (ChPT) have provided calculations for moments of the spin structure functions.

Spin-dependent sum rules have become important tools to study nucleon spin structure. One sum rule of great interest is the Gerasimov-Drell-Hearn (GDH) [4]. This sum rule relates an integral over the excitation spectrum of the helicity-dependent photoabsorption cross sections, $\sigma_{\frac{1}{2}}$ and $\sigma_{\frac{3}{2}}$, to a static property, the nucleon's anomalous magnetic moment. The expression for a spin- $\frac{1}{2}$ target is given by:

$$\int_{v_0}^{\infty} \left[\sigma_{\frac{1}{2}}(v) - \sigma_{\frac{3}{2}}(v) \right] \frac{dv}{v} = -\frac{2\pi^2\alpha}{M^2} \kappa^2, \quad (1)$$

where κ and M are the anomalous magnetic moment and mass of the target, v_0 the inelastic threshold, v the photon energy and α is the electromagnetic coupling constant. The subscript $\frac{1}{2}$ ($\frac{3}{2}$) corresponds to the case where the photon helicity is parallel (anti-parallel) to the target spin. This sum rule is applicable for any target with spin- S .

Originally derived for real photon absorption, the GDH integral was extended to virtual photon absorption ($Q^2 > 0$) [5]. Other generalizations exist and are described in [6, 7]. One approach is to replace the photoabsorption cross sections with the corresponding electroproduction cross sections:

$$\begin{aligned} I_{GDH}(Q^2) &= \int_{\nu_0}^{\infty} \left[\sigma_{\frac{1}{2}}(\nu, Q^2) - \sigma_{\frac{3}{2}}(\nu, Q^2) \right] \frac{d\nu}{\nu} \\ &= \frac{16\pi^2\alpha}{Q^2} \int_0^{x_0} \left[g_1(x, Q^2) - \frac{4M^2x^2}{Q^2} g_2(x, Q^2) \right] dx \end{aligned} \quad (2)$$

where $x_0 = \frac{Q^2}{2M\nu_0}$ and x is the Bjorken scaling variable.

The extension by Ji and Osborne [7] utilizes the relationship between the forward virtual Compton scattering amplitudes $S_1(Q^2)$ and $S_2(Q^2)$ and the $g_1(x, Q^2)$ and $g_2(x, Q^2)$ structure functions to form a Q^2 -dependent sum rule. This relationship provides a natural extension of the sum rule to electron scattering. This unique relation, valid at any four-momentum transfer (Q^2), can be used to make comparisons between theoretical calculations and experimental data, where they are available. The comparisons allow an investigation of the transition between the non-perturbative region and the perturbative region of QCD. The experiment described in these proceedings was specifically conducted to study the neutron spin structure functions in the low Q^2 region and to make a benchmark check of ChPT calculations used to calculate the sum rule.

THE EXPERIMENT

Experiment E97-110 [8] acquired data at Jefferson Lab in Hall A [9]. The inclusive reaction ${}^3\text{He}(\vec{e}, e')$ was examined with a longitudinally polarized electron beam scattered from either a longitudinally or transversely (in-plane) polarized ${}^3\text{He}$ target [9]. The data were collected using seven incident electron beam energies and two angles to obtain the necessary kinematic coverage at constant Q^2 . The experiment covered a kinematic range which includes the elastic, quasi-elastic and resonance regions up to an invariant mass $W = 2.5$ GeV. From these data, the polarized structure functions were extracted to form moments at very low Q^2 between 0.02 and 0.3 [GeV/c]².

The polarized electron beam was produced with a strained GaAs cathode, which was illuminated by a polarized diode laser. A Pockels cell was used to flip the beam helicity pseudo-randomly at 30 Hz. The beam polarization was measured using both Møller and Compton polarimeters [9]; the average polarization was $\sim 75\%$. The electron beam was used with a current of up to 10 μA .

The ${}^3\text{He}$ nuclei were polarized by spin-exchange optical pumping [8] with rubidium atoms and were oriented in either the longitudinal or transverse direction (with respect to the beam direction) with the aid of two sets of Helmholtz coils. By utilizing both polarization directions, the spin structure functions can be extracted without the need for models. Two independent polarimetries [9] were used to monitor the polarization: NMR and EPR. The average target polarization was $\sim 40\%$.

The scattered electrons were detected by one of the Hall A High Resolution Spectrometers (HRS) [9]. For this experiment, a horizontally-bending dipole magnet [10]

was placed in front of the spectrometer so that electrons with scattering angles of 6° or 9° could be detected; without this magnet, the minimum spectrometer angle is 12.5° . The HRS detector package consisted of drift chambers for tracking, a pair of scintillator planes for the data-acquisition trigger, and a gas Cherenkov counter associated with a two layer electromagnetic calorimeter for particle identification. With these detectors, the pion contamination was reduced by a factor of 10^4 .

Polarized cross-section differences were formed by combining the measured longitudinal and transverse asymmetries $A_{\parallel}$ and $A_{\perp}$ with the unpolarized cross section σ_0 : $\Delta\sigma_{\parallel,\perp} = 2\sigma_0 A_{\parallel,\perp}$. The asymmetries are corrected for dilution from unpolarized background, data-acquisition deadtime and beam charge asymmetry. The beam and target polarizations are then taken into account to generate the physics asymmetries. Since these quantities are defined within the Born approximation, radiative corrections were applied to the cross-section differences. The corrections were performed by using the prescription of Mo and Tsai for the unpolarized case [11] and extended to include polarized effects using the program POLRAD [12]. Finally, the ^3He spin structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$ were extracted from the Born polarized cross-section differences:

$$\Delta\sigma_{\parallel}(x, Q^2) = \frac{4\alpha^2}{MvQ^2} \frac{E'}{E} \left[(E + E' \cos \theta) g_1(x, Q^2) - \left(\frac{Q^2}{v} \right) g_2(x, Q^2) \right] \quad \text{and} \quad (3)$$

$$\Delta\sigma_{\perp}(x, Q^2) = \frac{4\alpha^2}{MvQ^2} \frac{E'}{E} E' \sin \theta \left[g_1(x, Q^2) + \frac{2E}{v} g_2(x, Q^2) \right], \quad (4)$$

where E is the beam energy, E' the scattered electron energy, θ the electron scattering angle, and v is the energy transfer of the electron.

PRELIMINARY RESULTS

Preliminary results for the ^3He $g_1(x, Q^2)$ and $g_2(x, Q^2)$ structure functions are shown in Figure 1 for six constant Q^2 values between 0.04 and 0.24 $[\text{GeV}/c]^2$ versus W . The g_1 results are indicated by the inverted-triangles, whereas the g_2 results by the filled-circles. The data are provided from the pion threshold at 1.073 GeV up to 2.0 GeV. The inner error bars represent the statistical uncertainty, and the outer error bars show the total uncertainty. For all six Q^2 values, the structure functions are approximately equal and opposite in the $\Delta(1232)$ resonance region, which is represented by the vertical-dashed line. After the Δ resonance, both structure functions are near zero, then become larger as W approaches 2.0 GeV.

From the extracted structure functions at constant Q^2 , various integrals can be formed such as the extended GDH integral and other moments of the spin structure functions. The first moment of the g_1 structure function is given by

$$\bar{\Gamma}_1(Q^2) = \int_0^{x_0} g_1(x, Q^2) dx, \quad (5)$$

FIGURE 1. Preliminary ^3He g_1 (inverted-triangles) and g_2 (circles) results (see text for details)

where x_0 is the inelastic threshold. This integral is related to the GDH sum rule as $Q^2 \rightarrow 0$ [13]:

$$\lim_{Q^2 \rightarrow 0} I_{GDH}(Q^2) = \frac{16\pi^2\alpha}{Q^2} \bar{\Gamma}_1(Q^2). \quad (6)$$

The Burkhardt-Cottingham (BC) sum rule [14], which is uniquely zero for any Q^2 , is related to the first moment of g_2 :

$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2) dx = 0. \quad (7)$$

For E97-110, the polarized ^3He target was used as an effective neutron target. The neutron moments were extracted from the measured ^3He quantities by using the prescription described in [16]. The systematic uncertainty due to this extraction was inferred to be 10% for $Q^2 \leq 0.1 \text{ [GeV/c]}^2$. In addition, we have used the parameterization in [15] to account for the unmeasured $W > 2.0 \text{ GeV}$ contribution.

In Fig. 2 the preliminary results are presented for the integral $\bar{\Gamma}_1^{\eta}$ compared to theoretical calculations and earlier measurements [17, 18, 19, 20]. The solid triangles represent the new data, and the inverted triangles show the results from a previous neutron experiment [20] in Hall A for $0.1 \leq Q^2 \leq 0.9 \text{ [GeV/c]}^2$. The error bars on the points include both statistical and systematic uncertainties. For the final results, we expect to significantly improve the (largely dominant) systematic uncertainties. The new results from experiment E97-110 agree well with the two model calculations [21, 22] and the data at larger Q^2 . The results also indicate a smooth transition as the four-momentum transfer squared approaches zero.

For our data, two calculations from Chiral Perturbation Theory exists [23, 24]. One of the calculations includes an estimate of the Δ -resonance contribution, which is represented by the band at low Q^2 . This band is the result of the uncertainties on the parameterization of the Δ resonance. Within the experimental uncertainties, the data have good agreement with the relativistic baryon calculation [23], and the three lowest- Q^2 points agree well with the heavy baryon calculation [24].

The first moment of $g_2(x, Q^2)$ is shown in Fig. 3 for the measured kinematic region (solid squares). The open diamonds represent the integral after inclusion of the elastic contribution. The solid triangles represent the full integral with an estimate of the deep inelastic scattering (DIS) contribution assuming $g_2 = g_2^{WW}$, where g_2^{WW} is the twist-2 part of g_2 derived by Wandzura and Wilczek [25]. The preliminary data agree well with the earlier neutron results [20], and the resonance data follow the MAID model [6]. The error band centered near -0.015 represents the systematic uncertainties. The darker band shows the total systematic uncertainty, whereas the lighter band shows the included contribution for the unmeasured DIS part. The new results, including the elastic and DIS contributions, are consistent with the BC sum rule expectation over the measured Q^2 region. A high- Q^2 point from the SLAC E155x collaboration [26], also consistent with zero but with a large uncertainty, is indicated by the open circle.

FIGURE 2. Preliminary neutron Γ_1 results (see text for details)

SUMMARY

Experiment E97-110 was conducted to provide precise spin structure data for the neutron and ^3He at low Q^2 between 0.02 and 0.3 $[\text{GeV}/c]^2$. From the measured structure functions, the generalized GDH integral and other moments of the spin structure functions are extracted. At low Q^2 , these quantities provide an important benchmark check of Chiral Perturbation Theory calculations. The preliminary results for $g_1(x, Q^2)$ and $g_2(x, Q^2)$ on ^3He and the first moments for the neutron have been presented. The structure functions versus Bjorken x are approximately equal with opposite signs in the Δ -resonance region. The preliminary $\bar{\Gamma}_1(Q^2)$ integral shows very good agreement with published data at higher Q^2 and the relativistic baryon calculation; however, only the three lowest- Q^2 points agree with the heavy baryon calculation. In addition, the integral of g_2^n is consistent with the BC sum rule prediction. Systematic checks are ongoing, and final neutron results are expected soon. Other moments of the spin structure functions, including the generalized forward spin polarizabilities [2] are currently being extracted.

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FIGURE 3. Preliminary neutron Γ_2 (right) results (see text for details)

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