DOE Final Report

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1 DOE Final Report Overview

This document is a final report for DOE grant DE-FG02-00ER41147. The research described herein was funded in large part by this grant with additional support from the National Science Foundation. The primary focus of Averett's research effort is centered around the polarized ^{3}He target in Hall A at Jefferson Lab. The close proximity of the College of William and Mary to Jefferson Lab has provided an outstanding opportunity to maintain a very active research program which still satisfying the demands of the college. Our research group includes four faculty, two post-doctoral fellows and eight graduate students. Averett also maintains a fully functional polarized ^{3}e target lab at William and Mary which allows him to support the research program at Jefferson Lab while also doing research on polarized targets themselves.

Since 1998, seven experiments using polarized ^{3}He have been completed by the Jefferson Lab Hall A Polarized ^{3}He Collaboration. Ten publications have been produced on this research and analysis of the two most recently completed experiments is underway. A description of the recent experiments and results is given below. In addition to target expertise, Averett has remained one of the most active collaborators in the data analysis of these experiments and maintains the largest on-site user group for this purpose as well.

1.1 The Low Q^2 Behavior of the Extended Gerasimov-Drell-Hearn Sum Rule

Ji and Osbourne [1] have shown that the spin structure function $G_1(\nu, Q^2) = g_1(x, Q^2)/M\nu$ can be connected through a dispersion relation to the virtual Compton amplitude $S_1(Q^2)$ as follows.

$$S_1(Q^2) = 4\int_{\nu_0}^{\infty} G_1(\nu, Q^2)\frac{d\nu}{\nu} \tag{1}$$

At $Q^2 = 0$, S_1 is directly related to the anomalous magnetic moment of the nucleon κ by the low-energy theorem, and using $G_1 \propto \sigma_{1/2} - \sigma_{3/2}$. This connection allows one to write down the familiar Gerasimov-Drell-Hearn Sum Rule [2] for real photons in terms of the helicity-dependent photo-absorption cross sections, $\sigma_{1/2}$ and $\sigma_{3/2}$,

$$I(Q^2 = 0) = \int_{\nu_0}^{\infty}\left[\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right]\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2, \tag{2}$$

where ν is the photon energy.

We can generalize the GDH integral in equation (2) for $Q^2 > 0$ by replacing the real photo-absorption cross sections, σ_i, with the corresponding virtual photo-absorption cross sections for transversely polarized photons, σ_i^T. For Q^2 below ~ 0.2 GeV^2, where non-perturbative QCD effects are important, $S_1(Q^2)$ can be calculated using chiral perturbation theory [1, 3]. For $Q^2 > 1.0$ GeV^2, $S_1(Q^2)$ can be calculated using pQCD methods such as higher-twist expansions. Though a solid theoretical framework exists, successfully modeling the behavior of the nucleon in the region between $0.02 < Q^2 < 1.0$ GeV^2 as it makes the transition from hadronic to partonic degrees of freedom, is challenging. The experiments described here have measured the GDH integral in this kinematic region. Jefferson Lab experiment E-94-010 made the first measurement of the Q^2 dependence of the neutron GDH integral in the range $0.1 < Q^2 < 0.9$ GeV^2 using inclusive scattering of longitudinally polarized electrons from polarized ^{3}He [4, 5, 6, 7]. For the first time, a sharp decrease towards the real photon GDH Sum Rule prediction was seen with decreasing Q^2 as the resonance contributions become important.

While the data clearly show the expected trend at low Q^2, it is not yet clear how they will approach the sum rule value as $Q^2 \to 0$. Models predict a negative slope at very low Q^2 which is

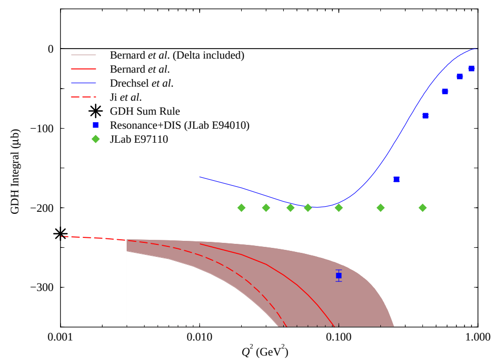

Figure 1: This plot shows the expected statistical uncertainties from Jefferson Lab experiment E-97-110 (green diamonds) for the neutron GDH integral as a function of Q^2. Data from the previous experiment, E-94-010, are show with blue squares. The curves represent model calculations as described in this document. The new experiment extends down to $Q^2 = 0.02$ GeV^2, allowing extrapolations to the real photon point, shown by the black star.

not seen in our data. To further address this issue, our collaboration recently completed E-97-110 "The GDH Rule and the Spin Structure of ^{3}He and the Neutron Using Nearly Real Photons" [8], which extended this measurement down to $Q^2 = 0.02$ GeV^2 using a new septum magnet, for extrapolation to the real photon point. The data are currently being analyzed by William and Mary graduate student Vincent Sulkosky for his doctoral thesis , with preliminary results expected in early 2007. Recent W&M post-doc Tim Holmstrom contributed 50% of his time to this analysis. Figure 1 shows the results from the first measurement and the expected statistical precision from the second experiment along with model calculations using MAID [9] and also Chiral Perturbation Theory [3, 10].

1.2 Duality in the Spin Structure Function g_1^n

Experiment, E-01-012 "Measurement of Neutron (^{3}He) Spin Structure Functions in the Resonance Region" [11] was recently completed using inclusive polarized electron scattering from polarized ^{3}He to look for quark-hadron duality in the neutron spin structure function g_1 and asymmetry A_1. Duality has been observed [12] in the unpolarized case (F_2 structure function) where the quark-like behavior of the nucleon in the deep inelastic region is an accurate average of the resonance structure seen at low Q^2. Experiment E-01-012 measured g_1 as a function of x in the resonance region up to $Q^2 = 5.4$ GeV^2. These resonance data will be compared to g_1 in the deep-inelastic region where smooth, non-resonant behavior is observed. If duality holds, the curves for g_1 in the resonance region will follow the trend of the smooth deep-inelastic curve. A plot showing preliminary results for $A_1^{^3He}$ in the range $Q^2 = 1.0$ to 3.6 GeV^2 is shown in Figure 2. William and Mary graduate student Vincent Sulkosky took a lead role in the preparation of the target system for this experiment and made a significant contribution to the manpower for running the experiment. Results should be submitted for publication in late 2006.

1.3 Measurement of Higher-Twist Effects in the Spin Structure Function g_2^n

Until recently, most experiments investigating nucleon spin structure in the deep-inelastic region focused on g_1 due to its simple interpretation in the quark-parton model. The g_2 structure function however, has no simple quark-parton model interpretation due to its additional sensitivity to non-pQCD contributions, known as higher-twist effects. In deep-inelastic scattering, both g_1 and g_2

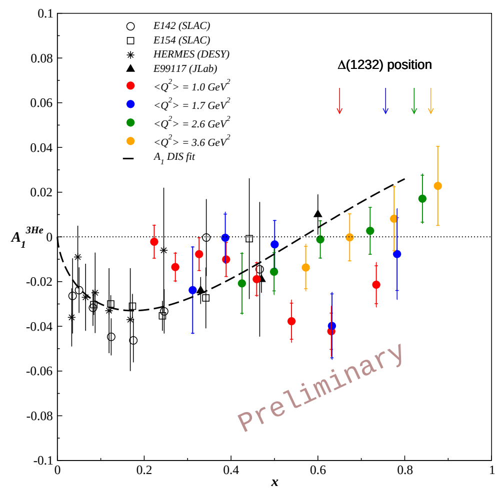

Figure 2: Preliminary data for A_1^{3He} versus x from Jefferson Lab experiment E-01-012 at four values of Q^2 from 1.0 to 3.6 GeV^2, along with world data. Though the data follow the general trend of the DIS fit, they tend to undershoot the DIS fit at higher x.

are dominated by the interaction of the virtual photon with a single, non-interacting quark. This is known as a leading twist (twist-2) contribution, and it is this simple picture that allows one to interpret g_1 in the parton model as a weighted sum over the individual quark distribution functions. In g_1, higher-order (higher-twist) contributions from soft gluon exchange or quark-mass effects are suppressed relative to the twist-2 contribution. These higher-twist contributions are not suppressed in g_2.

Wandzura and Wilczek [13] have exploited the fact that the twist-2 contribution is present in both g_1 and g_2 to write an expression for the twist-2 part of g_2, in terms of g_1,

$$g_2^{ww}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(x', Q^2)}{x'} dx'. \tag{3}$$

Next-to-leading order fits [14, 15] to the precise world data on g_1 allow one to accurately calculate g_2^{ww}. By making precise measurements of $g_2(x, Q^2)$ and subtracting g_2^{ww}, one can isolate the higher twist contributions to g_2. This feature of g_2 provides a unique opportunity to quantify the size of the higher-twist contributions.

Wolfgang Korsch (Univ. of Kentucky) and Averett were co-spokespersons for experiment E-97-103 [16], which made a precision measurement of the Q^2 dependence of g_2^n in the deep-inelastic region. Longitudinally polarized electrons were scattered inclusively from a transversely polarized ^{3}He target at five values of Q^2 in the range 0.58 to 1.36 GeV^2, and fixed $x \sim 0.2$. Analysis and final publication of these results was completed during the course of this grant. William and Mary graduate student Kevin Kramer was supported by Averett's DOE grant and received his Ph.D. from this experiment.

Figure 3 shows our data for g_2^n as a function of Q^2 along with calculations of g_2^{WW} from the BB [14] and AAC03e [15] NLO analyses. The data are more than 5σ above zero, and at lower Q^2, show a systematic positive deviation from g_2^{WW}, which we interpret as evidence for non-zero higher-twist contributions. In the OPE, the twist-2 and twist-3 contributions to g_2 enter at the same order in Q^2, with additional higher-twist contributions suppressed by powers of $1/Q$. Assuming these additional higher-twist contributions are small, we expect the quantity $g_2 - g_2^{WW}$ to be constant as a function of Q^2. When compared to g_2^{WW} from BB, a fit to our data gives

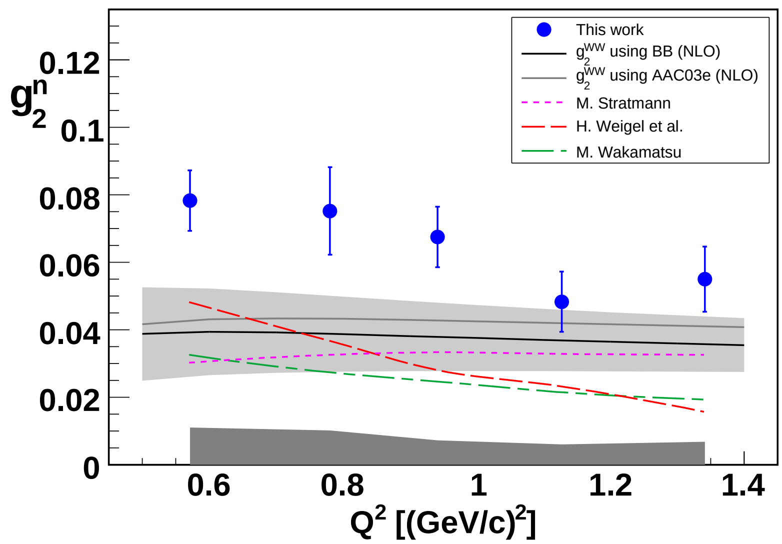

Figure 3: Results for g_2^n as a function of Q^2 for this experiment are shown along with previous measurements (see text). Data are shown with statistical uncertainties only. Results have been slightly displaced in x from the measured values to avoid overlap. The solid black curve shows g_2^{WW}, without uncertainties, at $Q^2 = 1.0$ (GeV$/c)^2$.

$g_2 - g_2^{WW} = 0.0262 \pm 0.0043 \pm 0.0080 \pm 0.0099$, with a reduced χ^2 of 1.4. The first two uncertainties are from the experiental statistical and systematic uncertainties and the third is from the uncertainty in the BB fit. Attempts to fit the data with functions that contain additional higher-twist dependence and/or logarithmic perturbative QCD corrections did not improve the quality of the fits.

Also shown in Figure 3 are chiral soliton model calculations from Weigel *et al.* [17, 18] and Wakamatsu [19], and a bag model calculation of the higher-twist contribution from Stratmann [20], combined with g_2^{WW} from BB. Our data indicate a positive contribution from higher-twist effects while the model calculations generally predict a negative contribution.

1.4 The Large-x Behavior of A_1^n in the Deep-Inelastic Region

One of the most recently published results from this collaboration was a measurement of the A_1^n asymmetry in at $x = 0.33$, 0.47 and 0.60 and corresponding $Q^2 = 2.7$, 3.5 and 4.8 GeV^2. Previous data in the DIS region at lower x were consistently negative or consistent with zero, despite strong theoretical prejudice for a large increase towards $A_1^n = 1$ as $x \to 1$ and $Q^2 \to \infty$. Asymmetry measurements were made by scattering longitudinally polarized electrons from a ^{3}He target polarized parallel or perpendicular to the incoming electron momentum. For the first time a zero-crossing in A_1^n was observed as x gets larger. Results from this experiment were recently published [21, 22] and are shown in Figure 4.

2 Summary

Over the past eight years, polarized ^{3}He research at Jefferson Lab has grown to be one of the most productive and active programs. Seven experiments are completed, four are scheduled for next year and three are approved for the 12 GeV upgrade in the hopefully near future. Averett has remained one of the most active on-site collaborators, serves as spokesperson for three of these experiments and maintains a fully functional polarized ^{3}He lab at William and Mary. Averett

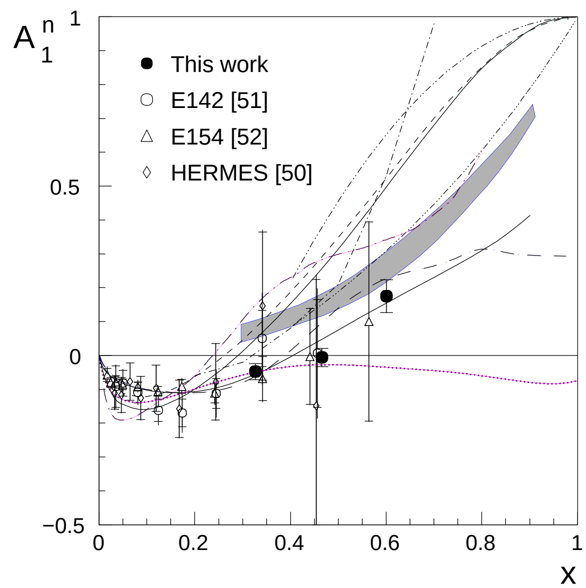

Figure 4: This plots shows A_1^n versus x from experiment E-99-117 at Jefferson Lab "This work" (solid black circles). Also shown are data from SLAC experiments E142 [23], E154 [24] and HERMES [25]. Note: Reference numbers in legend are not correct.

is/has supervised three doctoral students on this research, Kevin Kramer (Ph.D. 2003), Vincent Sulkosky (Ph.D. expected 2007) and Joseph Katich (Ph.D. expected 2009). Most of these students were funded fully, or in part, by this grant. Post-doc Timothy Holmstrom was funded 50% from this grant. Five undergraduate students completed their senior research under the supervision of Averett during this grant. There are no un-expended funds and all funds were spent within the original guidelines of the grant, which primarily covered salaries for post-doc (50%) and graduate students. Averett would like to thank the DOE for the support he has received through this OJI program and is enjoying a fruitful research program under his new DOE grant.

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