International Journal of Modern Physics A
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Neutron Spin Structure Study at Jefferson Lab Hall A

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With a high-intensity highly-polarized 6 GeV electron beam, and a high-density polarized ^{3}He target, we have carried out a number of experiments to study the neutron spin structure at Hall A in Jefferson Lab. Taking advantage of the high luminosity of Jefferson Lab, we completed two inclusive deep-inelastic-scattering experiments this summer. In the first precision measurements were made of the spin asymmetry A_1^nin the valence quark (high Bjorken x) region, and in the second higher-twist effects were studied via precision measurements of g_2^n. Physics motivation and preliminary results from the first experiment will be presented and discussed. I will also present nearly final results from an earlier experiment, which measured the generalized GDH sum for the neutron in the Q^2 range of 0.1 to 1 GeV^2. Planned near-term experiments will be briefly discussed.

1. Introduction

In the last thirty years lepton-nucleon deep-inelastic-scattering (DIS) experiments have provided us with extensive data on the spin-independent structure functions. A global analysis of the DIS data has not only established the quark-parton picture of the nucleon structure, but also extracted the distributions of the partons (valence quarks, sea quarks and gluons). The Q^2 evolution of the structure functions provided convincing evidence in support of QCD.

Measurements of the spin-dependent structure functions are less extensive. The excitement about the spin structure[1] was initially due to the so called 'spin crisis' from the CERN EMC experiment: the EMC results, combined with earlier SLAC results, indicated that the quark spins contribute only a small amount to the nucleon spin. Since then, substantial efforts, both theoretical and experimental, were devoted to understanding the puzzle. A new generation of experiments were carried out at SLAC, CERN and DESY. These experiments concluded that the quark carries about 20% of the nucleon spin, and the Bjorken sum rule[2] is verified to an accuracy of about 5%, which is another test of QCD. Attempts have been made to extract the parton spin distributions from a global analysis of the DIS spin structure function data. The uncertainties are much larger compared with the unpolarized parton distribution due to the fact that the polarized data coverage is not as extensive as that of the unpolarized data.

The study of the nucleon spin structure has reached a new stage. Regions of interests and pieces of puzzles are being investigated in detail to better understand the nucleon spin structure.

One region of interest is the high-x region, where the valence quark contributions are presumed to dominate. With sea quarks and explicit gluon contributions presumed to be not important, it is a clean region to test our understanding of the nucleon structure. Valence quark models[3] should be largely applicable in this region and perturbative QCD[4] is also able to make solid predictions in the large x (x → 1) limit. However, experimentally, it is a difficult region to perform polarization measurements due to the very small values of the spin dependent structure functions. This is especially evident in the neutron case. Taking advantage of the high luminosity at Jefferson Lab (10^{36} particles/s for polarized beam-polarized target), the first precision experiment JLab E99-117 was carried out this summer to measure the spin asymmetry A_1^n in the high-x region. Details of the experiment and preliminary results will be presented in Section 3.

Another experiment carried out this summer at Jefferson Lab was to study effects beyond leading twist. The leading twist gives the quark distributions in the nucleon, while higher twists give access to the quark-gluon interactions. Experiment JLab E97-103 measured the g_2 spin structure function. The deviation of g_2 from the leading twist part g_2^{WW}, which can be obtained from the measured g_1 structure function, gives the twist 3 (and higher twists) contribution. A short discussion of the experiment will be given in Section 4.

At the lower end of Q^2 ($Q^2 = 0$), there is another sum rule for spin structure, the Gerasimov-Drell-Hearn (GDH) sum rule[5]. A generalized GDH sum rule[6] connects the GDH sum rule with the Bjorken sum rule, and provides a clean way to test theories with experiments over the entire Q^2 range. We carried out an experiment to measure the generalized GDH sum for the neutron in the Q^2 range from 0.1 to 1 GeV^2. The near-final results will be presented in Section 5.

Finally, I will give a brief discussion on the planned near-term experiments in Section 5, including an experiment to study the quark-hadron duality for the neutron spin structure function.

2. Inclusive Polarized Lepton-Nucleon Scattering

For inclusive polarized lepton scattering off a polarized nucleon target, the cross section depends on four structure functions, $F_1(Q^2, x)$, $F_2(Q^2, x)$, $g_1(Q^2, x)$ and $g_2(Q^2, x)$, where Q^2 is the 4-momentum transfer, ν is energy transfer and $x = Q^2/2m\nu$ is the Bjorken scaling variable, F_1 and F_2 are the unpolarized and g_1 and g_2 the polarized structure functions. In the Bjorken limit, when Q^2 and ν goes to ∞ while the ratio x is kept constant, all structure functions become functions of x only. In the naive quark-parton model, F_1 and F_2 give the quark momentum distribution and g_1 gives the quark spin distribution. In QCD, g_2 can be decomposed into a leading twist contribution, g_2^{WW}, which is completely determined by g_1, and a higher twist (twist-3 and higher) contribution, which is sensitive to the quark-gluon correlation in the nucleon. Another physics quantity of interest is the virtual photon-nucleon asymmetry A_1, which is defined along the virtual photon direction

$$A_1 = \frac{g_1 + \gamma g_2}{F_1} \tag{1}$$

where γ is a kinematic factor. In the Bjorken limit, $A_1 = g_1/F_1$.

3. JLab E99-117: Precision Measurements of the Spin Asymmetry A_1^n in the High-x Region

3.1. *Physics in the high-x region*

To first approximation, the constituent quarks in the nucleon are described by the SU(6) wavefunctions. Isospin and SU(6) symmetries lead to three predictions:

$$R^{np} = \frac{F_2^n}{F_2^p} = \frac{2}{3}; \quad A_1^p = 5/9; \quad \text{and} \quad A_1^n = 0. \tag{2}$$

Experimental data on R^{np} agree poorly with the SU(6) quark model prediction even at high-x region ($x > 0.3$), which is a clear sign that SU(6) symmetry is broken for valence quarks. Valence quark models with broken SU(6) symmetry, e.g., the hyperfine interaction model[3], lead to a dominance of a 'diquark' configuration with $S = 0$ at high-x, which implies as $x \to 1$:

$$R^{np} \to \frac{1}{4}; \quad A_1^p \to 1; \quad and \quad A_1^n \to 1. \tag{3}$$

Another approach is with pQCD[4], which yields similar limiting values as previously when x approaches unity for both the proton and the neutron, namely $A_1^{n,p} \to 1$ for $x \to 1$. Note that in this theory $R^{np} \to 3/7$ versus 1/4 for the constituent quarks. Not only the limiting values at $x \to 1$ are important, but also the behavior in the high-x region, namely how do A_1^n, A_1^p and R^{np} approach their limiting values when x approaches 1, is sensitive to the dynamics of valence quark structure. This is discussed in detail by Boglione and Leader.[7]

3.2. *Experimental setup*

JLab E99-117[8] was carried out at Hall A in JLab this summer to measure A_1^n with high precision in the x region from 0.33 to 0.61 . The experiment measured asymmetries of inclusive scattering of a highly polarized (80%) 5.7 GeV electron beam on a high pressure (> 10 atm) (both longitudinal and transversely) polarized ^{3}He target. Beam currents were limited to 15 μA to minimize target depolarization. Beam polarization was measured with a double-arm Møller polarimeter once every a few days and continuously monitored with a Compton polarimeter. The average beam polarization was about $0.80 \times (1 \pm 0.03)$.

The heart of the JLab neutron spin structure program is the polarized ^{3}He target, which was built by the JLab polarized ^{3}He collaboration[9]. The polarized ^{3}He target was polarized by spin exchange with optically pumped Rubidium (Rb).[10] The average in-beam polarization with up to 15 μA current was $0.4 \times (1 \pm 0.04)$. The

^{3}He gas was contained in sealed glass cells with a density corresponding to about 10 atm at room temperature. The portion of the cell in the electron beam, the target chamber, was a long cylinder approximately 25 cm in length (target length was 40 cm for the other two experiments). The portion of the cell in which optical pumping took place, the pumping chamber, was irradiated with about 90 W of light from high-power diode laser arrays centered at the first transition line of Rb (795 nm). The polarization of the ^{3}He was monitored by two methods: the NMR technique of adiabatic fast passage calibrated with a water signal, and the EPR technique by observing the shift of the Rb electron paramagnetic resonance lines that is caused by collisions with the polarized ^{3}He nuclei. An independent check of the polarimetry was provided by measuring the asymmetry in elastic scattering, which depends on the product of the beam and the target polarizations.

The scattered electrons were detected with two high-precision spectrometers (with identical angular and momentum settings) at two scattering angles and three momentum settings (Table 1). The standard detection package (scintillators for trigger, vertical drift chambers for tracking, gas Cherenkov counters and shower counters for particle identification) with upgraded PID detectors were used to select electrons. The pion rejection efficiency achieved was better than 10^4 for both spectrometers, which is more than sufficient for the experiment.

Table 1. E99-117 Kinematics

E(GeV)	$\theta(^\circ)$	E'(GeV)	x	Q^2 (GeV^2)
5.734	45	1.458	0.61	4.9
5.734	35	1.737	0.48	3.6
5.734	35	1.319	0.33	2.7

At each kinematic point, data were collected for a target polarization in both parallel and perpendicular direction. To reduce systematic errors related to the beam and target polarization directions, data were taken for four different beam and target polarization configurations for parallel settings and for two configurations for perpendicular settings.

3.3. *Preliminary results*

Data analysis is underway. Raw parallel and perpendicular asymmetries were extracted for ^{3}He. After taking into account the beam and target polarization and the dilution factor, they were combined to form $A_1^{^3He}$. Using the most recent model,[9] nuclear corrections were applied to extract A_1^n. Preliminary results on A_1^n without radiative corrections are shown in Fig. 1.

From the plot, it is clear that this experiment greatly improved the precision of data in the high-x region, and for the first time, a cross-over from negative to positive side can be observed. It will shed light on our understanding of the valence quark structure of the nucleon.

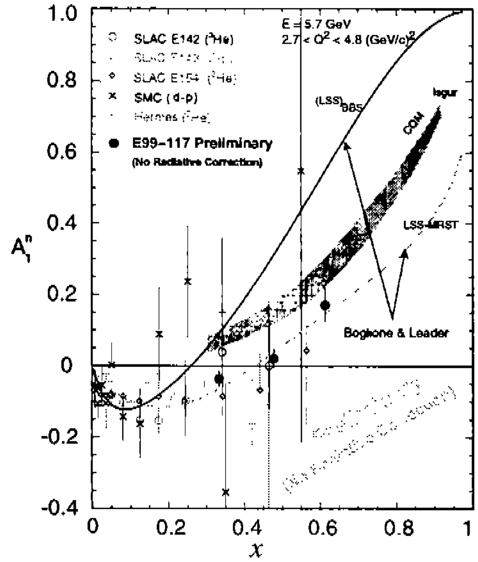

Fig. 1. Preliminary results from E99-117 on A_1^n compared with the world data and theoretical predictions from valence quark models and pQCD based models.

4. JLab E97-103: Search for higher-twist effects in the neutron spin structure function $g_2^n(x, Q^2)$

JLab E97-103[10] was carried out this summer right after E99-117. The experiment made a precision measurement of g_2^n at $x \approx 0.2$ for five different Q^2 values from 0.58 to 1.36 GeV^2. The precision reached is more than an order of magnitude improvement over the best world data. As reviewed in Section 1, the difference of g_2 from g_2^{ww} is a clean measure of twist-3 (and higher) effects, which is sensitive to quark-gluon correlations. Since higher twist effects are expected to be small, the existing world g_2 data show little difference from g_2^{ww}. This experiment will be the first precision measurement allowing us to extract higher twist effects.

The experiment used the same setup as the E99-117, except the target cell length was 40 cm. Most of the data were taken with the target polarization in perpendicular configuration, since it provides the main contribution to g_2. Special attention was paid to the precise determination of the target polarization direction and the control of beam helicity charge asymmetry. Data analysis is underway and initial results are expected in a few months.

5. JLab E94-010: Generalized GDH sum in the Q^2 range of 0.1 to 1 GeV^2

The first experiment at Jefferson Lab which used the polarized ^{3}He to study the neutron spin structure was the measurement of the generalized GDH sum at low Q^2 to study its Q^2 evolution.[11] The measurement of doubly-polarized inclusive cross sections was carried out in the end of 1998 with five beam energies from 0.86 to 5.1 GeV at a fixed scattering angle of 15.5°. The scattered electron momenta covered the quasi-elastic region, the resonance region and beyond. Electron beam polarization reached about 70%. It was monitored with a Møller polarimeter with a relative error of about 4%. The target was polarized in both parallel and perpendicular configurations. The average target polarization in beam (10-15 μA) was about 35%. It was monitored with the NMR technique, which was calibrated with the water NMR and EPR methods.

The parallel and perpendicular cross-section differences were obtained. The spin structure functions g$_1$, g$_2$ and σ_{TT} for ^{3}He were extracted. Interpolation to constant Q^2 values was performed. The GDH sums were formed from pion threshold to W^2 = 4 GeV^2. Finally, nuclear corrections were applied, using the prescription of Ciofi degli Atti and Scopetta[12], to extract the GDH sum for the neutron. The data analysis is prectitically completed. The near final results are shown in Fig. 2. The higher energy contributions (for W^2 from 4 to 1000 GeV^2 were estimated using the parameterization of Thomas and Bianchi[13]. Also shown for comparison are the high Q^2 results from the HERMES collaboration.[14]

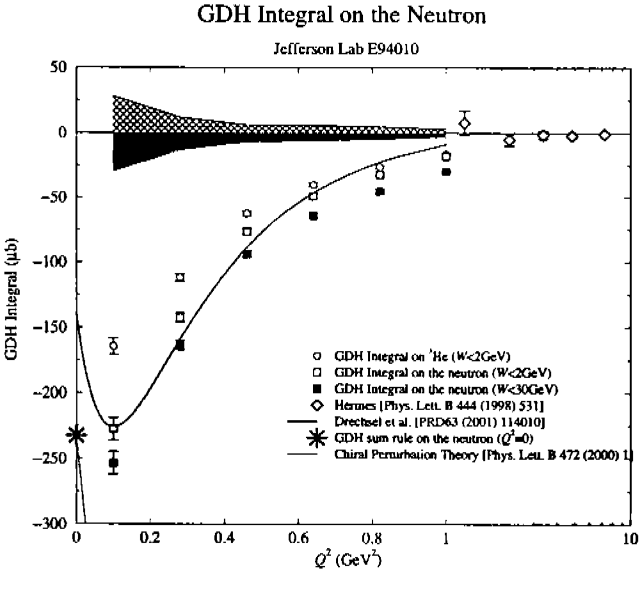

Fig. 2. Near final results of E94-010 on the Generalized GDH sum.

These data show a dramatic change in the value of the generalized GDH sum from what was observed at high Q^2. While not unexpected from phenomenological models, these data illustrate the sensitivity to the transition from partonic to hadronic behavior. These data provide a precision data base for twist expansion analysis, a check for Chiral Perturbation Theory (ChPT) calculations, and establish an important benchmark against which one can compare future calculations (such as Lattice Gauge Theory calculations).

6. Planned experiments

6.1. *E97-110: Generalized GDH sum with nearly real photons*

The previous experiment provided precision data on the generalized GDH in the intermediate Q^2, but did not go below the turn-around point (at $Q^2 \approx 0.1$ GeV^2) as predicted by most models. The next planned polarized ^{3}He experiment[15] is to extend the generalized GDH sum measurements to very low Q^2 (down to $Q^2 = 0.02$ GeV^2). ChPT calculations are expected to be valid at $Q^2 < 0.1$ GeV^2. The slope at $Q^2 = 0$ (real photon) point is especially of interest. Extrapolation to the real photon point provides an alternative way to test the original GDH sum rule.

With two new septum magnets, which are being assembled, the Hall A HRS spectrometers will be able to reach angles as low as 6°, and enable us to access the very low Q^2 range. The experiment is scheduled for the fall 2002. The very low Q^2 data will enable us to extract the slope and extrapolate to real photon point, providing a measurement of the GDH sum rule for the neutron at $Q^2 = 0$.

6.2. *E01-012: Test of quark-hadron duality in g_1^n*

Another approved experiment[16] of the neutron spin structure program is the test of quark-hadron duality in the neutron spin structure function g_1^n. Quark-hadron duality was first observed in the spin-independent structure function F_2 by Bloom and Gilman in the early 70s. It was further studied at JLab recently. The duality links the resonance region to the DIS region. With the origin of the local quark-hadron duality unclear, it is crucial to study the spin-flavor dependence of the quark-hadron duality. Duality has not yet been established for the spin structure functions. First resonance data from the generalized GDH sum experiments at low Q^2 (< 2 GeV^2) showed a first sign of approaching duality. The planned experiment will measure g_1^n (and A_1^n) in the resonance region for Q^2 range from 1 to 5.5 GeV^2. Combined with JLab E99-117 and the SLAC DIS data, it will provide a precision test of duality in g_1^n. If duality is established, these data will yield us A_1^n data in an x region very close to 1, providing further test of the valence quark models and the pQCD predictions.

7. Summary

With the highest polarized luminosity and flexibility in target polarization directions, the JLab polarized ^{3}He program has provided a set of high-precision data to study the neutron (and ^{3}He) spin structure in a wide kinematic range. Preliminary results were shown for the DIS A_1^n measurement in the high-x region. DIS g_2^n data were taken to study higher-twist effects. Nearly final results were presented for the generalized GDH sum rule. Extension of the generalized GDH sum measurements to very low Q^2 is planned for next year. A spin duality test of g_1^n is planned for the near future. A rich program is underway at Hall A in JLab to study the neutron spin structure, which will shed light on the valence quark structure, quark-gluon correlations and help understand the transition region between perturbative and non-perturbative regions of QCD.

Acknowledgements

I would like to thank Bo-Qiang Ma and the organizers of the Pacific-Spin2001 for the hospitality and for organizing this very successful symposium. The work presented was supported in part by the U. S. Department of Energy (DOE). The southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility for the DOE under contract DE-AC05-84ER40150.

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