Precision exploration of neutron spin structure at Jefferson Lab

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Abstract. Spin structure functions provide basic information about the spin of the quark distributions inside the nucleon. Experimental understanding of the nucleon spin in the kinematic region where the three basic (“valence”) quarks dominate the nucleon wave function is still rather poor. Jefferson lab, with its high quality, high polarization continuous electron beam, and a high density polarized ^3He target in experimental Hall A, provides the ideal opportunity to gather neutron spin structure data in the valence region with unprecedented precision. Two high precision neutron spin structure measurements were completed in Hall A last summer. The first experiment measured the spin asymmetry A_n^1 in the valence region while in second experiment higher-twist effects were studied via measurements of g_2^n . The planned upgrade of Jefferson lab CEBAF accelerator to 12 GeV will significantly increase the accessible kinematic range and the precision of these measurements.

INTRODUCTION

In the past three decades lepton-nucleon deep-inelastic scattering (DIS) experiments have provided us with extensive data on the sub-structure of the nucleon. A global analysis of the DIS data has not only established the quark-parton picture of the nucleon, but also extracted the distributions of the partons (valence quarks, sea quarks and gluons). In lepton-nucleon deep-inelastic scattering, the lepton interacts with the nucleon by exchanging a virtual photon with one of the quarks in the nucleon. This process is characterized by two variables, Q^2 and x . The quantity Q^2 is the four-momentum squared for the exchanged virtual photon, and $x = Q^2/(2Mv)^1$ is the fraction of the nucleon momentum carried by the struck quark (at the Bjorken scaling limit). The Q^2 evolution of the DIS data has helped establish Quantum Chromodynamics (QCD) as the fundamental theory governing the strong interaction.

One of the most fundamental properties of the nucleon is the structure of its valence quark distributions. At small values of the scaling variable x , sea quarks (quark-antiquark pairs), shadow the effects of valence quarks. As x increases beyond ~ 0.3 , the sea quark contributions to the nucleon wave function becomes increasingly small. This allows for a direct, clean probe of the valence quark distributions at large values of x ($x > 0.4$) [1]. Unfortunately due to limitations at high energy laboratories, the quality of valence region data in many experimental

fronts is rather poor. The lack of precision experimental data in the valence region is most apparent in the case of spin observables for the neutrons. This is mainly due to technical difficulties with polarized beams and targets, low luminosities available at high energy facilities and lack of a free neutron target.

In the ground state of the ^3He nucleus the two protons pair-up in a S-state with their spins anti-aligned. As a result, the neutron in ^3He carries almost 90% of the nuclear spin making polarized ^3He an ideal source for polarized neutrons [2]. The high-luminosity polarized ^3He target in experimental Hall A at Jefferson Lab, combined with the Jefferson Lab high polarization electron beam, provides the best opportunity to gather precision spin observable data for the neutron in the valence region.

The cross section for inclusive scattering of polarized leptons off a polarized nucleon target depends on two unpolarized structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$, and two polarized structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$. In the Quark-Parton model F_1 and F_2 are directly related to quark distributions inside the nucleon while g_1 is determined by the quark spin distributions. Another important observable A_1 , virtual photon asymmetry, is defined in terms of total photo-absorption cross sections $\sigma^{1/2}$ and $\sigma^{3/2}$

$$A_1 = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} \quad (1)$$

where super-scripts 1/2 and 3/2 indicate the total helicity of the photon-nucleon system.

In this paper we give a brief overview of two precision neutron spin structure measurements carried out in

¹ M is the mass of the nucleon and v is the energy transfer.

FIGURE 1. A schematic diagram of the hall A polarized ^3He target

experimental hall-A last Summer. Jefferson lab experiment 99-117 [3] used the hall A polarized ^3He target to measure virtual photon asymmetry for the neutron, A_1^n , with unprecedented precision up to $x \sim 0.61$. Experiment 97-103 [4] measured the g_2 structure function for the neutron. We will also describe some of the neutron spin physics opportunities that will become possible with the 12 GeV beam at Jefferson Lab. Jefferson Lab 12 GeV beam creates many other exciting opportunities to study the nucleon spin structure in inclusive, semi-inclusive and exclusive reactions in halls A, B and C. A detailed discussion of the proposed Jefferson Lab 12 GeV physics program can be found in the Jefferson Lab 12 GeV White-Paper [5].

EXPERIMENTAL SETUP

The Thomas Jefferson National Accelerator Facility, the world's premier medium energy electron scattering laboratory, is located in Newport News, Virginia. The facility consists of a state-of-the art continuous wave electron accelerator (CEBAF), three complementary experiment halls that utilize the beam to explore different aspects of nuclear physics, a free electron laser facility and an applied research center. CEBAF accelerator at Jefferson Lab is capable of simultaneously delivering high quality polarized electron beams of up to 6 GeV to the three

experiment halls. An upgrade of the accelerator and experimental equipment up to 12 GeV is highlighted as a high priority in the Nuclear Science Advisory Committee (NSAC) Long Range Plan and is expected in the near future.

The experimental hall A is instrumented with an identical High Resolution Spectrometer (HRS) pair capable of detecting and momentum analyzing charged particles up to 4 GeV. In the experimental program described here, both spectrometers were used to detect electrons. To take the full use of the 12 GeV beam, a new spectrometer, MAD (Medium Acceptance Device), is proposed for Hall A. This spectrometer will have a relatively large solid angle acceptance of 30 msr while providing low background conditions so that the full available beam-target luminosity can be used.

The heart of the Jefferson Lab Hall A neutron spin physics program is the polarized ^3He target constructed by the Jefferson Lab polarized ^3He collaboration. This polarized ^3He target is based on the principal of spin exchange between optically pumped alkali-metal vapor and noble-gas nuclei [11]. The main feature of the target is the sealed glass cell, which under operating conditions contains ^3He at about 10 atmospheres. As shown in Figure 1 the cell consists of two chambers; an upper chamber where the spin exchange takes place and a lower chamber through which the electron beam passes. The appropriate number density of the alkali-metal Rubidium in the upper chamber is maintained by keeping it at a temperature of 200 °C.

The main coils shown in Figure 1 are large Helmholtz coils used to apply a static magnetic field of about 25 Gauss. Also shown are the components for the NMR and EPR polarimetry. The optics system includes three diode lasers for longitudinal pumping and three for transverse pumping. A polarizing beam splitter lens system and quarter wave plates are required to condition each laser beam line and provide circular polarization.

An average target polarization of about 40% was achieved for the Summer-long run of two neutron spin experiments last year (E99-117 and E97-103).

JEFFERSON LAB EXPERIMENT 99-117: PRECISION MEASUREMENTS OF THE SPIN ASYMMETRY A_1^N IN THE HIGH-X REGION

Virtual photon asymmetry is an important observable in the study of dynamics of spin-flavor symmetry breaking. Early quark-parton models of the nucleon that preserve exact SU(6) symmetry require that $A_1^n = 0$ and $A_1^p = 5/9$. However, in nature the spin-flavor SU(6) symmetry is broken. Modern quark models with broken SU(6) sym-

FIGURE 2. Preliminary result of A_1^n from Jefferson Lab Experiment 99-117, compared with world data and theoretical predictions. Curves: predictions of $\frac{g_1}{F_1} \approx A_1$ from the pQCD NLO fit (LSS) to polarized DIS data [13], A_1^n from constituent quark model (light shaded band) [1], pQCD based model using BBS parameterization (LSS(BBS)) [10, 12], statistical model at $Q^2 = 4$ (GeV/c)² (J. Soffer) [14], local duality based model [15], chiral soliton model at $Q^2 = 3$ (GeV/c)² [16], and E155 fit at $Q^2 = 4$ (GeV/c)².

metry predict that both $A_1^p \rightarrow 1$ and $A_1^n \rightarrow 1$ as $x \rightarrow 1$ [1, 6, 7]. Perturbative-QCD calculations [8, 9] at the $x \rightarrow 1$ limit also show that $A_1^p \rightarrow 1$ and $A_1^n \rightarrow 1$ as $x \rightarrow 1$. Given the fundamental information that can be extracted from the spin observables at high x , it is unfortunate that there has been virtually no experimental data for A_1^n for $x \geq 0.4$. While firm pQCD predictions exist for A_1^n as $x \rightarrow 1$ and $Q^2 \rightarrow \infty$, the existing measurements at high x lack the precision to even distinguish any of the predictions from the naive SU(6) result.

Jefferson lab experiment 99-117 measured A_1^n over the x range from 0.33 to 0.61 by measuring asymmetries for scattering of highly polarized (80 %) 5.7 GeV electrons off hall A polarized ³He target. All the data was within the Deep Inelastic Scattering region with $2.74 < Q^2 < 4.9(\text{GeV}/c)^2$ and $4 < W^2 < 6.5(\text{GeV}/c)^2$. Beam current was limited to 15 μA to minimize target depolarization. A double-arm Moller polarimeter was used to measure the beam polarization once every few days, a Compton polarimeter was used to monitor the beam polarization continuously.

The Hall-A High Resolution Spectrometer pair was used in a symmetric configuration to detect scattered electrons at two scattering angles and three momen-

tum settings. At each kinematic point, asymmetries were measured with the target polarization aligned both parallel and perpendicular to the beam. To minimize systematic errors, data were taken for all four beam-target polarization direction configurations in the parallel case and in two configurations in the perpendicular case.

Analysis of the data from the experiment is almost complete. The nuclear corrections were applied using most recent models [17] to extract A_1^n from A_1^{3He} . As the preliminary results are in Fig. 2 indicates, E99-117 has greatly improved the precision of data in the high- x region and for the first time, a cross over of A_1^n from negative to positive is observed. The availability of 12 GeV beam at Jefferson Lab will allow the A_1^n measurement to be extended to $x \sim 0.8$ with high precision. The anticipated data are shown in Fig. 3. While an invariant mass cut of $W > 2$ GeV, would allow the deep inelastic continuum to be cleanly accessed, one may extend the measurements of A_1^n to even larger x by using quark-hadron duality in the resonance region.

FIGURE 3. Projected data for a measurement of A_1^n with 12 GeV beam at Jefferson Lab. The red filled circles are for the data in the DIS region ($W > 2$ GeV), while the filled squares show the possibility of extending the measurement to higher x by relaxing the invariant mass cut.

JEFFERSON LAB EXPERIMENT 97-103: SEARCH FOR HIGHER-TWIST EFFECTS IN THE NEUTRON SPIN STRUCTURE FUNCTION $G_2^N(X, Q^2)$.

While the g_1 structure function has a simple interpretation in the quark-parton model in terms of quark helicity distributions and has been the focus of extensive experimental programs over the last decade, there have been few dedicated experimental studies of the g_2 structure function. The g_2 structure function is related to the transverse polarization of the nucleon, and although it does not have a simple quark-parton model interpretation, it contains important information about quark-gluon correlations within the nucleon. In QCD the quark-gluon correlations are associated with so-called higher twist operators (where “twist” is defined as the difference between dimension and spin of an operator), which are suppressed by additional factors of $1/Q$ relative to the leading twist contribution (which is associated with free quark scattering). At large values of Q^2 , QCD allows one to relate moments of spin structure functions to the matrix elements of operators of given twist. The simplest twist-3 matrix element that contains information on quark-gluon

correlations is given by:

$$d_2(Q^2) = \int_0^1 dx x^2 [2g_1(x, Q^2) + 3g_2(x, Q^2)]$$

Note that because of the x^2 weighting in Eq.(2), d_2 is dominated by the large- x behavior of g_1 and g_2 . The physical significance of d_2 is that it reflects the response of a quark to the polarization of the gluon color field in the nucleon, $d_2 = (2\chi_B + \chi_E)/3$, with χ_B (χ_E) the gluon-field polarizability in response to a color magnetic (electric) field $\vec{B}$ ($\vec{E}$).

Jefferson Lab experiment 97-103 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 GeV². This experiment used the same setup as E99-117, except the target cell was 40 cm long. The main contribution to g_2 comes from the transverse asymmetry. Hence most of the data were taken with the target polarized perpendicular to the beam direction. Special attention was paid to the precise determination of the target polarization direction and to the control of beam helicity charge asymmetry.

The precision reached in E97-103 is an order of magnitude improvement over the best available world data. The data analysis is underway and final results are expected soon. These results will provide the first precision determination of higher-twist effects in g_2^n above the leading twist component of $g_2^{n(WW)}$.

Availability of the 12 GeV beam at Jefferson Lab will allow for a mapping of g_2^n over x and Q^2 with special focus on the high x region which dominates d_2 . These g_2^n data will enable the extraction of the d_2 matrix element for the neutron with a factor of 10 statistical improvement in the error over the best available world data. Projected uncertainties for such an experiment are indicated by the squares in Fig. 4.

SUMMARY

With the highest polarized luminosity in the world and flexibility in target polarization directions, the Jefferson Lab Hall-A polarized target provides a unique opportunity to gather high-precision neutron spin structure function data over a large kinematic range. Jefferson lab Experiment 99-117 provides the first high-precision A_1^n data in the high- x region while Experiment 97-103 allows for the first precision study of higher-twist effects in neutron spin structure functions through a precise measurement of g_2^n . The proposed Jefferson lab upgrade to 12 GeV will significantly increase the accessible kinematic range and the precision of these measurements.

FIGURE 4. The preliminary results for the g_2^n spin structure function from SLAC experiment E155x. The dashed curve shows the Wandzura-Wilczek [18] calculation of the leading twist contribution to g_2^n . The open squares are the expected uncertainties from an 11-GeV JLab measurement.

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