Quark-gluon correlations and Color Polarizabilities

Zein-Eddine Meziani,^{1, 2}

Department of Physics, Temple University, Philadelphia, PA 19122-6082

Abstract. We discuss the present status of the twist-3 matrix element in the spin sructure of the nucleon and describe two proposed experiments that will improve on the precision of the present measurements of the twist-3 and twist-4 matrix elements for both the proton and the neutron and consequently will improve on our knowledge of the “color polarizabilities” in the nucleon.

Keywords: Nucleon spin structure, , higher twists, quark-gluon correlations, color polarizabilities
PACS: 12.38Aw, 12.38.Qk, 13.60.Hb

INTRODUCTION

In inclusive polarized lepton-nucleon deep-inelastic scattering, one can access two spin-dependent structure functions of the nucleon, g_1 and g_2 . While g_1 can be understood in terms of the Feynman parton model which describes the scattering in terms of *incoherent* parton scattering, g_2 cannot. Using the operator product expansion (OPE) [1, 2], it is possible to interpret the g_2 spin structure function beyond the simple quark-parton model. However g_2 is exceedingly interesting because it provides a unique opportunity to study the quark-gluon correlations in the nucleon which are otherwise inaccessible. According to the optical theorem, g_2 is the imaginary part of the spin-dependent Compton amplitude for the process

$$\gamma^*(+1) + N(1/2) \rightarrow \gamma^*(0) + N(-1/2),$$

FIGURE 1. Compton amplitude of $\gamma^*(+1) + N(1/2) \rightarrow \gamma^*(0) + N(-1/2)$.

¹ On behalf of the Hall A, E06-114 and Hall C, E03-110 (SANE) collaborations

² This work is supported by DOE grant contract DE-FG02-94ER40844

FIGURE 2. Twist-two and twist-three contributions to Compton scattering

where γ^* and N denote the virtual photon and the nucleon, respectively, and the numbers in parentheses are the helicities (see Fig. 1). Thus this Compton scattering involves the t -channel helicity exchange $+1$. When it is factorized in terms of parton subprocesses, the intermediate partons must carry this helicity exchange. Because of the chirality conservation in vector coupling, massless quarks in perturbative processes cannot produce a helicity flip. Nevertheless, in QCD this helicity exchange may occur in the following two ways (see Fig. 2): first, single quark scattering in which the quark carries one unit of orbital angular momentum through its transverse momentum wave function; second, quark scattering with an additional transversely-polarized gluon from the nucleon target. The two mechanisms are combined in such a way to yield a gauge-invariant result. Consequently, g_2 provides a direct probe of the quark-gluon correlations in the nucleon wave function. In particular the piece of interesting physics is contained in the second moment in x of a linear combination of g_1 and g_2 ,

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

This specific combination of g_1 and g_2 filters out the free quark scattering interaction exposing the higher twist or quark-gluon interaction. The quantity $d_2(Q^2)$ is a twist-three matrix element which is related to a certain quark-gluon correlation, and describes how the gluon field inside the nucleon responds when this latter is polarized. Due to parity conservation, a color magnetic field $\vec{B}$ can be induced along the nucleon polarization (spin direction) while a color electric field $\vec{E}$ in the plane perpendicular to the polarization". In fact d_2 can be written as [3, 5]

$$d_2 = (2\chi_B + \chi_E)/3. \quad (2)$$

where χ_B and χ_E are the gluon-field polarizabilities defined in the rest frame of the nucleon using the color-singlet operators $O_B = \psi^\dagger g \vec{B} \psi$ and $O_E = \psi^\dagger \vec{\alpha} \times g \vec{E} \psi$:

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | O_{B,E} | PS \rangle. \quad (3)$$

where M is the nucleon mass and $\vec{S}$ its spin.

Presently d_2^p and d_2^n have been evaluated using state of the art computers in the framework of lattice QCD. The proton d_2 world data have a precision equivalent to that

of the present lattice QCD calculation. This situation might change soon with the rapid increase in computers processing speed. The neutron data lack the precision required for a meaningful comparison. Lattice QCD offers a powerful tool to investigate our understanding of the nucleon by direct comparison of quantities like d_2 . The present results are very encouraging but much experimental progress needs to be achieved for a definitive comparison with the data.

JLAB EXPERIMENT E06-114: PRECISION MEASUREMENT OF THE NEUTRON d_2 ; TOWARDS THE ELECTRIC χ_E AND MAGNETIC χ_B COLOR POLARIZABILITIES

The valence quark region (large x) provides a window on nucleon structure in a regime where the sea quarks contribution is small. This region is a good testing ground for nucleon quark models and for perturbative QCD calculations because predictions of spin observables like the asymmetries A_1^p and A_2^p are possible. Furthermore, measurements of the helicity dependent cross sections are essential for the determination of higher moments of spin structure functions g_1^p and g_2^p . These moments are the natural connection between experiment and observables calculable in lattice QCD. Lattice QCD calculations do not directly determine spin observables but rather several moments of the various polarized and unpolarized structure functions. Lattice QCD collaborations hope to calculate the moments of these structure functions with near-physical pion masses in the next few years employing Teraflop-Year computing resources. Results available today still require extrapolations to the chiral limit[9].

Fig. 3 shows how the proposed experiment JLab E06-114[11] will impact the neutron present comparison between theory and experiment if one uses 20 days of the 6 GeV polarized electron beam on the polarized ^3He target and the Bigbite spectrometer to detect the scattered electrons at large angle (40°). The improvement is rather impressive and will prove to be powerful as both the calculations and the experiment reach new precision levels.

JLAB EXPERIMENT E03-110: SPIN ASYMMETRIES ON THE NUCLEON EXPERIMENT (SANE)

Although there is a large world dataset for A_1^p , the trend of the data in the limit $x \rightarrow 1$ is not clear, and is completely inadequate for estimating all but the first moment of g_1^p . Our goal is to obtain precision A_1^p and A_2^p results at the largest possible x . A new experiment with a significant increase in Figure of Merit for making high x spin structure function measurements was proposed and approved. The experiment is called SANE (Spin Asymmetries on the Nucleon Experiment) [13], and is based on a 194 msr electron detector viewing the UVa polarized NH_3 target operating at 8.5×10^{34} proton-luminosity.

The proposed measurements of g_1^p and g_2^p (Fig. 4 shows the projected uncertainties of the proposed measurement) will allow us to determine d_2^p with unprecedented precision

FIGURE 3. The quantity $\bar{d}_2(Q^2)$ is shown at several values of Q^2 . The results of JLab E94-010[12] without the nucleon elastic contribution are the solid circles. The grey band represents their corresponding systematic uncertainty. The SLAC E155 [6] neutron result is the open square. The solid line is the MAID calculation[7] while the dashed line is a HB χ PT calculation[8] valid only at very low Q^2 . The lattice prediction [9] at $Q^2 = 5 \text{ GeV}^2$ for the neutron d_2 reduced matrix element is negative but close to zero. We note that many nucleon models not shown in this figure predict a negative or zero value at large Q^2 where the elastic contribution is negligible. The SLAC datum shows a positive value of d_2^n but with a rather large error bar. The projected errors of this proposal are the filled circles

at several values of $Q^2 < 6 \text{ (GeV/c)}^2$ for a significantly improved determination of this fundamental quantity.

The SANE experiment will be carried out the Jefferson Lab CEBAF and Hall C facilities and the UVa NH_3 polarized target. The goal is to perform the measurement of two asymmetries for two different orientations of the target magnetic field relative to the beam direction. And to extract in a model-independent fashion the proton A_1^p only limited by systematic errors and a simultaneous statistics limited measurement of g_2^p in the range $0.3 \leq x \leq 0.8$ at an average $Q^2 = 4.5 \text{ GeV}^2$. The scattered electrons will be detected in the Big Electron Telescope Array (*BETA*) detector.

The measured A_1 and g_2 will be used directly to:

1. study their Q^2 dependence at fixed x in both the DIS and resonance region,
2. probe the approach of A_1 to $x = 1$ at constant Q^2 in order to test quark models and pQCD, combining SANE's results with the world data sample,
3. determine $\bar{g}_2$ with high precision in the critical region $0.3 \leq x \leq 0.8$ at fixed Q^2 , and compute d_2^p combining SANE and SLAC data.

Finally, the non-singlet combination $d_2^p - d_2^n$ will be used as a true benchmark test with Lattice QCD calculations. This quantity is free from the disconnected diagrams (sea contributions) which are not presently evaluated in the Lattice determination of the singlet quantities for the proton or neutron.

FIGURE 4. Statistical uncertainties in $x^2 g_2^p$ and $x^2 g_1^p$ in $\Delta Q^2 = 1 \text{ GeV}^2$ bins as a function of x . The E155 fit [10] to g_1/F_1 was used to calculate g_1 and g_2^{WW} for the solid lines. The projected uncertainties for 6.0 GeV are shown as solid circles and for 4.8 GeV as hollow squares.

ACKNOWLEDGMENTS

I would like to thank the organizers for the invitation to speak about this subject.

REFERENCES

1. E. Shuryak and A. Vainshtein, Nuc. Phys. B **201** (1982) 141.
2. R. L. Jaffe and X. Ji, Phys. Rev. D **43** (1991) 724.
3. E. Stein *et al.*, Phys. Lett. B **353**, 107 (1995).
4. X. Ji, hep-ph/9510362.
5. B. W. Filippone and X. Ji, Adv. in Nucl. Phys. **26**, 1 (2001).
6. SLAC E155: P. L. Anthony *et al.*, Phys. Lett. B **553**, 18 (2003).
7. D. Drechsel, S. Kamalov and L. Tiator, Phys. Rev. D **63**, 114010 (2001).
8. C. W. Kao, T. Spitzenberg and M. Vanderhaeghen, Phys. Rev. D **67**, 016001 (2003).
9. M. Gockeler *et al.*, Phys. Rev. D **72**, 054507 (2005) [arXiv:hep-lat/0506017].
10. P.L. Anthony *et al.*, Phys. Lett. B **493**, 19 (2000).
11. Jefferson Lab experiment E06-114, S. Choi, X. Jiang, Z.-E. Meziani and B. Sawatzky spokespersons.
12. M. Amarian *et al.* [Jefferson Lab E94-010 Collaboration], Phys. Rev. Lett. **92**, 022301 (2004).
13. Jefferson Lab experiment E03-110, O. Rondon, S. Choi, and Z.-E. Meziani spokespersons.
14. M. Buenerd, "Study of the Background in the E154 Data", April 22, 1996. Unpublished.