Measurement of the Transverse Spin Structure of the Proton at Medium to Low Momentum Transfer*

H. Kang,[1,2] W. Armstrong,[3] A. Liyanage,[4] J. Maxwell,[5] J. Mulholland,[5] L. Ndukum,[6] A. Ahmidouch,[7] I. Albayrak,[4] A. Asaturyan,[8] O. Ates,[4] H. Baghdasaryan,[5] W. Boeglin,[9] P. Bosted,[10] E. Brash,[11,10] C. Butuceanu,[12] M. Bychkov,[5] P. Carter,[11] C. Chen,[4] J.-P. Chen,[10] S. Choi,[1,2] S. Covrig,[10] D. Crabb,[5] S. Danagoulian,[7] A. Daniel,[13] A.M. Davidenko,[14] B. Davis,[7] D. Day,[5] W. Deconink,[10] A. Deur,[10] J. Dunne,[6] D. Dutta,[6] M. E. Christy,[4] L. El Fassi,[15] C. Ellis,[10] R. Ent,[10] D. Flay,[3] E. Frlez,[5] D. Gaskell,[10] O. Geagla,[5] J. German,[7] R. Gilman,[15] J. Gomez,[10] Y.M. Goncharenko,[14] O. Hashimoto,[16] D. Higinbotham,[10] T. Horn,[10] G. Huber,[12] M. Jones,[7] M. K. Jones,[10] N. Kalantarians,[5] H-K. Kang,[1,2] D. Kawama,[16] C. Keppel,[4] M. Khandaker,[17] Y. Kim,[1,2] P.M. King,[13] M. Kohl,[4] K. Kovacs,[5] V.I. Kravtsov,[14] V. Kubarovsky,[18] Y. Li,[4] N. Liyanage,[5] W. Luo,[19] D. Mack,[10] V. Mamyan,[5] P. Markowitz,[9] T. Maruta,[16] Y.M. Melnik,[14] Z.-E. Meziani,[3] A. Mkrtchyan,[8] H. Mkrtchyan,[8] V.V. Mochalov,[14] P. Monaghan,[4] A. Narayan,[6] S. Nue Nakamura,[16] L. Pentchev,[20] D. Pocanic,[5] M. Posik,[3] A. Puckett, X. Qiu,[4] J. Reinhold,[9] S. Riordan,[5] J. Roche,[13] O. Rondon,[5] B. Sawatzky,[3] M. Shabestari,[5] K. Slifer,[21] G. Smith,[10] L. Soloviev,[14] P. Solvignon,[22] Nuruzzaman,[6] V. Tadevosyan,[8] L. Tang,[4] G. Toshiyuki,[16] A. Vasiliev,[14] M. Veilleux,[11] T. Walton,[4] F. Wesselmann,[23] S. Wood,[10] H. Yao,[3] Z. Ye,[4] and L. Zhu[4]

(SANE Collaboration)

[1] *Seoul National University, Seoul, Korea*
[2] *Institute for Nuclear and Particle Astrophysics, Seoul National University, Seoul, Korea*
[3] *Temple University, Philadelphia, PA*
[4] *Hampton University, Hampton, VA*
[5] *University of Virginia, Charlottesville, VA*
[6] *Mississippi State University, Jackson. MI*
[7] *North Carolina A&M State University, Greensboro, NC*
[8] *Yerevan Physics Institute, Yerevan, Armenia*
[9] *Florida International University, Miami, FL*
[10] *Thomas Jefferson National Accelerator Facility, Newport News, VA*
[11] *Christopher Newport University, Newport News, VA*
[12] *University of Regina, Regina, SK*
[13] *Ohio University, Athens, OH*
[14] *Institute for High Energy Physics, Protvino, Moscow Region, Russia*
[15] *Rutgers University, New Brunswick, NJ*
[16] *Tohoku U., Tohoku, Japan*
[17] *Norfolk State University, Norfolk, VA*
[18] *Rensselaer Polytechnic Institute, Troy, NY*
[19] *Lanzhou University, Lanzhou 730000, Gansu, People's Republic of China*
[20] *College of William and Mary, Williamsburg, VA*
[21] *University of New Hampshire*
[22] *Argonne National Laboratory, Argonne, IL*
[23] *Xavier Unniversity, New Orleans, LA*

(Dated: December 2, 2016)

The spin structure of the proton has been investigated in the high Bjorken x and low to medium momentum transfer Q^2 region. Using Jefferson Lab's polarized electron beam on a polarized target, the scattered electrons have been detected by HMS spectrometer of Hall-C. By rotating the spin direction of the polarized target, both the parallel and perpendicular spin asymmetries $A_\parallel$ and $A_\perp$ have been measured. These asymmetries produced the physics asymmetries A_1 and A_2 and spin structure functions g_1 and g_2. We found Q^2 dependence of the asymmetries at resonance region $1.1\ GeV < W < 1.6\ GeV$ and a possible negative longitudinal virtual photon amplitude at the Roper resonance. Also we observed an indication for a negative d_2 value, which characterizes the higher twist effect in the nucleon.

PACS numbers: 13.60.-r, 13.40.Gp, 13.88.+e, 14.20.Dh

Inelastic lepton-nucleon scattering has long been a powerful tool to investigate the structure of nucleon. Ever since experiments with polarized lepton beam and nuclear target were technically accessible, various experiments have studied the nucleon spin structure. One of these first experiments, the EMC experiment has found out that the valence quarks of the proton do not fully explain the proton's spin [1]. It has been the starting point of a series of intensive studies of spin structure of the nucleon. For example, several experiments at SLAC [2], CERN [3], DESY [4], and JLab [5] have followed until recently. Most of these studies have usually concentrated on deep inelastic scattering (DIS) region with relatively large momentum transfer(Q^2), which can be understood using perturbative QCD. But lower momentum transfer regions have received attention recently due to its non-perturbative features. In such regions, nucleon resonances can be dominant, and intermediate phenomena between short and long distance structures can be studied.

The full description of the spin structure of the nucleon requires two spin structure functions g_1 and g_2. The g_1 structure function is easier to understand in terms of the difference of quark distribution functions for different spin directions with respect to the target nucleon. In naive quark model at DIS limit, g_1 structure function can be written as

$$g_1(x) = \sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)], \qquad (1)$$

where $q_i^{\uparrow(\downarrow)}(x)$ is the quark distributions for two different spin directions with respect to the spin of the nucleon. The g_2 structure function is more complex and especially $g_2(x) = 0$ in naive quark model. The g_2 structure function contains contributions from higher twist effects. Under the formalism of the operator product expansion (OPE) method for QCD[6, 7], it can be shown that the twist-2 contribution to g_2 can be derived from g_1 by Wandzura-Wilczek relation [8],

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(x', Q^2)}{x'} dx', \quad (2)$$

where g_2^{WW} is the leading-twist contribution to g_2. Then the remaining part, $\bar{g}_2 = g_2 - g_2^{WW}$ can be used to investigate higher twist effects. The higher twist component of g_2 can be interpreted as an increased quark-gluon correlation. Since each order of higher twist effect adds $1/\sqrt{Q^2}$ term, the study on $\bar{g}_2$ can be done more favorably at low Q^2 region. Especially twist-3 contribution could be measured by the third moments of $\bar{g}_2$ [7],

$$d_2 = 3 \int_0^1 x^2 \bar{g}_2 dx = \int_0^1 x^2 (2g_1 + 3g_2) dx. \qquad (3)$$

Due to technical difficulties, experiments with longitudinally polarized nuclear targets have been dominant so far in the kinematic region of large Bjorken x and low to medium momentum transfer Q^2. As a result, most of the experiments have been focused on the spin structure function g_1. The g_2 structure function can be directly studied only with transverse target polarization with respect to that of the beam. In this respect, Jefferson Lab offers quite a unique opportunity to study g_2 structure function of the nucleon.

After the previous JLab experiment E01-006 (RSS) produced successful results on this higher twist contribution [9, 10], the upgraded successor E07-003 investigated wider kinematic region [11]. As a measurement of the spin asymmetries of the proton, it has been carried out in Hall C at Thomas Jefferson National Laboratory (JLab) by Spin Asymmetries of the Nucleon Experiment (SANE) Collaboration. Using a polarized electron beam and a polarized ammonia target, it produced asymmetry data for both parallel and near-perpendicular spin configurations of the beam and the target. The world data of proton spin asymmetries, especially perpendicular asymmetry $A_\perp$, are still scarce for quite large kinematic region, except a few data points from SLAC experiments[2, 4, 9, 12, 13]. SANE will provide precision data for these unexplored region.

SANE used two detector complexes, Big Electron Telescope Array (BETA) and High Momentum Spectrometer (HMS) for this purpose. BETA covered a large solid angle of 200 msr, and served as a main detector. HMS, a built-in spectrometer of Hall C, collected complementary data. Although HMS was not the main detector of the experiment, in the end, we managed to collect a good amount of data with HMS independently of BETA. HMS has been located toward the right of the beam direction.

As an inclusive double spin asymmetry measurement, polarized electron beam of 4.7 and 5.9 GeV has been used. The nominal beam current was 90 nA. Average beam polarization was about 73 %. It was measured by a Møller polarimeter routinely all along the experiment[14]. The spin direction of the electron beam has been flipped at a rate of 30 Hz on a pseudo-random basis to minimize systematic errors.

The HMS detected the scattered electrons at various scattering angles, 15.4°, 16.0°, 20.2°. Combination of the beam energy and the momentum of the scattered electrons measured with HMS defines the kinematic range of the experiment. The new data covers four-momentum transfer, Q^2 of 0.8, 1.3, and 1.9 (GeV/c)^2, for the region from the resonance up to invariant mass of $W = 2.3$ GeVc^2. They can also extend the kinematic region in W at roughly the same values of Q^2 of the previous JLab E01-006 (RSS) experiment, allowing better determination of the integrals involving g_2 and the Q^2 dependence of A_1 and A_2 in the resonance region.The detector package of the HMS is composed of hodoscope planes, wire chambers, a Čerenkov detector, and a lead glass calorimeter. A detailed description of the equipments can be found in Ref. [15, 16].

Solid $^{14}NH_3$ was used for the polarized proton target. The target cell of the frozen ammonia was 3 cm long and cooled down with liquid ^{4}He. The necessary magnetic field has been provided by 5 T superconducting magnet. The protons inside the ammonia molecule have been polarized by the process of the Dynamic Nuclear Polarization (DNP) with the provided microwave radiation. The degree of the polarization has been monitored by an NMR system in real time and an average of 67% has been achieved during the experiment. For asymmetry measurement in near-perpendicular configuration, the whole target magnet was rotated by 80° with the direction of the electron beam. The target system as a whole has been developed by University of Virginia [17].

Granular type of the frozen ammonia does not fill the target cell completely and the actual amount of the target material is quantified by the packing fraction. Using Monte Carlo (MC) simulation based on empirical fit of inelastic cross section [18], simulation results with an assumed value of the packing fraction have been compared with the actual HMS data. In this way, the packing fraction and the corresponding dilution factor have been deduced. The technical details are the same as the method used in JLab E01-006 (RSS) experiment [19]. The experimental data and the MC simulation result show a good agreement and the packing fractions of SANE have been determined to be 56 - 62 % with an error of 4.5 % point. The packing fractions and the dilution factors determined from the HMS data will also be used to correct the data taken with BETA.

Beam polarization was measured by Møller Polarimeter routinely. It used the Møller scattering on the iron foil, which was polarized by 4 T superconducting solenoid. The measurement was fitted by the following parameters: the polarization at the source, the degree of imbalance between north and south linac, and a global correction from the beam energy [20]. The beam polarization of each run, therefore, was an extrapolation of this fit. The NMR signal from the pickup coil inside the target cell gave the Q-curve of resonant circuit. The Q-curve area was calibrated by the known polarization at the thermal equilibrium [21].

The raw asymmetries have been corrected by the charge and dead time asymmetries between the two spin directions of the electron beam. The charge asymmetries from the beam current monitor was cross-checked with the false asymmetries from the unpolarized carbon target. After dividing raw asymmetries by beam and target polarization and dilution factor, the physical asymmetries can be obtained.

Finally, the radiative corrections are applied to deduce Born asymmetries. Since the experiment involves both polarized beam and target, the procedure of POLRAD [22] has been used. The starting parametrization for the Born asymmetries has been constructed by fitting the measured asymmetries as a function of Q^2 and W. The fitting function includes appropriate resonances with Breit-Wigner formula and a polynomial term with dependence on Q^2. The iterative unfolding procedure has been repeated until the convergence of the parametrization of the Born asymmetries.

Applying all the required corrections, the physics asymmetries can be expressed by the following equation:

$$A_{\parallel,\perp} = \frac{1}{f C_N P_b P_t f_{RC}} \frac{N_+ - N_-}{N_+ + N_-} + A_{RC}, \qquad (4)$$

where $N_\pm$ is the charge-normalized yield for positive (negative) beam helicity, f is the dilution factor, C_N is the correction for a tiny ^{14}N nuclear polarization, P_b and P_t are the beam and target polarizations, and f_{RC} and A_{RC} are radiative corrections to the unpolarized total cross sections and asymmetries, respectively.

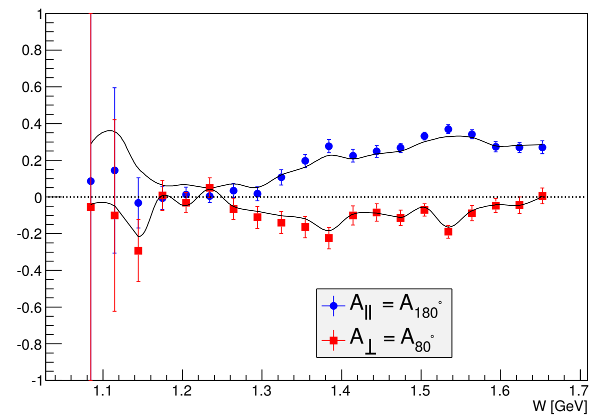

FIG. 1. The fully corrected asymmetries, without radiative correction (curves) and with radiative correction (points) for both configurations of the polarization direction for the beam and the target. $A_\perp$ in this plot means the near-perpendicular asymmetry A_{80°.

The fully corrected asymmetries are shown in Fig. 1. $A_\perp$ in this plot means the near-perpendicular asymmetry A_{80°.

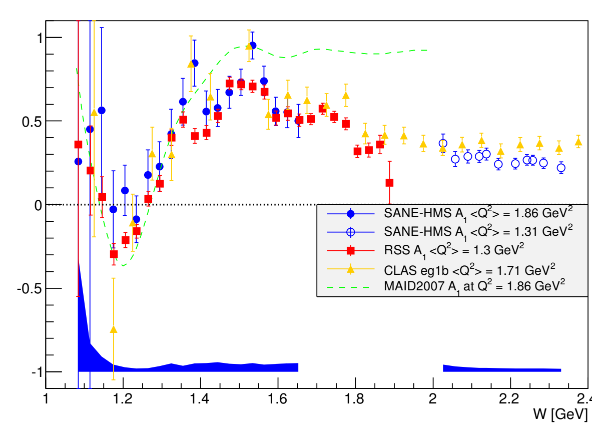

FIG. 2. Virtual photon asymmetry A_1 from our data and comparison with those from other experiments [5, 9] and MAID fits [23], smaller error bars indicating systematic uncertainty.

The measured asymmetries are a linear combinations of virtual photon asymmetries A_1 and A_2, or the spin structure functions g_1 and g_2 [24]. Fig. 2 shows the virtual photon asymmetry A_1. The figure shows a good agreement with the previous measurements from JLab CLAS at similar value of Q^2. The JLab E01-006 (RSS) data were taken at somewhat lower values of Q^2 and the difference between the RSS and SANE data might indicate Q^2 evolution of A_1 asymmetry. This difference can be understood as an evolution of a few resonances as a function of Q^2, especially for the resonances around $W \approx$ 1.4 and 1.5 GeV/c^2.

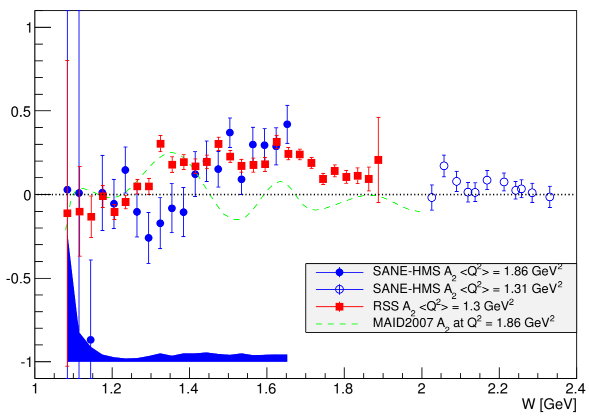

FIG. 3. Virtual photon asymmetry A_2 from our data, JLab E01-006 (RSS) [9] and MAID fits [23], smaller error bars indicating systematic uncertainty.

The main result from SANE-HMS is the first measurement of A_2 asymmetries in this kinematic region, which is shown in Fig. 3. Previously, only JLab E01-006 (RSS) result at somewhat smaller Q^2 and a few empirical fits have existed. SANE data found a resonance structure at 1.2 GeV/c^2 $< W <$ 1.4 GeV/c^2 with zero or negative value of A_2. The peak position of the resonance has been determined at 1.323 $\pm$ 0.010 GeV/c^2 from the fitting of the data. It is interesting to note that although Q^2 difference between RSS and SANE-HMS is just ~ 0.6 (GeV/c)^2, the value of A_2 for the resonance shows a sign change from RSS to SANE-HMS. It could be an indication of a large and negative transverse-longitudinal interference contribution at this resonance, since $A_2 = \sigma_{LT}/\sigma_T$. Compared to the fitting parameters for A_1, it could be an indirect evidence of two poles of Roper resonance [25].

Our g_2 shown in Fig. 4 is quite different from JLab E01-006 (RSS), and it is due to large Q^2 dependence of A_2. As with A_2, SANE-HMS g_2 is the first measurement in this kinematic region, $\langle Q^2 \rangle = 1.86$ (GeV/c)^2 and $0.47 < x < 0.87$. Non-zero difference between g_2 and g_2^{WW}, obtained from the measured g_1, shows higher twist effect.

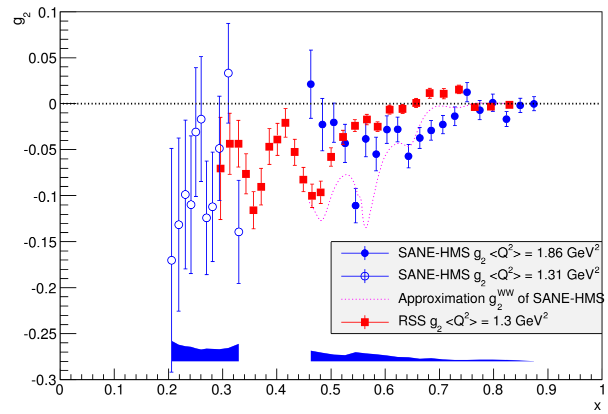

FIG. 4. Virtual photon asymmetry A_2 from our data and RSS [9] and MAID fits [23], smaller error bars indicating systematic uncertainty.

Using the fitting function evaluated at $Q^2 =$ 1.9 (GeV/c)^2, d_2 integral has been obtained. We find $\bar{d}_2 = -0.0087 \pm 0.0014$ over the measured x region. It is the first negative result experimentally obtained [4, 9, 13]. Though theoretical predictions of d_2 using Bag Model [26–28], Lattice QCD [29], and Chiral Soliton models [30, 31] are all positive, QCD sum rule based predictions[32–34] are negative, and the values are compatible with our result.

In summary, the spin structure functions of the proton have been measured in medium to low Q^2 region. Especially, we have measured the virtual photon asymmetries and the spin structure functions of the proton at $\langle Q^2 \rangle = 1.86$ (GeV/c)^2 in the resonance region for the first time. When compared with the previous result at somewhat lower Q^2, the asymmetries and spin structure functions show Q^2 evolution clearly. We also calculated the corresponding d_2 integral and its value turns out to be negative.

* The title and author list to be determined for submission

[1] J. Ashman *et al.* (EMC Collaboration), Phys. Lett. B **206**, 364 (1988).
[2] K. Abe *et al.* (E143 Collaboration), Phys. Rev. D **58**, 112003 (1998).
[3] E. S. Ageev *et al.* (COMPASS Collaboration), Phys. Lett. B **612**, 154 (2005).
[4] A. Airapetian *et al.*, Eur. Phys. J. C **72**, 1921 (2012).
[5] K. V. Dharmawardane *et al.* (CLAS Collaboration), Phys. Lett. B **641**, 11 (2006).
[6] J. Kodaira, S. Matsuda, K. Sasaki, and T. Uematsu, Nucl. Phys. B **159**, 99 (1979).
[7] R. Jaffe, Comments Nucl. Part. Phys. **19**, 239 (1990).
[8] S. Wandzura and F. Wilczek, Phys. Lett. B **72**, 195 (1977).
[9] F. R. Wesselmann *et al.* (RSS Collaboration), Phys. Rev.

Lett. **98**, 132003 (2007).

[10] K. Slifer *et al.* (RSS Collaboration), Phys. Rev. Lett. **105**, 101601 (2010).

[11] J. Jourdan *et al.*, *Update to TJNAF E-03-109: Spin Asymmetries on the Nucleon Experiment-SANE*, Tech. Rep. (2006).

[12] P. L. Anthony *et al.* (E155 Collaboration), Phys. Lett. B **458**, 529 (1999).

[13] P. L. Anthony *et al.* (E155 Collaboration), Phys. Lett. B **553**, 18 (2003).

[14] M. Hauger *et al.*, Nucl. Instrum. Meth. **A462**, 382 (2001), arXiv:nucl-ex/9910013 [nucl-ex].

[15] M. K. Jones *et al.* (Resonance Spin Structure Collaboration), Phys. Rev. C **74**, 035201 (2006).

[16] A. Liyanage, *Proton form factor ratio, $\mu_p G_E^P/G_M^P$ from double spin asymmtry*, Ph.D. thesis, Hampton University (2013).

[17] D. Crabb and D. Day, Nucl. Instrum. Methods Phys. Res. Sect. A **356**, 9 (1995).

[18] P. E. Bosted and M. E. Christy, Phys. Rev. C **77**, 065206 (2008).

[19] O. A. Rondón, *The Packing Fraction and Dilution Factor in RSS*, Tech. Rep. (2006).

[20] J. M. Grames *et al.*, Phys. Rev. ST Accel. Beams **7**, 042802 (2004).

[21] J. D. Maxwell, *Probing proton spin structure: a measurement of g_2 at four-momentum transfer of 2 to 6 GeV^2*, Ph.D. thesis, University of Virginia (2011).

[22] I. Akushevich, A. Ilyichev, N. Shumeiko, A. Soroko, and A. Tolkachev, Acta Phys. Polon. B **28**, 563 (1997).

[23] F. Lee, T. Mart, C. Bennhold, and L. Wright, Nucl. Phys. **A695**, 237 (2001), arXiv:nucl-th/9907119.

[24] M. Anselmino, M. Boglione, and F. Murgia, Phys. Lett. B **362**, 164 (1995).

[25] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **74**, 045205 (2006).

[26] X. Song, Phys. Rev. D **54**, 1955 (1996).

[27] M. Stratmann, Zeitschrift für Physik C Particles and Fields **60**, 763 (1993).

[28] X. Ji and P. Unrau, Phys. Lett. B **333**, 228 (1994), hep-ph/9308263.

[29] M. Göckeler, R. Horsley, W. Kürzinger, H. Oelrich, D. Pleiter, P. E. L. Rakow, A. Schäfer, and G. Schierholz, Phys. Rev. D **63**, 074506 (2001).

[30] H. Weigel and L. Gamberg, Nucl. Phys. A **680**, 48 (2001), quark Nuclear Physics 2000.

[31] M. Wakamatsu, Phys. Lett. B **487**, 118 (2000).

[32] E. Stein, P. Górnicki, L. Mankiewicz, A. Schäfer, and W. Greiner, Phys. Lett. B **343**, 369 (1995).

[33] I. Balitsky, V. Braun, and A. Kolesnichenko, Phys. Lett. B **242**, 245 (1990).

[34] B. Ehrnsperger and A. Schäfer, Phys. Rev. D **52**, 2709 (1995).