Spin Physics Program in Jefferson Lab's Hall C

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Abstract. The nucleon spin structure has been studied at Jefferson Lab's Hall C in experiments RSS (E01-006) and SANE (E07-003), which measured double spin asymmetries using the U. of Virginia solid polarized target and CEBAF's 6 GeV polarized electrons. The proton longitudinal spin structure g_1 and transverse structure g_2 have been investigated at kinematics extending from the elastic point to DIS, for four-momenta squared ranging from 0.8 to 5 GeV^2. The neutron structures have been measured in the region of the nucleon resonances at 1.3 GeV^2 on a deuteron target. Results of both experiments will be highlighted. A brief survey of approved experiments for the 12 GeV program will also be presented.

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PROBING NUCLEON STRUCTURE WITH POLARIZED ELECTROMAGNETIC SCATTERING

Inelastic inclusive electromagnetic scattering is described by hadronic and leptonic tensors. The hadronic tensor $W_{\mu\nu}$, representing the target, is reduced by application of symmetries to two unpolarized structure functions, W_1 and W_2, and two spin-dependent ones, G_1 and G_2, all of which are functions of the energy transfer ν and the four-momentum transfer $Q^2 = -q^2$. The spin dependent anti-symmetric part of the tensor is:

$$W^A_{\mu\nu} = 2\varepsilon_{\mu\nu\lambda\sigma} q^\lambda \Big\{ M^2 S^\sigma G_1(\nu, Q^2) + \big[M\nu S^\sigma - p^\sigma S\cdot q \big] G_2(\nu, Q^2) \Big\}. \quad (1)$$

The four structure functions, G_1, G_2, W_1 and W_2, contain all the information on nucleon structure that can be extracted from inclusive EM scattering. In the deep inelastic scattering (DIS) regime at high energy the structure functions scale, up to log corrections, as functions of only the Bjorken scaling variable $x = Q^2/(2M\nu)$, with M being the nucleon mass. The scaling unpolarized functions are the familiar $F_1(x)$ and $F_2(x)$. The corresponding spin dependent ones are

$$\lim_{Q^2,\nu\to\infty} (M\nu) M G_1(\nu, Q^2) = g_1(x), \qquad \lim_{Q^2,\nu\to\infty} (M\nu)\nu G_2(\nu, Q^2) = g_2(x).$$

The longitudinal spin structure function (SSF) $g_1(x)$ can be described in terms of quark helicity distributions of each flavor, $g_1(x) = (1/2)\sum e_q^2 \big(q_q^{\uparrow}(x) - q_q^{\downarrow}(x)\big)$, $q = u, d, s,$ ... The transverse structure g_2 has no partonic equivalent.

The hadronic tensor is also related, by the optical theorem, to the forward virtual Compton amplitude. Hence, the SSF's are related to the virtual photon absorption cross sections, $\sigma^T_{1/2}$, $\sigma^T_{3/2}$, for photon helicities $+1$, -1, and to the transverse–longitudinal interference $\sigma^{TL}_{1/2}$. The spin asymmetries (SA) A_1 and A_2 are constructed from these cross sections and the unpolarized scaling $F_1(x, Q^2) = MW_1(\nu, Q^2)$:

$$A_1(x, Q^2) = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{1}{F_1}\big(g_1 - \gamma^2 g_2\big), \qquad A_2(x, Q^2) = \frac{\sigma^{TL}}{2\sigma^T} = \frac{\gamma}{F_1}(g_1 + g_2) = \frac{\gamma}{F_1} g_T,$$

where $2\sigma^T = \sigma^T_{3/2} + \sigma^T_{1/2}$, $\gamma^2 = (2xM)^2/Q^2$, and g_T is the transverse polarized structure function. The Soffer-Teryaev limit applies to $A_2 \le \sqrt{R(1+A_1)/2)} \le R$, where $R = \sigma_L/\sigma_T$.

g_1 and g_2 can be separated by measuring cross section differences for opposite beam helicities with target spins parallel and transverse to the beam. g_2 dominates the cross section difference for opposite beam helicities with orthogonal beam and target spins

$$\Delta\sigma_\perp = 4\alpha^2 E'^2 \sin\theta \cos\phi \big(MG_1 + 2EG_2\big)/(EQ^2),$$

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where E is the beam energy and E', θ, and ϕ are the scattered particle energy, and its polar and azimuthal angles. g_1 is a twist-2 quantity (plus higher order QCD corrections), while g_2 has both twist-2 and twist-3 contributions. Operators of both twist-2 (the “handbag" Feynman diagram) and twist-3 (quark-gluon correlations beyond the usual logarithmic or α_S corrections) contribute in leading order to the Compton amplitude for transverse polarized scattering. This unique feature of transverse polarized scattering allows access to sub-leading, twist-3 processes in a direct measurement [1], opening a window on the confinement of quarks and gluons inside nucleons.

In terms of quark distributions $g_T(x) = (1/2)\sum e_q^2 g_T^q(x)$ can be decomposed as [2]

$$g_T^q(x) = \int d^2k_t \frac{\overrightarrow{k_t}^2}{2M} \frac{g_{1T}^q(x, \overrightarrow{k_t}^2)}{x} + \frac{m}{M} h_1^q(x) + \tilde{g}_T^q(x), \tag{2}$$

where the first term involves the twist-3 chiral-even transverse momentum dependent distribution (TMD) $g_{1T}^q(x, \overrightarrow{k_t}^2)$ with k_t representing the (unobservable) quark transverse momentum. The twist-2 chiral-odd transversity TMD $h_1(x)$ is suppressed by the quark mass m. The last term, $\tilde{g}_T(x)$, represents twist-3 quark-gluon interactions. The twist-2 part (Wandzura-Wilczek) of $g_2 = g_2^{WW} + \overline{g}_2$, with $g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 dy\ g_1(y, Q^2)/y$, can be used to isolate twist-3 contributions that come from qg interactions and from g_{1T} (neglecting m dependent terms)

$$\overline{g}_2(x) = \frac{1}{2}\sum e_q^2 \Big[\tilde{g}_T^q(x) - \int_x^1 \frac{dy}{y}\left(\tilde{g}_T^q(y) - \hat{g}_T^q(y)\right)\Big]. \tag{3}$$

The twist-3 term $\hat{g}_T$ may not vanish in the Lorentz invariant relation [3] $g_2(x) = dg_{1T}^{(1)}(x)/dx + \hat{g}_T(x)$.

HALL C SPIN EXPERIMENTS

The Hall C Spin Structure Program at 6 GeV consisted of inclusive measurements of the SSF's in the nucleon resonances - *RSS* [4, 5, 6], and of the proton SSF at high Bjorken x - SANE, for which preliminary results are available. A precision measurement of the deuteron spin structure g_1^d/F_1^d, which was planned to run after SANE did not take data in Hall C, but was partially completed in Hall B, as part of eg1/DVCS. A semi-inclusive measurement to do a Flavor Decomposition of Spin - SemiSANE has been moved to the 12 GeV program, along with an experiment with real polarized photons to study Wide Angle Compton Scattering - WACS, which, although not related to spin structure, involves the use of polarized beam and target.

The *RSS* [1] experiment was designed to make high precision and high resolution measurements of the spin structure of the proton and deuteron in the region of the nucleon resonances At $Q^2 \sim 1.3$ GeV^2 the experiment focused on the dependence of the SA's $A_1(W, Q^2)$ and $A_2(W, Q^2)$ on the final state's invariant mass W. Additional goals were to explore the effects of quark-gluon interactions which can be represented by twist-3 matrix elements calculable in Lattice QCD, and probe the extension of local DIS-resonances duality, observed in unpolarized scattering, to spin degrees of freedom.

The Spin Asymmetries of the Nucleon Experiment - SANE was carried out in Hall C at JLab, by the SANE collaboration [7]. The proton spin structure was measured in the region of $0.3 \leq x \leq 0.8$, for 2.5 GeV$^2 \leq Q^2 \leq$ 6.5 GeV^2, filling a major gap in the data on the transverse spin asymmetry. SANE's goal is to learn all we can about proton spin structure from an inclusive double polarization measurement.

Both experiments used many identical pieces of Hall C standard equipment: the beam line upstream of the polarized target, the Møller polarimeter, and the High Momentum Spectrometer (HMS). Some modifications to the polarized target and to the downstream beam line were required for SANE, including shielding to reduce beam line background.

High energy polarized electrons were delivered into the Hall by CEBAF. The beam polarization P_b was about 75%. The beam current was limited to about 100 nA because of the target cryogenic restrictions.

The HMS was the only detector used in *RSS*. For SANE's measurement, electrons in DIS kinematics were also detected in the *Big Electron Telescope Array* (BETA), a novel large solid angle non-magnetic detector consisting of

[1] Resonances Spin Structure – *RSS* Collaboration (JLab E-01-006): U. Basel, Florida International U., Hampton U., U. Massachusetts, U. Maryland, Mississippi S. U., North Carolina A&T U., U. of N. C. at Wilmington, Norfolk State U., Old Dominion U., S. U. New Orleans, U. of Tel-Aviv, TJNAF, U. of Virginia, Virginia P. I. & S. U., Yerevan Physics I.; O. A. Rondon-Aramayo, UVA and M. Jones, JLab, Spokesmen.

four subsystems: a 1744-elements lead glass calorimeter (*BigCal*), which was built for G_E^p/G_M^p (TJNAF E04-108/E04-019); a gas Cherenkov with a 5.9 GeV/c pion momentum threshold, built by Temple University; a 26-elements Lucite Cherenkov hodoscope, built by North Carolina A&T State U.; and a forward tracking hodoscope, built by Norfolk State U. and U. of Regina. The detector configuration is shown on the left panel of Fig. 1, along with a simulated DIS electron event. BETA's solid angle after cuts is 194 msr.

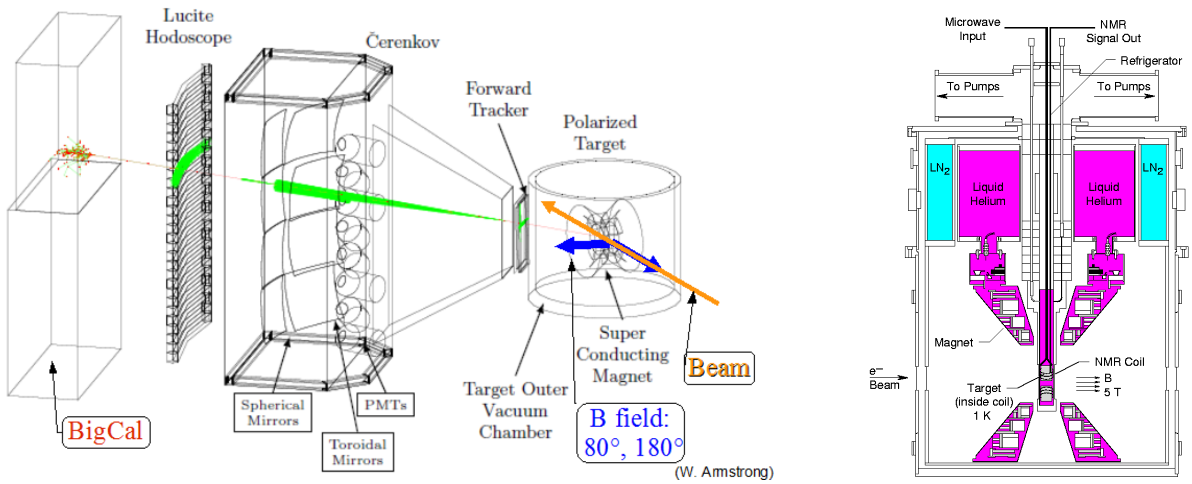

FIGURE 1. LEFT: BETA with DIS electron simulation. (Drawing by W. Armstrong). RIGHT: Diagram of the polarized target.

The polarized target uses a 5 T field to achieve in-beam polarizations P_t of 70% for protons and 20% for deuterons, by dynamic nuclear polarization of frozen ammonia at 1 K. Its field axis can be aligned along a wide range of angles relative to the beam. A diagram of the target is shown on the right panel of Fig. 1.

DATA

Double spin asymmetries were measured for each field direction. Raw asymmetries ε were formed from the difference over the sum of yields N^+, N^- for each beam helicity, after beam charge normalization and live time corrections. The measured asymmetries for each orientation are $A_m = \varepsilon/(fP_bP_t)$, where f is the fraction of events scattered off polarized protons. The physics asymmetries include corrections for the elastic radiative tail, internal and external radiative effects and elastic asymmetry, and for the background of e^+, e^- pairs resulting from π^0 Dalitz and γ decays. BETA's data are more sensitive to this background than the HMS, because of the telescope's non-magnetic design. The physics asymmetries were combined to obtain A_1 and A_2 with the aid of the unpolarized structure function R [8]. The SSF's g_1 and g_2 are then obtained from A_1 or A_2 and F_1 [8]. Table 1 summarizes the data collected in both experiments.

TABLE 1. Data collected by *RSS* and SANE

Experiment	Detector	Particle	Scattering Type	Beam Energy	Field Axis	Target
RSS	HMS	e	Inclusive Inelastic & Elastic	5.76 GeV	180°,90°	NH_3, ND_3 C, He
SANE	BETA	e, π^0	Inclusive Inelastic	5.9, 4.7 GeV	180°,80°	NH_3
	HMS	e	Inclusive Inelastic	5.9, 4.7 GeV	180°,80°	NH_3, C, He
			Inclusive Elastic	5.9 GeV	80°	NH_3
	BETA+HMS	$e-p$	Coincidence Elastic	5.9 GeV	80°	NH_3

A_1 and A_2 data published by *RSS* [4] indicate the presence of a resonant structure at W around 1350 MeV, which has attracted interest from theoreticians [9]. This observation motivated the collection of additional data at $Q^2 \simeq 1.8$ GeV^2 during SANE, to test the persistence of the feature. SANE preliminary results for A_1 are shown on the left panel of Fig. 2, along with the *RSS* A_1 at $Q^2 = 1.3$ GeV^2, and Hall B eg1b data at 1.7 GeV^2. The right panel shows the corresponding results for A_2. Additional HMS data were taken during SANE at $Q^2 = 1.3$ GeV^2 to extend the kinematic range of the *RSS* experiment from $W = 1.9$ GeV to ~ 2.3 GeV, and at 0.8 GeV^2 for radiative corrections.

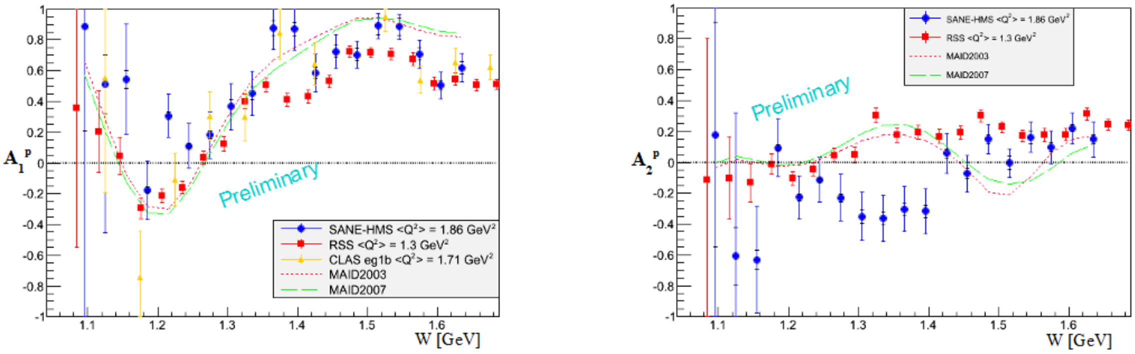

FIGURE 2. LEFT: SANE preliminary results for A_1 at ~ 1.8 GeV^2 (blue circles) along with the *RSS* A_1 [4] at 1.3 GeV^2 (red squares) and the CLAS eg1b [10] data at 1.7 GeV^2 (yellow triangles). The curves are the MAID parametrizations [11] . RIGHT: SANE preliminary results for A_2 at ~ 1.8 GeV^2 (blue circles) along with the *RSS* A_1 [4] at 1.3 GeV^2 (red squares).

Highlights of preliminary results for BETA $A_1^p(W)$ along with SLAC and CLAS data are shown on the left panel of Figure 3. The corresponding results for A_2 are displayed on the right panel. SANE error bars are total errors.

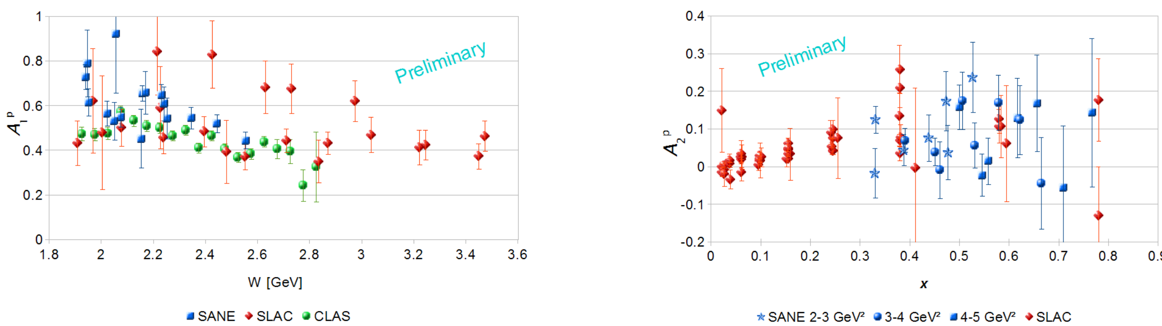

FIGURE 3. LEFT: SANE's preliminary 2012 results for A_1^p plotted as a function of W (squares). Results from SLAC [12, 13] (diamonds) and from CLAS [10] (circles) are also shown (CLAS results of different Q^2 values at the same W bin have been merged). RIGHT: SANE's preliminary 2012 results for A_2^p plotted as a function of Bjorken x for three ranges of Q^2 (stars, circles and squares). Results from SLAC are shown as diamonds.

The *RSS* results for g_2^p and g_2^d [5] at 1.3 GeV^2 are displayed on the left panel of Fig. 4. The difference between the measured SSF and its twist-2 part g_2^{WW} is evident, reflecting the substantial presence of twist-3 processes. Preliminary $x^2 g_2$ results for SANE and older world data are shown on the right panel of Fig. 4, plotted along with g_2^{WW} calculated using parton distribution functions - PDF's. Twist-3 contributions at the higher $Q^2 >\sim 3$ GeV^2 of these data are less obvious, compared to *RSS*.

Quark-gluon correlations are best quantified by using the operator product expansion - OPE to connect quark matrix elements a_n of twist-2 and d_n of twist-3, with the moments of the SSF's. In the Cornwall-Norton (C-N) formulation, the OPE is

$$\begin{aligned}\int_0^1 x^n g_1(x,Q^2)dx &= \frac{1}{2}a_n + TMC, \quad n = 0,2,4,\ldots \\ \int_0^1 x^n g_2(x,Q^2)dx &= \frac{n}{2(n+1)}(d_n - a_n) + TMC, \quad n = 2,4,6,\ldots \qquad (4)\end{aligned}$$

where TMC are target mass corrections of order M^2/Q^2 that cannot be neglected at low Q^2 kinematics, in which case Nachtmann moments are needed to extract matrix elements free of TMC. Results on $d_2(Q^2 = 1.3)$ GeV^2 for the proton, deuteron and neutron, calculated using Nachtmann and C-N moments have been published by *RSS* [5], which found d_2 to be non-zero at the several sigmas level. The twist expansion to $n = 2 \leq 1.3/M_0^2$, with $M_0 \sim 0.5$ GeV, remains valid in the resonances, per resonances–DIS duality. SANE plans to calculate Nachtmann and C-N moments of the SSF's to extract the twist-2 a_0, twist-3 d_2, and, possibly, the twist-4 f_2, after subtracting the twist-2 target mass correction a_2.

Three new spin structure experiments have been approved to run in Hall C with the upgraded 11 GeV CEBAF beam. Two are measurements of the neutron spin structure A_1^n [17] and the twist-3 d_2^n [18] using a ^{3}He polarized gas target. A measurement of the deuteron tensor structure b_1 [19] has also been conditionally approved.

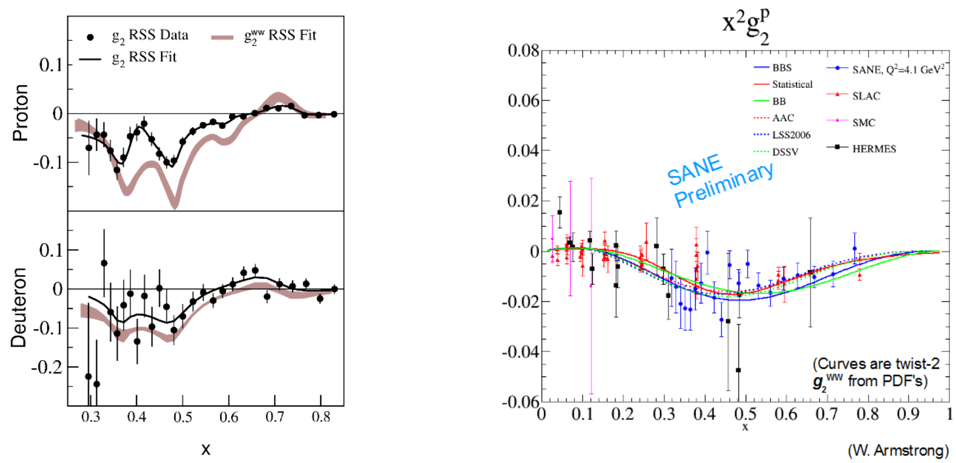

FIGURE 4. LEFT: *RSS* results for g_2^p and g_2^d (solid circles), fit to data (solid), and g_2^{WW} (band) calculated from the *RSS* fit to G_1 [14] (Reprinted with permission from AIP Conf. Proc. 1343, 322 (2011). Copyright 2011 American Institute of Physics) RIGHT: SANE preliminary results for g_2 (blue circles) along with SLAC [12, 13] (red triangles), SMC (magenta symbols) [15], and HERMES [16] (black squares). The curves are g_2^{WW} from PDF's.

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