The spin structure of the nucleon: status and plans for JLab at 11 GeV

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The nucleon spin structure functions (SSF) describe, as their name implies, fundamental properties of the nucleon because they are directly related to the quark helicity distribution and quark-gluon interactions. The SSF's form the antisymmetric part of the hadronic tensor in lepton-nucleon scattering [1,2]. As a consequence, the SSF's can be measured in inclusive inelastic scattering of polarized leptons on polarized nucleons.

When the incident lepton helicity is aligned with the target nucleon spin, the cross section is dominated by g_1, the longitudinal SFF. g_1 can be interpreted in the parton model in terms of helicity densities of the different quark flavors, weighted by the square of the quark charges e_i:

$$g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 [q_i^{\uparrow}(x, Q^2) - q_i^{\downarrow}(x, Q^2)], \qquad i = u, \bar{u}, d, \bar{d}, s, \bar{s}, ... \tag{1}$$

where $x = Q^2/(2M\nu)$ is the Bjorken scaling variable, Q^2 is the four-momentum transfer, M is the nucleon mass and $\nu = E - E'$ is the lepton energy loss.

When the target spin is perpendicular to the lepton helicity, the cross section is dominated by g_2, the transverse SSF. g_2 probes a combination of transverse and longitudinal parton polarization distributions inside the nucleon. g_2 is understood to be made up of two components: a twist-2 part g_2^{WW} and a mixed twist-2/twist-3 part $\overline{g_2}$ [3–5]

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) - \overline{g_2}(x, Q^2). \tag{2}$$

The SSF have been extensively measured in a broad kinematic range, from the deep inelastic scattering regime (DIS) [6–15] through the nucleon resonances up to the pion production threshold [16–21], with both real [22,23] and very high Q^2 virtual photons. From those measurements we have learned that the quarks contribute at most only 30% of the nucleon spin, and that there are small but not negligible quark - gluon interactions in the region of $0.2 \leq x \leq 0.4$.

In spite of the broad DIS SSF program, significant gaps remain in the coverage of the Q^2, x plane, in the region $0.2 \leq x$ for $1 \leq Q^2 \leq 20$, as Fig. 1 and 2 show. In these figures the thick curve with (green) square symbols represents the locus of final state invariant mass $W = 2$ GeV, above which no resonant structures can be discerned in the spectra. The other curves and isolated points represent the central values at the indicated beam energies and scattering angles where measurements of g_1 have been made (SLAC and HERMES,) and of g_2 (SLAC, by experiment) on protons and deuterons. The curve marked with crosses in Fig. 1 is the upper Q^2 limit of the region covered by the Hall B measurement [17,18] of the parallel spin asymmetry ($A_{\|}$) on protons and deuterons. The thick curve with (yellow) circles is the recent Hall C measurement [21] of both parallel and perpendicular ($A_{\perp}$) asymmetries for protons and deuterons. The limited coverage is specially striking for g_2, for which hardly any data exist for $W < 2$ GeV. This region is

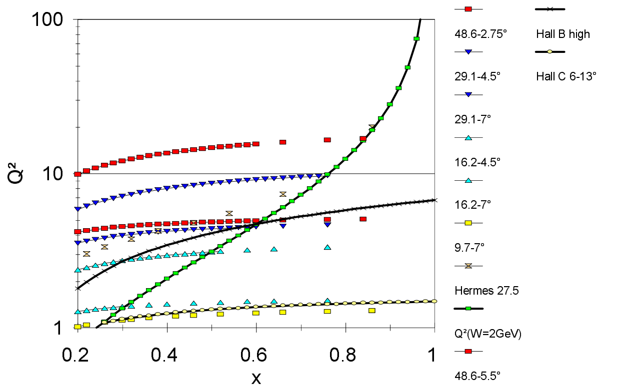

Figure 1. g_1 data for 1 GeV$^2 \leq Q^2 \leq 20$ GeV^2. The region of $W \leq 2$ GeV is indicated by the thick curve with square markers.

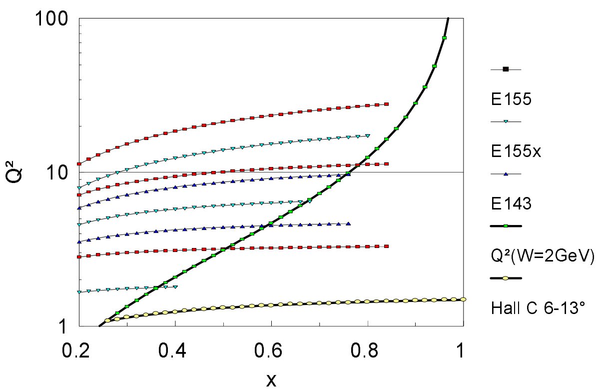

Figure 2. g_2 data for 1 GeV$^2 \leq Q^2 \leq 20$ GeV^2. Symbols are indicative only.

of particular interest for the JLab 11 GeV upgrade, since it is included inside the yellow and blue shaded areas of Fig. 3. The blue area is the region where $A_{\|}$ data from Hall B are available. The yellow area represents the additional range in Q^2 and x that would be covered by 11 GeV beams with scattered electrons detected at angles $\theta \leq 27.5°$. At this angle, the curve of constant E, θ intersects the $W = 2$ GeV curve at $Q^2 = 10$ GeV^2. Measurements of $A_{\|}$ and $A_{\perp}$ could be carried out very efficiently throughout the entire area with suitable polarized targets and spectrometers. Both $A_{\|}$ and $A_{\perp}$ are required to separate the SSF's or the spin asymmetries A_1 and A_2, which are the physical quantities of interest.

The physics goals of SSF studies with the JLab upgrade appear to be:

- extension of the DIS measurements into the region of the nucleon resonances to make a detailed exploration of local (Bloom-Gilman [24]) duality in SSF's. This property that has been studied in detail for the proton's F_2 unpolarized SF [25], but it has only recently began to be explored for the SSF's. An example is shown in Fig. 4, for $Q^2 = 1.5$ GeV^2. Local duality must be tested by comparing DIS and resonances SSF data as a function of scaling variables at constant Q^2. For data taken in the conventional constant beam energy–constant scattering angle method, the constant Q^2 condition will be reasonably approximated with the 11 GeV upgrade. For comparison, the data of Fig. 4 were taken at 16.2 GeV, which has a variation of Q^2 over the resonances of less than ±3% (lowest set of triangles in Fig. 1).
- measurement of the twist-3 part of g_2 with improved precision than current [14,19].
- measurement of the spin asymmetry $A_1 = (g_1 - (Q^2/\nu^2)g_2)/F_1$ at x near 1. Data for this asymmetry are available only up to $x \leq 0.85$, and only for a few values of Q^2.

The equipment required for these measurements needs to have the following characteristics:

- Spectrometer: capable of detecting high momentum scattered particles. At fixed Q^2 rates are higher for smaller scattering angles and higher beam energies than vice versa, but the final energy E' is correspondingly higher. Moreover, high E' requires very good momentum resolution to resolve the rich structure of the resonances and make meaningful local duality comparisons.

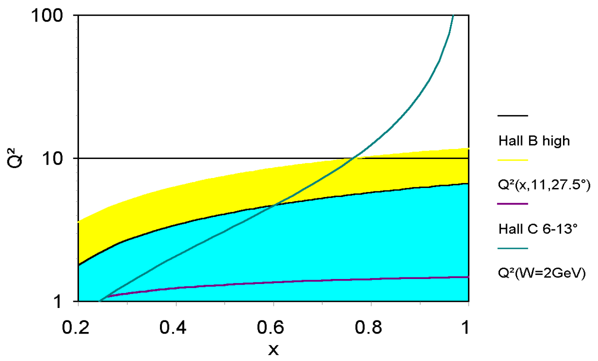

Figure 3. Range of Q^2, x for E=11 GeV and $\theta \leq$27.5° (yellow). Blue is range of Hall B $A_{\|}$ data. Purple curve is Hall C's $A_{\|}$, $A_{\perp}$range.

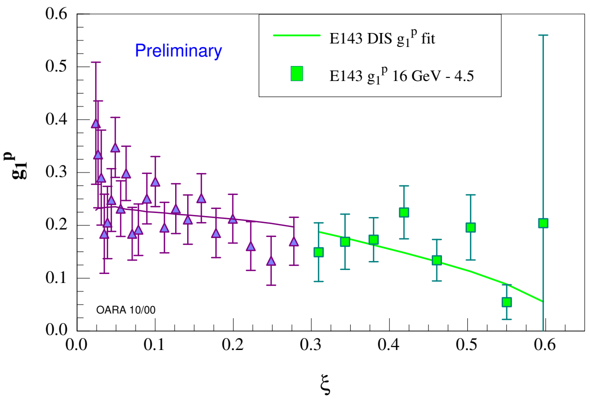

Figure 4. g_1 resonances (green squares) and DIS (purple triangles) data from SLACs' E143 and extrapolation of E143's global fit to g_1/F_1.

Hall C's planned Super HMS meets this requirement, although its proposed solid angle $\leq$ 0.003 sterradian may not be adequate at some kinematics. Alternatively, large Q^2 can be reached with large scattering angles, at which the final momentum may be smaller than 7.5 GeV/c, which is the current upper limit at JLab (Hall C's HMS which has a solid angle twice as large as that planned for the SHMS). A proposed Hall A large solid angle spectrometer Medium Acceptance Device ($\sim$ 30 msr) may be an option, provided it could accept momenta up to about 6 GeV/c and have the necessary resolution.

- Polarized target and beam: Solid or gaseous polarized targets that can operate at beam currents corresponding to luminosities of $\geq$ 100 Hz/nb, and effective beam and proton target polarizations of 80% (40% for deuteron or ^{3}He targets).

Examples of possible choices of kinematics for measurements of the spin asymmetries in the region of the resonances up to Q^2 = 8 GeV^2 are given in the table below. It should be possible to extend the four-momentum to $\sim$ 10 GeV^2. Note that because of the larger HMS solid angle compared to the SHMS, the intermediate Q^2 region can probably be explored better with the former device, with beam energy less than 11 GeV, as illustrated by the first and last rows of the table. Note also the relative widths of invariant mass and final energy bins. Finally, it must be pointed out that a large momentum bite is needed to measure the entire region in one momentum setting.

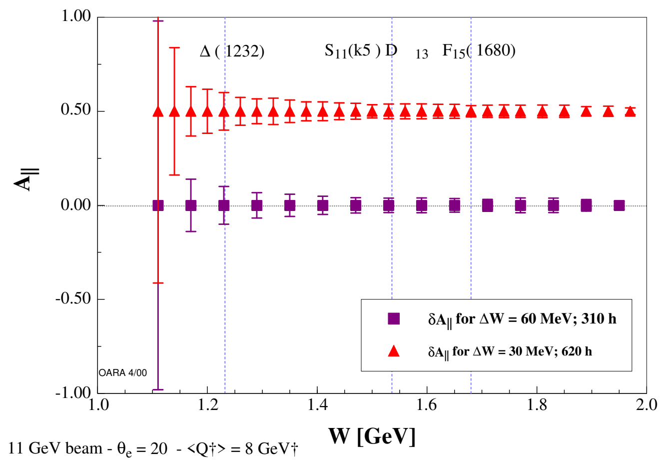

Figure 5. Expected errors for possible measurements at $Q^2 = 8$ GeV^2 with an 11 GeV beam.

E GeV	θ	$\langle Q^2\rangle$ GeV^2	$\frac{1}{2}\Delta Q^2$ GeV^2	$E'(\Delta 1232)$ GeV	$\Delta E'$ MeV	ΔW MeV	Spectrometer	σ_{Mott} nb/sr	Acceptance $\pm\,\delta$
11	12.5°	4.2	0.30	8.34	31	30	SHMS	301	7.2 %
	16°	6	0.43	7.33	27	30	(S)HMS		7.2 %
	20°	8	0.56	6.25	24	30	HMS		7.2 %
	20°	8	0.56	6.25	45	60	HMS		7.2 %
9	16°	4.2	0.37	6.32	28	30	HMS	170	9.0 %

Table 1
Possible kinematics for SSF studies at 11 GeV. Assumptions: NH_3 target with 80% polarization, 80% polarized beam, 100 Hz/nb luminosity, target dilution 0.22, solid angle 6.4 msr (SHMS 3 msr), mass range $1.1 \le W \le 2$ GeV.

The expected errors in the experimental asymmetry $A_{\parallel}$ for a possible measurement on a proton target at $Q^2 = 8$ GeV^2 (corresponding to rows 3 and 4 of the table) are shown in Fig. 5, where $A_{\parallel}$ is plotted as a function of the invariant mass, at fixed arbitrary values 0 and 1/2. Two levels of resolution in W, 30 and 60 MeV, are considered. The error bars represent the statistical uncertainties for 620 hours with 30 MeV bins and 310 h with 60 MeV bins. The latter is the absolute minimum resolution required to resolve the individual resonances. No allowance is being made for experimental overhead, nor for the measurement of $A_{\perp}$, required to separate A_1 and A_2 (about 10% additional time).

The measurement of the deuteron asymmetries would require about 1.5 times longer for comparable errors. Of course, the measurements at lower Q^2 would involve significantly shorter run times. One would expect that ${g_1}^{p,d}$ could be measured in the resonances for two or three values of Q^2 from ~ 4 GeV^2 to ~ 8 GeV^2 in about six to eight weeks of beam time at 100% efficiency. A set of measurements would be needed in order to be able to either evolve or interpolate the structure functions to constant Q^2 for computing the duality integrals and averages.

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