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Experimental studies at low Q^2 of the spin structure of the nucleon at Jefferson Lab

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We summarize the experimental program of Jefferson Lab that studies the nucleon spin structure at low Q^2. This program completes the precise experimental mapping of the nucleon spin structure functions $g_1(\nu,Q^2)$ and $g_2(\nu,Q^2)$ and their moments started at SLAC, CERN and DESY at high Q^2, and continued at Jefferson Lab at intermediate Q^2. The results presented cover the domain where Chiral Effective Field Theory (χEFT) should describe the strong interaction. They provide a comprehensive set of benchmark measurements for χEFT. The preliminary conclusion is that nucleon spin structure data are still challenging for χEFT in spite of the notable improvements in these calculations.

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1. Nucleon spin structure studies at Jefferson Lab

Jefferson Lab (JLab), is an accelerator situated in Virginia, USA, that produces an up-to 12 GeV electron beam serving four experimental halls (A, B, C and D). Its main purpose is to study Quantum Chromodynamics (QCD) using high-energy electrons scattering off fixed targets. Prior to the start of the 12 GeV program in 2014, JLab provided a 6 GeV beam to three experimental halls (A, B and C). The low-Q^2 spin structure experimental program at JLab ran in Halls A and B during the 6 GeV era, and consists of four inclusive doubly-polarized experiments: two in Hall A [1] (E97-110 and E08-027) and two in Hall B [2] (E03-006 and E06-017, grouped under the EG4 denomination). Its main goal is to provide data to check spin-dependent calculations of Chiral Effective Field Theory (χEFT), an effective approach to QCD that should describe it at low energy/momentum, in particular at low Q^2 (Q^2 is the absolute value of the square of the 4-momentum transferred from the beam to the target). This program is the continuation of a previous program at intermediate Q^2 which ran late in the late 1990s-early 2000s and that had started to reach into the χEFT domain. This initial program consisted of two experiments, E94-010 in Hall A, which measured moments of the spin structure functions g_1 and g_2 on the neutron down to $Q^2 = 0.1$ GeV^2 [3], and EG1 in Hall B, which measured of g_1 and its moments on proton and neutron down to $Q^2 = 0.05$ GeV^2 [4]. The goal of the intermediate Q^2 program was to map the transition between the partonic to hadronic description of the strong force. We will discuss these two programs. Other experiments on the nucleon spin structure at JLab are reviewed in [5]

2. Moments and spin sum rules

The chief observables measured by the low- and intermediate-Q^2 spin programs are moments of g_1 and g_2 and their associated sum rules. Of particular interest are the:

- Gerasimov-Drell-Hearn sum rule (GDH) [6]:
$$\int_{\nu_0}^{\infty} \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu} d\nu = -\frac{4\pi^2 s \alpha \kappa^2}{M^2},$$
where $\sigma_{3/2}$ and $\sigma_{1/2}$ denote the photoproduction cross sections for which the photon spin is parallel or antiparallel to the target spin s, respectively, ν is the photon energy, ν_0 is the inelastic threshold, M is the target mass, and α the QED coupling. The sum rule, derived for real photons, was later extended to $Q^2 > 0$ [7] by several type of:

- Generalized GDH integrals, e.g.:
$$\begin{aligned} I_{TT}(Q^2) &= \frac{M^2}{4\pi^2\alpha} \int_{\nu_0}^{\infty} \frac{\kappa_f}{\nu} \frac{\sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)}{\nu} d\nu \\ &= \frac{2M^2}{Q^2} \int_0^{x_0} \big[g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2)\big] dx \end{aligned}$$
where κ_f the virtual photon flux [5, 7] and $x = Q^2/(2M\nu)$ is the Bjorken scaling variable. The full sum rule was eventually extended [8] as the:

- Generalized GDH sum rule:
$$\Gamma_1(Q^2) \equiv \int_0^{x_0} g_1(x, Q^2) dx = \frac{Q^2 S_1}{8},$$
with S_1 the polarized covariant VVCS amplitude [8]. This sum rule is related to the:

- Bjorken sum rule [9]:

$$\Gamma_1^{p-n}(Q^2) = \frac{g_A}{6}\left[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s(Q^2)}{\pi}\right)^3 + ...\right] + O(1/Q^2),$$

  where g_A is the nucleon axial charge, $\alpha_s(Q^2)$ is the strong coupling [10] that corrects the sum rule for DGLAP evolution [11]. $O(1/Q^2)$ are higher twists corrections.

  These sum rules involves first moments. Others involving higher moments are the

- Generalized forward spin polarizability sum rule [12]:

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x,Q^2)\right]dx.$$

- LT-polarizability sum rule:

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x,Q^2) + g_2(x,Q^2)\right]dx. \tag{2.1}$$

- Burkhardt-Cottingham (BC) sum rule [13]:

$$\Gamma_2(Q^2) \equiv \int_0^1 g_2(x,Q^2)dx = 0. \tag{2.2}$$

- d_2 sum rule: $d_2(Q^2) = \int_0^1 x^2\left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]dx.$

Apart from the GDH sum rule which stands at $Q^2 = 0$, all these sum rules are valid for any Q^2. Thus, QCD can be studied by measuring a sum rule integral at various Q^2 and comparing it to the other sum rule side (“static" side) computed using techniques adapted to the Q^2 regime: at large Q^2, pQCD and OPE; at intermediate Q^2, lattice QCD; and at low Q^2, effective analytical approaches to non-perturbative QCD, such as χEFT.

3. Lessons from the JLab intermediate Q^2 program

In Hall A, E94-010 measured Γ_1^n, Γ_2^n, γ_0^n and δ_{LT}^n in the $0.1 \leq Q^2 \leq 0.9$ GeV^2 range [3]. The Hall A neutron information was extracted from a ^{3}He target, which is polarized using optical pumping and spin-exchange techniques. The lowest Q^2 data were compared to χEFT predictions [14, 15, 16], but only γ_0^n agreed with them. (Γ_2^n is not compared with χEFT, since the “static side" of the BC sum rule, Eq. (2.2), is trivial). Chiefly surprising was the disagreement for δ_{LT}, since it was expected to be reliably predicted by χEFT due to the (supposed at the time) lack of Δ_{1232} resonance contribution, which was either not included in χEFT calculations, or included phenomenologically. Furthermore, the additional x^2 weighting in the δ_{LT} integral, Eq. (2.1), reduces the usual experimental uncertainty due to the unmeasured low-x part of the integral. The discrepancy became known as the “δ_{LT} puzzle". Data on $g_1^{^3He}$ and $g_2^{^3He}$ are also available.

In Hall B, EG1 provided Γ_1^p, Γ_1^n, γ_0^p and γ_0^n in the $0.05 \leq Q^2 \leq 3$ GeV^2 domain [4]. The proton data were obtained using a longitudinally polarized NH$_3$ DNP target. A ND$_3$ target provided the neutron information. The lack of transverse polarization prevented to measure Γ_2 and δ_{LT}. Here again, only γ_0^n agreed with the χEFT predictions available at the time [14, 15, 16].

Halls A and B data were combined to form the Bjorken sum Γ_1^{p-n} and to provide an isospin analysis of the data [17]. The resulting Γ_1^{p-n} agrees with χEFT [14, 15, 16], validating the argument that χEFT should reliably predict Γ_1^{p-n} since the Δ_{1232} does not contribute to it [18].

In all, the conclusions that emerged from the first generation of experiments [3, 4] and of χEFT predictions [14, 15, 16] were:

- The validity domain of χEFT is smaller than the several tenths of GeV^2 initially hoped for, possibly only up to ≈ 0.1 GeV^2 (this depends on the observable).
- There are no precise data below ≈ 0.1 GeV^2: the experiments were designed for higher Q^2.
- The discrepancy for δ_{LT}^n is puzzling. There is no data for δ_{LT}^p.

The comparison between data and χEFT is summarized in Table 1.

This state of affairs showed the necessity of an experimental program optimized to cover the chiral domain, and for improved χEFT calculations.

Table 1: Comparison between the first generation of moment data and of χEFT predictions. The bold fonts denote moments for which χEFT was expected to provide robust predictions. "**A**" means that data and calculations agree up to at least $Q^2 = 0.1$ GeV^2, "**X**" that they disagree and "-" that no calculation was available. $p{+}n$ indicates either deuteron data without deuteron break-up contribution, or proton+neutron moments added together with neutron information either from D or ^{3}He.

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$	d_2^p	d_2^n
Bernard *et al.* [14]	**X**	**X**	**A**	**X**	**X**	**A**	**X**	**X**	**X**	-	**X**
Ji *et al.* [15]	**X**	**X**	**A**	**X**	-	-	-	-	-	-	-
Kao *et al.* [16]	-	-	-	-	**X**	**A**	**X**	**X**	**X**	-	**X**

4. The JLab low Q^2 program

Experiments at low Q^2 were conducted at JLab to address the issues and puzzles just discussed. E97-110 [20] and E08-027 [21] ran in Hall A and the EG4 run group ran in Hall B [22].

4.1 Experiment E97-110

The main goal of E97-110 [20] is to measure the generalized GDH sums for the neutron and ^{3}He at $0.02 \leq Q^2 \leq 0.3$ GeV^2. The experiment ran in JLab's Hall A and data were taken at two scattering angles, 6° and 9°, using a polarized ($\approx 85\%$) electrons of energies 4.2, 2.8, 2.2, 2.1, 1.5 and 1.2 GeV for the 6° data and 4.4, 3.8, 3.3, 2.2, and 1.2 GeV for the 9° data. The ^{3}He target can be polarized longitudinally or transversally (in the horizontal plane) with respect to the beam, which allows to measure g_1 and g_2. The time shared between longitudinal and transverse data taking was optimized for maximal precision on the GDH integrant $\sigma_{TT} \propto g_1 - \frac{Q^2}{\nu^2} g_2$. To reach low Q^2 while covering enough x range to form integrals, small scattering angles are required. They were reached by adding a "septum" magnet to one of the Hall A spectrometers. This lowered its minimal angle from 12.5° to 6°. g_1 and g_2 were extracted using the difference of polarized cross-sections:

$$\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow} = \frac{4\alpha^2}{MQ^2}\frac{E'}{E\nu}\left[g_1(E+E'\cos\theta) - Q^2\frac{g_2}{\nu}\right], \quad \sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow} = \frac{4\alpha^2}{MQ^2}\frac{E'^2}{E\nu}\sin\theta\left[g_1 + 2E\frac{g_2}{\nu}\right],$$

which advantageously cancels contributions from unpolarized materials in the target or the beam-line. The $\downarrow$ and $\uparrow$ represent the beam helicity while $\Downarrow$, $\Uparrow$ and $\Rightarrow$ indicate the direction of the target polarization. E97-110 is described in more details in N. Ton's contribution to these proceedings.

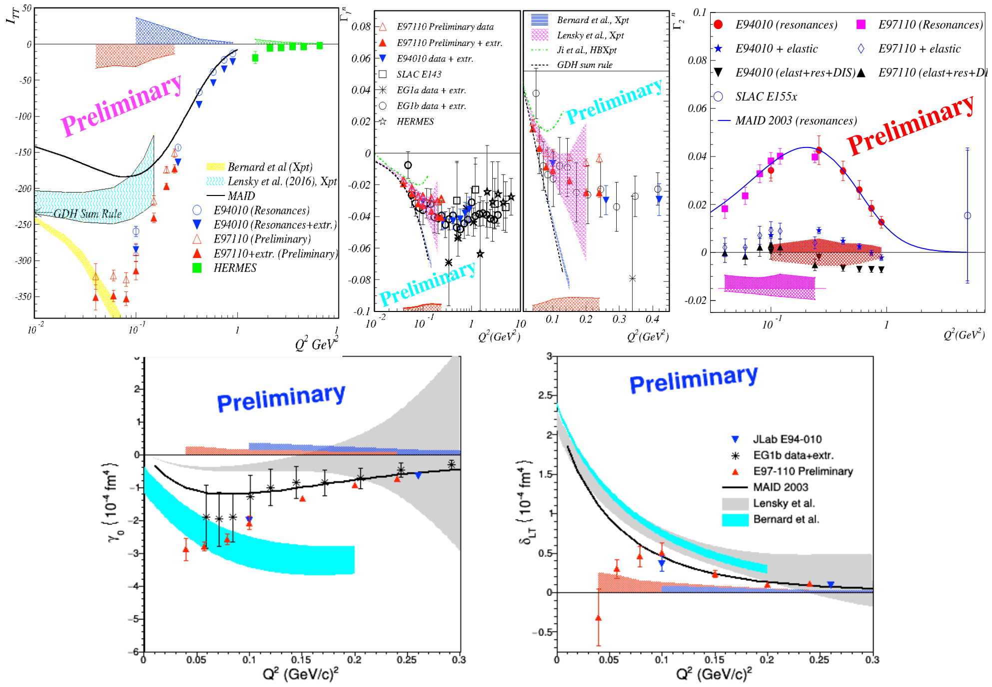

Figure 1: Preliminary neutron results from E97-110 for I^n_{TT} (top left), Γ^n_1 (top center), Γ^n_2 (top right), γ^n_0 (bottom left) and δ^n_{LT} (bottom right). The open symbols are for the measured part of the moments. The solid ones include an estimate of the unmeasured low-x contribution (and elastic for Γ^n_2). The low-x contribution is negligible for γ^n_0 and δ^n_{LT}. Also shown are recent χEFT calculations, the MAID model and results of earlier experiments E155, HERMES and E94-010 at larger Q^2.

Fig. 1 shows preliminary results for I^n_{TT}, Γ^n_1, Γ^n_2, and higher moments γ^n_0 and δ^n_{LT}. E97-110 agrees well with the E94-010 and EG1b data (when available). The I^n_{TT} data disagree with the χEFT result of Lensky *et al.* [23] and agree with that of Bernard *et al.* [19] for the lowest Q^2 points. If the GDH sum rule holds then a sharp turn-over must occur below $Q^2 \approx 0.05$ GeV^2. Compared to E94-010, the lowest Q^2 value has been reduced by factor of ≈ 2.5, which provides data to test of χEFT well into the chiral domain. More data down to $Q^2 = 0.02$ GeV^2 are being analyzed and will check further χEFT and the status of the turn-over. The Γ^n_1 data agree with Lensky *et al.* over a large Q^2-range and agree with Bernard *et al.* for a smaller range. Γ^n_2 data seem to agree with the BC sum rule. However, the unmeasured low-x part, difficult to assess, causes a large uncertainty. The bottom plots in Fig. 1 show higher moments. As for I^n_{TT}, the γ^n_0 data disagree with Lensky *et al.* and agree with Bernard *et al.* for the lowest Q^2 points. For δ^n_{LT}, while the new χEFT calculations agree with E94-010 and thus seem to have resolved the δ^n_{LT} puzzle, E97-110 data at lower Q^2 may renew the puzzle.

4.2 Experiment group EG4

EG4 [22] consists of two experiments, E03-006 (proton) and E06-017 (neutron), whose goal is to measure the generalized GDH sum at very low Q^2. they ran in Hall B using polarized electrons of energies of 3.0, 2.3, 2.0, 1.3 or 1.0 GeV scattering off a longitudinally polarized target containing either NH_3 or ND_3. The H or D were polarized using the DNP technique. This allowed to measure g^p_1 and g^D_1, from which neutron information will be extracted. As mentioned, measuring moments at low Q^2 asks for high beam energy and small scattering angle. The latter was reached by setting the CLAS field polarity to outbend electrons and by installing the target 1 m upstream its nominal location. g_1 is extracted using cross-section difference. This demands a well controlled (i.e high) detection efficiency at small angles. For this purpose, a new Cerenkov counter was installed in one CLAS sector. It allowed to measure cross-sections down to 6°. EG4 is presented in more details in K. Slifer's contribution to these proceedings.

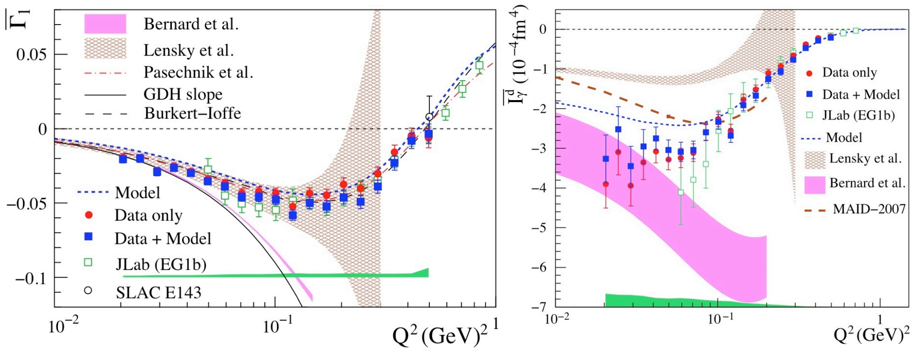

Figure 2: EG4 results for $\overline{\Gamma_1^d}$ (left) and $\overline{\gamma_0^d}$ (right). The circles are for the measured part of the integral, while the squares include an estimate of the unmeasured low-x contribution. Also shown are χEFT calculations, several phenomenological models and earlier results from E143 and EG1b at larger Q^2.

Fig. 2 shows results for $\overline{\Gamma_1^d}$ and $\overline{\gamma_0^d}$. The bar means that the deuteron photodisintegration contribution is not included in the moments. Hence they represent approximately the sum of the proton and neutron moments. The EG4 and EG1b data agree well. The $\overline{\Gamma_1^d}$ data agree with the χEFT results of Lensky *et al.* and also that of Bernard *et al.* but only for the lowest Q^2 points. The models of Pasechnik *et al.* [24] and Burkert-Ioffe [26] agree well with the data. The $\overline{\gamma_0^d}$ data disagree with the Lensky *et al.* results. The ones from Bernard *et al.* again agree for lowest Q^2 points. The Maid model [25] disagrees below $Q^2 < 0.1$ GeV^2. The low Q^2 reach of the data is decreased by a factor of ≈2.5, compared to the earlier experiments, testing χEFT well into the chiral domain. The EG4 data also display a much improved precision. Analysis for $\overline{\Gamma_1^p}$, and $\overline{\gamma_0^p}$ for the proton is on-going, with final results expected within 2019.

4.3 Experiment E08-027

The main goal of E08-027 [21] is to measure δ_{LT}^p down to Q^2=0.01 GeV^2. Γ_1^p, Γ_2^p, γ_0^p, g_1^p and g_2^p are also being extracted from the data. Beside testing for the first time χEFT using δ_{LT}^p, E08-027 provides the first high-precision data to study the BC sum rule on the proton and the first g_2^p data at low enough Q^2 to be useful to proton hyperfine studies. The experiment ran in Hall A using polarized electrons of 3.4, 2,3, 1.7 or 1.2 GeV. A NH$_3$ target similar to that of EG4 was used, but with transverse polarization capability, in addition to the longitudinal one, to access g_2^p and consequently δ_{LT}^p. It was the first use of such target in Hall A and new equipment was needed to characterize the beam of low current imposed by the target. Chicanes and a local beam dump were installed to accommodate the target transverse magnetic field. The small angle necessary to reach low Q^2 was provided by septum magnets. g_1^p and g_2^p are obtained from cross-section differences. E08-027 is discussed more extensively in K. Slifer's contribution to these proceedings.

The preliminary δ_{LT}^p data, ranging $0.045 \leq Q^2 \leq 0.13$ GeV^2, agree well with the Lensky *et al.* calculations but not with the Bernard *et al.* ones. The data also agree with the MAID model [25]. γ_0^p

Table 2: Same as Table 1 but for the newest experiments and χEFT results. The * signals preliminary data.

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^p}$	$\boldsymbol{\delta_{LT}^n}$	d_2^p	d_2^n
Bernard *et al.* [19]	**X**	**X**	**A**	**X**	**X**	**A**	**X**	**X**	**X***	**X***	-	-
Lensky *et al.* [23]	**X**	**A**	**A**	**A**	**A**	**X**	**X**	**X**	**A***	**X***	NA	**A**

is available at $Q^2 = 0.045$ GeV^2 and show tensions with the EG1b data (which agree with Lensky *et al.*) and Bernard *et al.* (which disagrees with EG1b and Lensky *et al.*).

5. Current state of testing χEFT with spin sum rules.

The experiments above are testing χEFT well into the chiral domain and with improved precision. On the theory side, two recent predictions are available (Lensky *et al.* [23] and Bernard *et al.* [19]). Table 2 summarizes how they compare for $Q^2 \leq 0.1$ GeV^2. It shows that a satisfactory description of nucleon spin structure by χEFT remains challenging. Some observables, such as Γ_1^{p-n}, are well described over large ranges, while others, such as δ_{LT}^n, remain refractory to a χEFT description. Others have mixed success, agreeing with one χEFT calculation but not the other. The two calculations generally disagree with each other. Since several of the experimental results discussed are preliminary, one has wait for the final results to confirm the above conclusion.

6. Summary and perspective

The JLab low Q^2 experimental program was the last stage to complete the experimental mapping from high to low Q^2 of g_1, g_2 and their moments for nucleons and light nuclei. It complements the intermediate Q^2 program of JLab and the high Q^2 programs of SLAC, CERN and DESY.

The EG4 deuteron data are published [22]. The others data, from E97-110, EG4-proton and E08-027 are in final analysis stage, with preliminary results available and final results expected within 2019. Thus, a comprehensive set of data (both nucleons, and both g_1 and g_2 moments and their combinations) will be available shortly to test χEFT. Meanwhile, theory groups are improving calculations and studying the origin of the difference between their predictions. A preliminary conclusion is that in spite of notable improvements compared to the early calculations, χEFT describes the nucleon spin structure at low Q^2 with mixed success, depending on the specific theoretical approach and on the observable. The data analyses must be finalized before to draw firm conclusions but it seems that describing the nucleon spin structure remains a challenge for χEFT.

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