JLAB HALL B
NUCLEON SPIN STRUCTURE EXPERIMENTS

SEBASTIAN KUHN
OLD DOMINION UNIVERSITY
OVERVIEW

• SCIENTIFIC GOALS
  • Polarized Parton Distribution Functions
  • Valence Quarks, Resonances and Duality
  • Sum Rules, Higher Twist, and $\chi$PT

• RESULTS FROM THE 6 GEV ERA
  • EG1
  • EG1-DVCS
  • EG4

• THE FUTURE PROGRAM
  • CLAS12
  • Run Group C
  • The EMC$^2$ Effect

• OUTLOOK AND SUMMARY
A_{1}(x->1)

\begin{align*}
\frac{1}{2} = S_p &= \frac{1}{2} \sum q \int q(x) dx + \sum L_q + J_G \\
\Delta q, \Delta \bar{q}, \Delta G
\end{align*}

Duality

OPE, twist >2

Constituent Quark Model

(SU(6))
Inclusive lepton scattering

Parton model: DIS can access

\[ F_1(x) = \frac{1}{2} e_i^2 q_i(x) \left( \text{and } F_2(x) = 2x F_1(x) \right) \]
\[ g_1(x) = \frac{1}{2} \sum_i e_i^2 \, q_i(x) \left( \text{and } g_2(x) \approx g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy \right) \]

At finite \( Q^2 \): pQCD evolution \((q(x, Q^2), \Delta q(x, Q^2))\) ⇒ DGLAP equations and gluon radiation

\[ g_1(x, Q^2)_{pQCD} = \frac{1}{2} \sum_q e_q^2 \left[ (\Delta q + \Delta \bar{q}) \otimes \left( 1 + \frac{\alpha_s(Q^2)}{2\pi} \delta C_q \right) \otimes \Delta G \otimes \frac{\delta C_G}{N_f} \right] \]

⇒ access to gluons. \( \delta C_q, \delta C_G \) − Wilson coefficient functions

SIDIS: Tag the flavor of the struck quark with the leading FS hadron ⇒ separate \( q_i(x, Q^2), \Delta q_i(x, Q^2) \)

Jefferson Lab kinematics: \( Q^2, M^2 \) ⇒ target mass effects, higher twist contributions and resonance excitations

- Non-zero \( R = \frac{F_2}{2xF_1} \frac{4M^2x^2}{Q^2} + 1 \) \( g_2^{HT}(x) = g_2(x) \cdot g_2^{WW}(x) \)
- Further \( Q^2 \)-dependence (power series in \( \frac{1}{Q^2} \))

Traditional “1-D” Parton Distributions (PDFs) (integrated over many variables)
VALENCE REGION AND MODERATE Q\(^2\): SFS FOR X→1

Valence quark polarization

SU(6)-symmetric proton wave function in the “naïve” quark model:

\[ p\uparrow = \frac{1}{\sqrt{18}} (3u\uparrow [ud]_{S=0} + u\uparrow [ud]_{S=1} - \sqrt{2}u\downarrow [ud]_{S=1} - \sqrt{2}d\uparrow [uu]_{S=1} - 2d\downarrow [uu]_{S=1}) \]

In this model: \( d/u = 1/2, \Delta u/u = 2/3, \Delta d/d = -1/3 \) for all \( x \rightarrow 1 \)

\[ \sum_q \Delta q = 1 \Rightarrow S_p = \frac{1}{2} \sum_q \Delta q = \frac{1}{2} \Delta S; \quad g_A^{(3)} = \Delta u - \Delta d = 5/3; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s = 1 \]

Relativistic Correction: lower component reduces axial charge, adds to orbital angular momentum (p-wave)

\[ \sum_q \Delta q = \Delta S \approx 60\%; \quad g_A^{(3)} = \Delta u - \Delta d \approx 1.26; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s \approx 0.6 \]

Hyperfine structure effect: \( S=1 \) suppressed => \( d/u = 0, \Delta u/u = 1, \Delta d/d = -1/3 \) for \( x \rightarrow 1 \) => \( A_{1p} = 1, A_{1n} = 1, A_{1D} = 1 \)

pQCD: helicity conservation (q↑↑p) => \( d/u = 2/(9+1) = 1/5, \Delta u/u = 1, \Delta d/d = 1 \) for \( x \rightarrow 1 \)
DUALITY

Asymptotically Free Quarks: regime of pQCD

Long Distance Physics: hadronic observables

FIG. 40. Averages of $Q^2 \alpha_s(x, Q^2)$ vs $Q^2$ over limited spans in $x$ corresponding to prominent “resonance regions” as indicated by the ranges in $W$. Symbols are the same as in Fig. 39.
THE LIMIT $Q^2 \to 0$: \textit{GDH Sum Rule}

\[ I_{GDH} = \frac{M^2}{8\alpha\pi^2} \int_{thr}^{\infty} \left( \sigma_{1/2} - \sigma_{3/2} \right) \frac{d\nu}{\nu} = -\frac{1}{4} \kappa^2 \]

- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties

- based on very general principles, as gauge invariance, dispersion relation, low energy theorem

- at finite $Q^2$ can be related to the integral of the spin structure function $g_1$

\[ \Gamma_1 = \int g(\nu, Q^2) d\nu \quad \xrightarrow{Q^2 \to 0} \quad \frac{Q^2}{2M^2} I_{GDH} \]

- strong variation of nucleon spin properties as a function of $Q^2$

- $Q^2$-dependence described by Chiral Perturbation Theory ($\chi$PT) at low $Q^2$
The Limit $Q^2 \rightarrow 0$: Spin Polarizability

\[ \int_{\text{thr}}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{dv}{v^3} = 4\pi^2 \gamma_0 \]

- $\gamma_0$ measures the response ("stiffness") of the nucleon spin against electromagnetic deformations along the spin axis.

- Follows from same dispersion relation and low energy theorem (limit of forward Compton scattering) as GDH sum rule.

- Can also be extended to finite $Q^2$:

  \[ \Gamma_3^N = \int x^2 g_1^N(x,Q^2) dx \xrightarrow[Q^2 \to 0]{Q^2 \to 0} \frac{Q^6}{16\alpha M^2} \gamma_0^N \]

- Much more sensitive to low-energy (high $x$) part of the integral -> ideal for Jlab.

- Plus other polarizabilities: $\delta_{LT}$.

\[ \Rightarrow \text{Chiral Perturbation Theory should be able to predict} \]

$\gamma_0(Q^2)$, $\delta_{LT}(Q^2)$ and $b$ in

\[ \Gamma_1(Q^2) = -\frac{\kappa^2}{8M^2} Q^2 + bQ^4 + \ldots \]
JEFFERSON LAB IN PERSPECTIVE

Past: $6 \text{ GeV}$

$Q^2 < 6 \text{ GeV}^2$

$x > 0.1 \ldots 0.6$

$W = 0.9 \ldots 3 \text{ GeV}$

Now: $12 \text{ GeV}$

$Q^2 = 1 \ldots 13 \text{ GeV}^2$

$x = 0.06 \ldots 0.8$

$W < 4 \text{ GeV}$
SPIN STRUCTURE FUNCTIONS IN THE LAST 40 YEARS

SATO, MELNITCHOUK, KUHN, ETHIER, and ACCARDI

FIG. 15. Comparison of the JAM15 IMC fits (red curves, with the average indicated by the black solid curve) with corresponding fits excluding all Jefferson Lab data (yellow curves, with the average given by the black dashed curve) for the twist-2 PDFs $\Delta u^t$, $\Delta d^t$, $\Delta s^t$ and $\Delta g$, the twist-3 distributions $D_u$ and $D_d$, and the twist-4 functions $H_p$ and $H_n$ at $Q^2 = 1$ GeV$^2$. Note that $x$ times the distribution is shown. For illustration each distribution is represented by a random sample of 50 fits.


RESULTS FROM EG1B

\[ Q^2 = 5.7 \text{ GeV}^2 \]
\[ Q^2 = 4.9 \text{ GeV}^2 \]
\[ Q^2 = 4.1 \text{ GeV}^2 \]
\[ Q^2 = 3.4 \text{ GeV}^2 \]
\[ Q^2 = 2.9 \text{ GeV}^2 \]
\[ Q^2 = 2.4 \text{ GeV}^2 \]
\[ Q^2 = 2.0 \text{ GeV}^2 \]
\[ Q^2 = 1.7 \text{ GeV}^2 \]
\[ Q^2 = 1.4 \text{ GeV}^2 \]
\[ Q^2 = 1.2 \text{ GeV}^2 \]
\[ Q^2 = 1.0 \text{ GeV}^2 \]
\[ Q^2 = 0.84 \text{ GeV}^2 \]
\[ Q^2 = 0.70 \text{ GeV}^2 \]
\[ Q^2 = 0.59 \text{ GeV}^2 \]
\[ Q^2 = 0.49 \text{ GeV}^2 \]
\[ Q^2 = 0.41 \text{ GeV}^2 \]
\[ Q^2 = 0.35 \text{ GeV}^2 \]
\[ Q^2 = 0.29 \text{ GeV}^2 \]
\[ Q^2 = 0.24 \text{ GeV}^2 \]
\[ Q^2 = 0.20 \text{ GeV}^2 \]
\[ Q^2 = 0.17 \text{ GeV}^2 \]
\[ Q^2 = 0.14 \text{ GeV}^2 \]
\[ Q^2 = 0.12 \text{ GeV}^2 \]
\[ Q^2 = 0.10 \text{ GeV}^2 \]
\[ Q^2 = 0.084 \text{ GeV}^2 \]
\[ Q^2 = 0.071 \text{ GeV}^2 \]
\[ Q^2 = 0.059 \text{ GeV}^2 \]
\[ Q^2 = 0.050 \text{ GeV}^2 \]
\[ Q^2 = 0.042 \text{ GeV}^2 \]
\[ Q^2 = 0.035 \text{ GeV}^2 \]
The SF $g_{1p}$ – recent results at low $Q^2$

**EG4**

Final Results on $g_{1}$ or $A_1F_1$

- Final value on $g_{1}$ is calculated...
- Combined over all Hve beam energies and all target types.

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**Preliminary**
The SF $g_{1d}$ – recent results at low $Q^2$

EG40$^{-4}$ fm$^4$ deuteron

![Graph showing recent results at low $Q^2$ for the SF $g_{1d}$ with data and model predictions.](image-url)
THE FUTURE

High precision inclusive SSFs on p, d, n in the region $0.05 < x < 0.8$

$W > 2; Q^2 > 1$

$\Delta^n_1$ with SHMS/HMS

$E = 11$ GeV

$g_n^{\text{HMS}}$ from B&B scen. 1 $@ 5.0$ GeV$^2$

$t = 3 \times 200$ hrs, no $W$ cut
CLAS12

Forward Detector (FD) - TORUS magnet - HT Cherenkov Counter - Drift chamber system - LT Cherenkov Counter - Forward ToF System - Pre-shower calorimeter - E.M. calorimeter - Forward Tagger - RICH detector

Central Detector (CD) - Solenoid magnet - Silicon Vertex Tracker - Central Time of Flight - Central Neutron Detector - MicroMegas

Beamline - Diagnostics - Shielding - Targets - Polarimeter - Faraday Cup

Number of readout channels > 100,000
RUN GROUP C

- Experiments with CLAS12 and a longitudinally polarized p/d target
- Tentatively scheduled for 6 months in 2021-2022 (First Installment)
- Just passed Experimental Readiness Review
- Comprises 6 approved experiments

<table>
<thead>
<tr>
<th>Proposal ID</th>
<th>Title</th>
<th>Contact Person</th>
<th>PAC Rating</th>
<th>Awarded Days</th>
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<td>E12-06-109</td>
<td>Longitudinal Sping Structure of the Nucleon</td>
<td>Kuhn</td>
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<td>E12-06-109A</td>
<td>DVCS on the neutron with polarized deuterium target</td>
<td>Niccolai</td>
<td>RG proposal</td>
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<td>Spin-Orbit Correlations with longitudinally polarized target</td>
<td>Avakian</td>
<td>A-</td>
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<td>E12-09-007(b)</td>
<td>Study of partonic distributions using SIDIS K production</td>
<td>Hafidi</td>
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<td>E12-09-009</td>
<td>Spin-Orbit correlations in K production with polarized targets</td>
<td>Avakian</td>
<td>B+</td>
<td>103</td>
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</tbody>
</table>

Total number of approved beam (PAC) days: 185 (120 p, 60 d, 5 auxiliary)
POLARIZED TARGET –
FROZEN AMMONIA AND DEUTERATED AMMONIA IN 1K LIQUID HE BATH AND 5 T MAGNETIC FIELD, IRRADIATED WITH 140 GHZ MICROWAVES

Photos courtesy of J. Brock
Stable operation at ~1 K
Heat shield < 28 K
Fast cool-down: 3 hr following LN2
Low helium consumption: < 5 L/hr

Passed Experimental Readiness Review 6/19
INCLUSIVE + TAGGED SSF – HALL B

Improved PDFs from NLO analyses

Better determination of Higher Twist vs. $x$

Improved coverage to evaluate moments
QUARK POLARIZATION FROM KAON SIDIS

See talk by
K. Hafidi
Tuesday morning
3D Partonic Structure

From 1-D to 3-D:

Traditional “1-D” Parton Distributions (PDFs) (inclusive, integrated over many variables)

3-D Picture of parton flavor, spin and momentum (TMDs)

$ q(H, \vec{S}, x, \vec{k}, h, \vec{s}; Q^2) $
pDVCS simulations with RGC setup

pDVCS event generator (GENEPI): DVCS-BH on proton target, $t<-1.2$ GeV$^2$
- Cell target, NH$_3$, noFT configuration
- Analysis (PID + channel selection cuts)

Electron kinematics

Proton kinematics

Photon kinematics

After exclusivity cuts
n DVCS Target Spin and Double Spin Asymmetries

First time measurement of longitudinal target-spin asymmetry and double (beam-target) spin asymmetry

\[ \Delta \sigma_{UL} \sim \sin \phi \ \text{Im}\{F_1 \tilde{H} + \xi (F_1 + F_2)(\mathcal{H} + x_B/2 \mathcal{E}) - \xi kF_2 \tilde{E} + \ldots\} \]

\[ \Delta \sigma_{LL} \sim (A + B \cos \phi) \ \text{Re}\{F_1 \tilde{H} + \xi (F_1 + F_2)(\mathcal{H} + x_B/2 \mathcal{E}) - \xi kF_2 \tilde{E} + \ldots\} \]

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

\[ L = 3/20 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1} \]
Run time = 40 days
\[ P_t = 0.4; \ P_b = 0.85 \]

\[ eND_3 \rightarrow e(p)n\gamma \]
CLAS12 + Longitudinally polarized target + CND

Will run in 2021
CLAS12: projections for flavor separation \((\text{Im} H, \text{Im} E)\)

\[
(H,E)_{u}(\xi,\xi,t) = \frac{9}{15} [4(H,E)_{p}(\xi,\xi,t) - (H,E)_{n}(\xi,\xi,t)] \\
(H,E)_{d}(\xi,\xi,t) = \frac{9}{15} [4(H,E)_{n}(\xi,\xi,t) - (H,E)_{p}(\xi,\xi,t)]
\]

\[
\frac{1}{2} \int_{-1}^{1} x dx (H^q(x,\xi,t=0) + E^q(x,\xi,t=0)) = J^q
\]

Fits done to all the projected observables for \( pDVCS \) (BSA, ITSA, IDSA, tTSA, CS, DCS) and \( nDVCS \) (BSA, ITSA, IDSA) of the CLAS12 program.
Worm gear TMDs are unique (no analog in GPDs)

H. Avakian, RGC, May 30

TMDS – CLAS12 (LONG. POL. P,D)

\[ A_1 p_T \] distr.

\[ + \sin \phi \] (Higher Twist)

u quark
\((\pi^+)\)

Worm Gear

\[ \pi^+ \quad \pi^- \quad \pi^0 \]
TIMELINE RUN GROUP C

...followed by experiment with transversely polarized p target (HD-ICE)
TMDS – CLAS12
TRANSVERSE HD-ICE (?)

Sivers

Collins

+ worm gear,
pretzelosity

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{UL} \]
POLARIZED EMC EFFECT?

Quark-Meson Coupling Model (QMC)

EMC effect
Polarized EMC effect

$g_{1p}^A / g_{1p}$
$F_{2N}^A / F_{2N}$

$Q^2 = 5 \text{ GeV}^2$
$\rho = 0.16 \text{ fm}^{-3}$

Cloet et al., PRL 95, 052302

Chiral Quark Soliton Model (CQS)


Nuclear matter, $Q^2 = 10 \text{ GeV}^2$

Valence + sea

CBT CQS

Valence only

7Li


Experiment: $^9$Be
Unpolarized EMC effect
Polarized EMC effect: $R_{As}^{(3/2)}$

$R_{As}^{(3/2)} = \frac{g_{1A}^{JH}}{g_{1p}^{JH} + g_{1n}^{JH}}$


x-rescaling
Polarized EMC Effect?

E12-14-001 with CLAS12 at JLab: Ratio of $g_1$ and $A_1$ for $^7$Li vs. free p
OUTLOOK: COMPLETING THE PICTURE

- $\Delta u/u$ and $\Delta d/d$ at high $x$?
- Nuclear effects on nucleon structure
- Understanding the sea – $s$, $\bar{u} - \bar{d}$, $\Delta \bar{u} - \Delta \bar{d}$?
- Orbital angular momentum? $\rightarrow$ GPDs in 3D
- Axial and Tensor charges of the nucleon
- Full mapping of all TMD PDFs in the valence and sea region
- Gluon helicity distribution at large $x$ and a small $x$? What is the integral $\Delta G$?
- Test of universality
- Test of prediction that time-odd TMDs (e.g., Sivers asymmetry) change sign in Drell-Yan processes
- What happens at really small $x \ll 0.01$?
ENERGY LEVELS IN A HYDROGEN-LIKE ATOM

Putting it all together – example HFS (courtesy K. Griffioen, W&M):

\[ E_{\text{HFS}}(e^- p) = 1.4204057517667(9) \text{GHz} = (1 + \Delta_{QED} + \Delta_R^p + \Delta_S^p) E_F^p + \ldots \]

(21 cm)

Zemach: \[ \Delta_Z = -2\alpha m_e \langle r \rangle_Z (1 + \delta_{Z}^{\text{rad}}) \]

\[ \langle r \rangle_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[ G_E(Q^2) \frac{G_M(Q^2)}{1 + \kappa} - 1 \right] \]

\[ \delta_{Z}^{\text{rad}} = \frac{\alpha}{3\pi} \left[ 2 \ln \frac{\Lambda^2}{m^2} - \frac{4111}{420} \right] \]

Measurements of form factors, (generalized) polarizabilities and (spin) structure functions at small \( Q^2 \) are crucial.
PREDICTED DATA FROM CLAS12 - DIS

Proton \[ W > 2; Q^2 > 1 \]

Deuteron

\[ A_{1}^{p} \] vs \[ x \]

\[ A_{1}^{d} \text{ (D-state corrected)} \] vs \[ x \]

- \( Q^2 = 1-2 \text{ GeV}^2 \)
- \( Q^2 = 2-5 \text{ GeV}^2 \)
- \( Q^2 = 5-9 \text{ GeV}^2 \)
- \( Q^2 > 9 \text{ GeV}^2 \)

\( \text{pQCD} \)

\( \text{SU(6)} \)
\( \Delta D/D \) FROM DIS

As proposed

Up-to-date estimate for 1\(^{st}\) run of RGC
$\Delta D/D$ INCLUDING SIDIS
## Comprehensive Program with Longitudinal and Transverse H, D targets

<table>
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<tr>
<th>Experiment</th>
<th>Quantity</th>
<th>Physics</th>
<th>Target</th>
<th>particle species</th>
<th>Kinematics</th>
<th>beam request</th>
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<td>E12-07-107</td>
<td>$A_{UL} \sin \phi$</td>
<td></td>
<td>NH$_3$</td>
<td>$\pi^+, \pi^-, \pi^0$</td>
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<td>$A_{UL} \sin 2\phi$</td>
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