SBS Overview

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The Super BigBite Spectrometer in Hall A

Proton form factors ratio, \( GFp(5) \) (E12-07-109)

- What is it? An (up to) 2.5 T\(\cdot\)m dipole magnet with vertical bend, a cut in the yoke for passage of the beam pipe to reach forward scattering angles, and a flexible/modular configuration of detectors.
- Designed to operate at luminosities up to \(10^{39}\) cm\(^{-2}\) s\(^{-1}\) with large momentum bite, moderate solid angle
- Time-tested “Detectors behind a dipole magnet”, two-arm coincidence approach—historically most productive in fixed-target expts.
- **Large solid-angle + high luminosity @ forward angles = most interesting physics!**
SBS Original Motivation: Proton $G_E/G_M$ From Polarization Transfer

  - 810 INSPIRE-HEP citations (6/21/2017)
  - 735 INSPIRE-HEP citations (1/27/2017)
  - 210 INSPIRE-HEP citations (6/21/2017)
- Among the most widely cited results from JLab

\[ \frac{\mu_{G_{Ep}}}{G_{Mp}} \]
\[ Q^2 (\text{GeV}^2) \]

\[ \frac{Q^2_{F_{2p}}}{F_{1p}} \]
\[ Q^2 (\text{GeV}^2) \]

\[ P_t = -\sqrt{\frac{2\varepsilon(1 - \varepsilon)}{\tau}} \frac{r}{1 + \frac{\varepsilon}{\tau} r^2} \]
\[ P_\ell = \frac{\sqrt{1 - \varepsilon^2}}{1 + \frac{\varepsilon}{\tau} r^2} \]
\[ r \equiv \frac{G_E}{G_M} = -\frac{P_t}{P_\ell} \sqrt{\frac{\tau(1 + \varepsilon)}{2\varepsilon}} \equiv \frac{R}{\mu_p} \]
\[ P_n \equiv 0 \]
JLab detector landscape

A range of $10^4$ in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).

The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments
SBS was found to be the best match to the physics.

GEM allows a spectrometer
with open geometry (large acceptance) at high L.

Figure credit: B. Wojtsekhowski (JLab)
Nucleon Electromagnetic Form Factors: Definitions

$$\mathcal{M} = \frac{4\pi \alpha}{q^2} \bar{u}(k') \gamma^\mu u(k) g_{\mu\nu} \bar{u}(p') \left[ F_1(q^2) \gamma^\nu + F_2(q^2) \frac{i\sigma^\nu q\alpha}{2M} \right] u(p)$$

Invariant amplitude for elastic eN scattering in the one-photon-exchange approximation

- The most general possible form of the nucleon current consistent with Lorentz invariance, parity conservation and gauge invariance is described by two form factors $F_1$ (Dirac) and $F_2$ (Pauli):
  - $F_1$ describes the helicity-conserving amplitude (charge and Dirac magnetic moment)
  - $F_2$ describes the helicity-flip amplitude (anomalous magnetic moment contribution)

Sachs Form Factors $G_E$ (electric) and $G_M$ (magnetic), are experimentally convenient linearly independent combinations of $F_1$, $F_2$:

$$G_E \equiv F_1 - \tau F_2$$
$$G_M \equiv F_1 + F_2$$
$$\tau \equiv \frac{Q^2}{4M^2}$$

Differential cross section in the nucleon rest frame:

Rosenbluth formula

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha^2}{Q^2} \left( \frac{E'_e}{E_e} \right)^2 \cot^2 \left( \frac{\theta_e}{2} \right) \left( G^2_E + \frac{\tau G^2_M}{1 + \tau} \right)$$
$$\varepsilon^{-1} \equiv 1 + 2(1 + \tau) \tan^2 \left( \frac{\theta_e}{2} \right)$$

Rosenbluth Separation Method: Measure cross section at fixed $Q^2$ as a function of $\varepsilon$ to obtain $G_E^2$ (slope) and $G_M^2$ (intercept).
Precision elastic $ep$ cross sections in Hall A

![Graph showing data](image)

- Data collected in spring 2016
- Data collected in dedicated GMp period in Fall 2016
- Data collected parasitically with DVCS in Fall 2016

Error bar reflects twice statistical uncertainty

- Elastic $ep \rightarrow ep$ cross section at large $Q^2$ is dominated by $G_{Mp}$.
- Existing data for $Q^2 \geq 10 \text{ GeV}^2$ come from a single experiment at SLAC (Sill et al., Phys. Rev. D, 48(1), 29 (1993)) with large uncertainties
- The absolute elastic $ep$ cross section data serve as the “anchor” for the determination of all four nucleon EMFFs
Experiment E12-07-109 ($G_E^p/G_M^p$ at large $Q^2$)

- Original motivation for SBS concept. Need large solid angle to overcome rapidly falling cross section at large $Q^2$ in elastic $ep$ scattering. New double proton polarimeter with GEM-based tracking and hadronic calorimeter-based trigger.
- Lead-glass electromagnetic calorimeter to detect the scattered electron in coincidence (using two-body kinematic correlations to aid tracking in high-rate environment and reject inelastic background events); also provides a selective trigger for high-energy electrons.

40-cm liquid hydrogen target: Luminosity $8 \times 10^{38}$ cm$^{-2}$s$^{-1}$

Electron arm: Lead-glass EM calorimeter and scintillator based coordinate detector

Proton Arm: SBS dipole, GEM trackers and CH$_2$ analyzers for proton polarimetry, iron-scintillator HCAL for trigger
The SBS GEP experiment in ~11 days running will dramatically improve the statistical precision in $\mu G_E/G_M$ at $Q^2$ in the range overlapping GEp-II/III, and in 30 days will reach comparable precision at 12 GeV$^2$ to that of GEp-II/III at 5-6 GeV$^2$.

Data of such precision carry significant discovery potential and may (or may not) settle the questions of a zero crossing of $G_E^p$ and the onset (or lack thereof) of dimensional scaling.

Combined with GEN, GMN, GMP experiments, full flavor decomposition of $F_1$ and $F_2$ becomes possible up to 10 GeV$^2$. 

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**Kinematics and expected accuracy**

<table>
<thead>
<tr>
<th>$E$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$\theta_E$ (deg)</th>
<th>$P_e$ (GeV)</th>
<th>$\Theta_p$ (deg)</th>
<th>$P_p$ (GeV)</th>
<th>Days</th>
<th>$\Delta \mu G_E/G_M$</th>
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<tr>
<td>6.6</td>
<td>5.0</td>
<td>25.3</td>
<td>3.94</td>
<td>29.0</td>
<td>3.48</td>
<td>1</td>
<td>0.023</td>
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<td>8.8</td>
<td>8.0</td>
<td>25.9</td>
<td>4.54</td>
<td>22.8</td>
<td>5.12</td>
<td>10</td>
<td>0.032</td>
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<tr>
<td>11.0</td>
<td>12.0</td>
<td>28.2</td>
<td>4.60</td>
<td>17.4</td>
<td>7.27</td>
<td>30</td>
<td>0.074</td>
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Experiment E12-09-019 ($G_M^n$ at large $Q^2$)

Electron arm: BigBite Spectrometer

Neutron/proton Arm: SBS dipole, HCAL, and coordinate detector (not shown) for charged-particle veto

10-cm liquid deuterium/hydrogen target (luminosity $\sim 2 \times 10^{38}$)

- Neutron magnetic form factor at large $Q^2$ is obtained from the ratio of quasi-elastic $d(e,e'\text{n})p/d(e,e'\text{p})n$ cross sections on a deuterium target and precise knowledge of elastic ep cross section.
- SBS dipole deflects protons to separate from neutrons; nucleon momentum is measured using time-of-flight method to separate quasi-elastic/inelastic channels.
- Existing BigBite spectrometer with upgraded detector package detects the scattered electron.
SBS $G_{\text{Mn}}$ projected Results

- SBS as neutron arm w/48D48 + HCAL
- Magnet sweeps low-energy charged particles out of acceptance and deflects quasi-elastic protons to separate quasi-elasitically scattered p/n at HCAL, and ”CDet” acts as additional charged-particle veto
- BigBite as electron arm w/upgraded 12 GeV detector package (including re-use of GEMs, built for GEP, not otherwise in use during BigBite expt’s.), new GRINCH Cherenkov counter, new timing hodoscope.
- Standard LH2/LD2 target
Detector configuration same as GMN experiment

High-luminosity polarized $^3\text{He}$ target based on spin-exchange optical pumping and convection-driven circulation of polarized gas between optical pumping chamber and target chamber.

Reach $Q^2 = 10 \text{ GeV}^2$ (approximately tripling $Q^2$ reach of the data)

- Polarized $^3\text{He}$ as effective polarized neutron target
  - Atomic electrons bound in closed 1S shell
  - Nuclear ground state dominated by S-state with unpaired neutron carrying nuclear spin-1/2
High-luminosity Polarized $^3$He target development

- Significant recent progress by UVA group (Cates) in the development of high-luminosity polarized $^3$He targets for SBS SIDIS and GEN experiments based on convection-driven circulation of polarized gas
- Acceptable spin relaxation times now demonstrated in prototype cells with glass-to-metal seals
- Conceptual and engineering designs for GEn-II target underway
The SBS Form Factor Program—Summary

- SBS high-$Q^2$ form factor program:
  - Map transition to perturbative regime—running of dressed quark mass function
  - Imaging of the nucleon charge and magnetization densities in impact-parameter space in the infinite momentum frame.
  - Precision high-$Q^2$ form factors have significant impact on GPD extraction from DVCS
- GMP: Proton magnetic form factor—improve on world data precision up to 16 GeV$^2$ (completed in Hall A, 2016)
- GEP: Proton electric form factor, increase $Q^2$ range from 8.5 → 12 GeV$^2$
- GEN: Neutron electric form factor, increase $Q^2$ range from 3.4 → 10 GeV$^2$
- GMN: Neutron magnetic form factor, increase $Q^2$ range from 5 → 13.5 GeV$^2$
Semi-Inclusive Deep Inelastic Scattering

- Detecting leading (high-energy) hadrons in DIS collisions, the SIDIS process N(e,e’h)X provides access to additional nucleon structure information that is inaccessible in DIS:
  - quark flavor
  - quark transverse motion
  - quark transverse spin

- Goal of SIDIS studies is (spin-correlated) 3D imaging of quarks in momentum space.


\[
\begin{align*}
  z & = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{\nu} \\
  p_T & = p_h - \frac{p_h \cdot q}{|q|^2} q \\
  W'^2 & = (M + \nu - E_h)^2 - (q - p_h)^2
\end{align*}
\]
Transverse target spin effects in SIDIS

<table>
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<th></th>
<th>quark</th>
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<tbody>
<tr>
<td>U</td>
<td>q</td>
<td>L</td>
</tr>
<tr>
<td>L</td>
<td>Δq</td>
<td>T</td>
</tr>
</tbody>
</table>

- **Collins effect**—chiral-odd quark transversity DF; chiral-odd Collins FF
- **Sivers effect**—access to quark OAM and QCD FSI mechanism
- “Transversal helicity” $g_{1T}$—real part of S wave-P wave interference (Sivers = imaginary part) (requires polarized beam)
- “Pretzelosity” or Mulders-Tangerman function—interference of wavefunction components differing by 2 units of OAM

\[ A_{UT}(\phi, \phi_S) = \frac{1}{P_T} \frac{d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)}{d\sigma(\phi, \phi_S) + d\sigma(\phi, \phi_S + \pi)} \]

\[ = A_{UT}^{Collins} \sin(\phi + \phi_S) + A_{UT}^{Sivers} \sin(\phi - \phi_S) + A_{UT}^{Pretz} \sin(3\phi - \phi_S) \]

\[ A_{UT}^{Collins} \propto \delta q \otimes H_{1T}^\perp \]

\[ A_{UT}^{Sivers} \propto f_{1T}^\perp \otimes D_1 \]

\[ A_{UT}^{Pretz} \propto h_{1T}^\perp \otimes H_{1T}^\perp \]

\[ D_1 = \text{unpolarized fragmentation function} \]

\[ H_{1T}^\perp = \text{Collins fragmentation function} \]

\[ A_{LT}(\phi, \phi_S) = \frac{1}{P_e P_T} \frac{Y_+(\phi, \phi_S) - Y_-(\phi, \phi_S)}{Y_+(\phi, \phi_S) + Y_-(\phi, \phi_S)} \]

\[ \sim A_{LT}^{cos(\phi - \phi_S)} \cos(\phi - \phi_S) \]

\[ \sim g_{1T} \otimes D_1 \]
E12-09-018: Transverse Target SSA in $^3$He(e,e’h)X

Electron Arm: BigBite Spectrometer @30 deg.

- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized $^3$He.
- 40 (20) days production at $E = 11$ (8.8) GeV—significant $Q^2$ range at fixed $x$
- Collins, Sivers, Pretzelosity, $A_{LT}$ for $n(e,e’h)X$, $h = \pi^+/\pi^-/\pi^0/K^+/K^-$
- Re-use HERMES RICH detector for charged hadron PID
- Reach high $x$ (up to $\sim 0.7$) and high statistical FOM ($\sim 1,000X$ Hall A E06-010 @6 GeV)

High-luminosity Polarized $^3$He Target
($1.2 \times 10^{37}$ cm$^{-2}$ s$^{-1}$)

Hadron Arm: Super BigBite Spectrometer @14 deg.

JLab E12-09-018 in Hall A: Approved for 64 beam-days, $A^-$ rating by PAC38 (2011)
Projected $A_{UT}^{Sivers}$ precision vs. $x$  

Projected $A_{UT}^{Collins}$ precision vs. $x$

- E12-09-018 will achieve statistical FOM for the neutron $\sim$100X better than HERMES proton data and $\sim$1000X better than existing neutron data from Hall A at 6 GeV a
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.
Acknowledgements

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• UConn grad student: Freddy Obrecht
• UConn postdoc: Eric Fuchey
Summary and Conclusions

- SBS is a moderate solid angle, large momentum-bite magnetic spectrometer designed to operate at the highest practically achievable luminosity at relatively forward angles. Optimized for the study of hard (large $Q^2$) exclusive and semi-inclusive coincidence ($e,e'N$), ($e,e'h$) processes

- GEM-based tracking is the enabling technology

- Currently approved physics program:
  - E12-07-109 (GEP/GMP): 45 days, A-
  - E12-09-016 (GEN/GMN): 50 days, A-
  - E12-09-018 (Transversity): 64 days, A-
  - E12-09-019 (GMN): 25 days, B+
  - ”C1” approved, E12-15-006: pion structure function via tagged DIS: 27 days, A-

- Large, active and growing collaboration

- DOE-funded SBS program is complete as of ~March 2017

- First SBS experiment (GMN) went through ERR last week

- New proposals in the pipeline, including but not limited to:
  - A1n with BB+SBS
  - GEn/GMn via recoil polarimetry
  - Wide-angle Compton Scattering

- Multi-year, high-impact physics program starting as soon as 2019 in Hall A

- Lots of work to do, opportunities for collaboration, Ph.D. theses

6/22/17  Hall A/C Summer Collaboration Meeting
Backup Slides
Reaching toward high $Q^2$ in Lattice QCD

- A. J. Chambers et al. (QCDSF/UKQCD/CSSM collaborations):
  - arXiv:1702.01513v1 [hep-lat]
  - Significant breakthrough in the use of the Feynman-Hellman theorem to compute hadronic matrix elements in lattice QCD; allows access to matrix elements via two-point correlators as opposed to complicated analysis of three-point functions, by relating matrix elements to energy shifts.
  - Improved ability to extract weak signals from relatively “noisy states”
  - Allows to reach higher momentum transfers than previously possible.

![Graph](image)

**FIG. 3.** Ratio $G_E/G_M$ for the proton from application of the Feynman–Hellmann method, from a variational analysis of three-point functions [25], and from experiment [5–7]. Note this is not scaled by the magnetic moment of the proton $\mu_p$, as this would require phenomenological fits to the low $Q^2$ data, which is not the focus of this work.

$$\frac{\partial E_\psi}{\partial \lambda} = \left\langle \psi \left| \frac{\partial H}{\partial \lambda} \right| \psi \right\rangle$$
Exposing the dressed-quark mass function

High-$Q^2$ nucleon FFs ($Q^2 > 5 \text{ GeV}^2$) are especially sensitive to momentum-dependent dressed-quark mass function in the few-GeV region, see e.g.,:


- SIDIS data from HERMES on proton target, COMPASS on proton and deuteron targets
- Data on azimuthal asymmetries in $e^+/e^-$ annihilation to pion pairs from BELLE and BaBar collaborations—very recent, high statistical precision
- First look at combined $z$ and $p_T$ dependencies of Collins FFs.
- Note—d quark transversity is poorly constrained—proton data dominated by u quarks, limited sensitivity to d from COMPASS deuteron and JLab Hall A $^3$He data.
Sivers effect—Existing knowledge


- Fits to most recent HERMES and COMPASS SIDIS Sivers data with TMD/DGLAP evolution
- As in the case of Collins/Transversity, d-quark Sivers is poorly constrained by existing data
  - Proton data dominated by u-quarks
  - Limited precision/sensitivity to d quark from COMPASS deuteron/JLab Hall A $^3$He data
- Wide, independent coverage of x, z, p_T, ϕ_h ± ϕ_S in a single kinematic configuration.
- At least four (preferably 8) target spin directions to achieve full ϕ_S coverage
- Q^2, x strongly correlated due to dimensions of BigBite magnet gap.
- Data at E = 11, 8.8 GeV provide data for significantly different Q^2 at same x
- Systematics control → independent spectrometers, detectors in field-free regions, straight-line tracking, simple, well-defined (but adequately large) acceptance, etc.
SBS+BB Projected Precision in 2D (x,z) binning

- 2D Extraction: Sivers $A_{UT}$ in $n(e,e'\pi^+)X$, 6 x bins $0.1 < x < 0.7$, 5 z bins $0.2 < z < 0.7$
- Curves are theory predictions (Anselmino et al.) with central value and error band

Uncertainty in this x, z bin ~ 0.6%

Large neutron $\pi^+$ asymmetry expected at high z, large uncertainty
SBS RICH detector

GEANT4-simulated RICH performance in SBS

Expected RICH PID performance in SBS for $\pi/K/p$
Highlights of RICH PMT testing @UConn

- **ADC input range = 2 Vpp; 1 count = 0.12 mV**
- This signal ~9.6 mV (after NINO amplifier) = ~2.4 mV raw signal amplitude
- FWHM ~14 ns
- Gate width for charge integration = 72 ns
- PMT in this example is at HV = +1,340 V

**Examples of single-ph.e. charge spectra**

- **One-ph.e. peak**
- **Two-ph.e. shoulder**

**Note: pedestal position is ~500 channels**

- 2,158 RICH PMTs (manufactured 1997-1998) tested at UConn during summer and fall 2016 by UConn grad. students Freddy Obrecht and Nilesh Deokar
- 32 PMTs rejected
- 1,934 needed for RICH → 10% spare capacity for experiment